FACULTY OF LAW AND CRIMINOLOGY

APPLICATION OF REMOTE MEASUREMENTS FOR COMPLIANCE MONITORING AND ENFORCEMENT OF SO_2 AND NO_X EMISSIONS UNDER MARPOL ANNEX VI



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Acknowledgements

Archimedes, the renowned mathematician, once famously stated, "Give me a place to stand and a lever long enough, and I will move the world." This PhD might not be the lever long enough to move the world, however my main motivation for writing this dissertation was to provide a meaningful contribution to both the scientific world and the policy level for reducing the impact of shipping on our society and natural environment.

Referring to Plato's cave allegory, it is imperative that we recognize the reality brought to light and strive to move forward, rather than turning inward and falling back into inactivity. Therefore, my ultimate hope is that this thesis will enhance the understanding of the impact of air pollution from ships on the environment. It is my fervent desire that this thesis will not remain a text gathering dust on a bookshelf or remains ones and zeros in an elusive digital cloud. Rather, I would be delighted if my findings could be implemented in the field and assist operators, colleagues, and fellow scientists in their endeavors to combat air pollution at sea. But even more, I hope this thesis will help to inspire policymakers to adopt new regulations that will have a tangible impact on safeguarding the global environment and its inhabitants. As rejecting reality in the face of overwhelming evidence would render us no better than Simplicio, who refused to accept the Copernican system where the earth orbits the sun, in Galileo's famous Dialogue concerning the two chief world systems.

But enough about scientists and philosophers from long forgotten times. We are all fools for love and while love makes us blind and makes us do crazy things. It also provides a lifeline, a level of support not to be surpassed by anything. Therefore, there is no one that I ever could be more grateful to than Rebecca Gualandi, you have been the force by my side during the last stretch of this PhD rat-race, you provided me with insights I would not have been able to take from anyone else. Your invaluable feedback and support during the proofreading were the cherry on my PhD cake.

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I must admit, it was one hell of a ride since 2015. I vividly recall a particular moment during a dark and rainy day in Antwerp. I was in my car, exhausted from recent flights, engaged in a phone conversation with Ronny about our potential involvement in the CompMon project. The discussions with the EU funding agency had been challenging for our entire team, causing headaches and uncertainties. Ronny expressed his doubts, concerned about the substantial costs and slim chances of success with the sniffer sensor. As I tried to persuade Ronny to proceed with the project, I realized that I was risking my professional career for chasing my ideals. Finally, he agreed to go forward with the project, and the rest ... is history.

"The Earth has enough resources for our need but not for our greed."
– Mahatma Gandhi

"The truth is: the natural world is changing. And we are totally dependent on that world. It provides our food, water and air. It is the most precious thing we have and we need to defend it."
– Sir David Attenborough

"The things of nature do not really belong to us, we should leave them to our children as we have received them. "
– Oscar Wilde

Application of remote measurements for compliance monitoring and enforcement of SO_2 and NO_X emissions under MARPOL Annex VI

By Ir. Ward Van Roy

Chapters

Abstracts

Abbreviations

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Part I

Chapter 1: 'Airborne monitoring of compliance to sulfur emission regulations by ocean-going vessels in the Belgian North Sea area.' (2022) Atmospheric Pollution Research (13) 101445.

Chapter 2: 'Airborne monitoring of compliance to NOx emission regulations from ocean-going vessels in the Belgian North Sea area.' (2022) Atmospheric Pollution Research (13) 101518.

Chapter 3: 'Measurement of Sulfur-dioxide emissions from ocean-going vessels in Belgium using novel techniques.' (2022) Atmosphere (13) 1756.

Part II

Chapter 4: 'The Role of Belgian Airborne Sniffer Measurements in the MARPOL Annex VI Enforcement Chain.' (2023) Atmosphere (14) 623.

Part III

Chapter 5: 'Assessment of the effect of international maritime regulations on air quality in the southern North Sea.' (2023) Atmosphere (16) 969.

Chapter 6: 'Assessment of the international maritime regulations' impact in the North & Baltic Sea.' (submitted to Nature Communications, 2023).

Part IV

Chapter 7: 'Current progress in developing a MARPOL Annex VI enforcement strategy in the Bonn Agreement through remote measurements' (Submitted to Marine Policy, 2023).

Chapter 8: 'Policy recommendations for international regulations addressing air pollution from ships.' (Submitted to Marine Policy, 2023).

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SUPPLEMENTARY MATERIAL: SNIFFER QUALITY ASSURANCE AND MAINTENANCE MANUAL 360

Abstract (English)

This doctoral dissertation describes how and to what extent airborne monitoring can contribute to the development of a strategy for monitoring and enforcing emission regulations for shipping. It also examines the impact of international regulations, established with the aim of reducing air pollution from shipping, using airborne monitoring. A series of five published scientific articles and three manuscripts submitted for publication approach the subject in a step-by-step manner, from the technical level to a more holistic and regulatory level. The thesis is divided into four parts representing each step, containing several chapters per part. Each chapter includes one article. The general introduction outlines the scope and the wider legal and operational framework of the thesis. The general conclusions list the main findings of the different chapters.

The first step of this thesis was to find technical solutions to set up an airborne monitoring method for ship emission. Therefore, in the first Part, the first three chapters address the topic from a more technical perspective. Building on the scientific findings of previous research, an empirically based methodology for conducting airborne monitoring is proposed for both SO_x and NO_x emissions. The first three chapters describe not only the developed methodologies, but also provide the measurement results. Overall, this first part shows that the described monitoring techniques are now scientifically mature.

The first chapter presents the basic monitoring methodology and shows that international regulations on SO_2 emissions can be effectively monitored by airborne measurements. The monitoring efforts furthermore confirmed that international regulations on SO_2 were relatively well observed and have therefore effectively contributed to significant reductions of SO_2 emissions. On the other hand, the second chapter also shows that these reductions were not achieved for NO_x. The research reveals that the average NO_x emissions of more recently built ships are significantly higher than those of older ships. Moreover, it was found that Tier III ships, for which the regulations aim to drastically reduce the NO_x emissions, are being introduced very slowly due to the implementing requirements in the NO_x regulations.

The third chapter describes the significantly improved monitoring methodology that was developed for SO_x emission measurements. This was obtained by applying several innovative techniques. The study also successfully demonstrates, for the first time, that ships equipped with after-treatment systems, also known as scrubbers, account for a significantly larger proportion of potential emission violations. An important aspect of these three articles is the comprehensive manual that was subsequently updated and published in the supplementary material. This manual ensures methodological uniformity and guarantees the quality of the measurements that were carried out. This manual can therefore serve as a starting point for developing a quality assurance system when setting up a monitoring program in other countries.

After these more technically oriented chapters. The next step of this thesis was to examine the added value of aerial monitoring for port inspection authorities. The fourth chapter demonstrates that the elaborated air monitoring program in Belgium has had a positive impact on the follow-up and sanctioning of emission violations by ships. For example, it was demonstrated that port inspection authorities in Belgium and other European Member States were able to follow up on a high proportion of reported potential violations. This follow-up led to a high proportion of detected infringements and deficiencies and, consequently, sanctions. Through a cost-benefit analysis, the study additionally shows that aerial surveillance pays off financially.

For the next step of this thesis, the extent to which the international rules can fulfil their objectives was assessed based on remote monitoring results. In Part 3, the impact of the regulations on the air quality in Belgium and the wider North and Baltic Sea area is described in two chapters. Chapter 5 focuses on Belgium, whereas Chapter 6 looks at the whole North Sea and Baltic Sea emission control area.

For the analysis of the impact for Belgium, the Belgian airborne monitoring results from 2015-2019 were first corrected to be analyzed in conjunction with the data from 2020-2022. Secondly, the data from the Belgian air quality monitoring stations in the region of Flanders were analyzed from 2000-2022. This shows that the international regulations were effective in reducing SO_2 pollution in Belgium. The reductions in SO_2 match the implementation of several SO_2 emission restrictions for ships. However, it was also found that SO_2 emissions from scrubbers provide an increasing reason for concern. It was demonstrated that, although, the global sulfur gap reduced the average SO_2 emissions and non-compliance rate in Belgium waters, it also resulted in an increase of the use of scrubbers. In light of this evolution, the results of the research show that SO_2 emissions from these scrubber ships are on average substantially higher than from other ships. This evolution combined with an increase of the non-compliance rate and the increase of global shipping as a whole will inevitably result in an increase in shipping related SO_2 emissions.

While SO_2 emissions from non-ship sources (like energy production, road transport, etc.) will follow a decreasing trend, ship related SO_2 emissions are expected to increase. Therefore, it is concluded that shipping as a source for SO_2 emissions will gain in importance in the following years. It is projected that by 2030, SO_2 from shipping will contribute to 7% of the total anthropogenic SO_2 emissions in Flanders, whereas this was only 3% in 2020. In addition, it was demonstrated that the international NO_x regulation did not have any impact on the already historically high NO_x polluted region of Flanders. It was even demonstrated that by 2025, the shipping sector will be the largest contributor of NO_x pollution in Flanders and may contribute to up to 40% of all anthropogenic NO_x emissions in Flanders by 2030.

The sixth chapter of this thesis describes the impact of the regulations for the entire emission control area. Therefore, the results of the Belgian airborne monitoring and port inspection efforts were complemented by the remote monitoring results from other Bonn Agreement Contracting Parties. In addition, a satellite analysis was performed on TROPOMI data. These analyses show that the various international regulations had varying degrees of success in improving air quality. It was demonstrated that similarly to what was observed in Belgium, the SO_2 concentrations in the other countries of the emission control area decreased significantly in 2015. However, results show that they are now rising again. It was also confirmed that the introduction of the NO_x emission control area in the North Sea and Baltic Sea has not yet contributed to the hoped-for reduction in NO_x emissions from shipping.

The last step of this thesis was to formulate recommendations for policymakers based on the experience gained. In Part 4, the seventh chapter of this dissertation describes the cooperation with the other contracting parties of the Bonn Agreement regarding MARPOL Annex VI. The chapter provides an overview of the efforts that have been made and that are planned for an effective monitoring strategy within the Bonn Agreement. The eighth and closing chapter of this thesis describes the legal consideration of remote measurements. For this purpose, the legal entities and instruments involved with regard to MARPOL Annex VI were analyzed to evaluate whether remote measurements would be found acceptable for legal follow up. In addition, this chapter sets out legal recommendations that could make an effective contribution on the ground to reducing air pollution from shipping. These recommendations are discussed within the Bonn Agreement and within IMO's subsidiary bodies and will, albeit slowly, find their way into the IMO decision-making bodies.

Abstract (Dutch)

Deze doctoraatsthesis beschrijft in hoeverre luchttoezicht kan bijdragen tot de ontwikkeling van een strategie voor de monitoring en handhaving van de emissieregelgeving voor de scheepvaart. Daarnaast wordt nagegaan wat de gerealiseerde impact is van deze internationale emissieregelgeving op basis van het uitgevoerde luchttoezicht. Een reeks van vijf gepubliceerde en drie voor publicatie ingediende artikels benaderen het onderwerp stap voor stap, gaande van het technische niveau naar een meer holistisch en regelgevend niveau. De thesis is verdeeld in vier delen die elk, in verschillende hoofdstukken, een stap in dit proces beschrijven, waarbij elk hoofdstuk één artikel omvat. Daarnaast schetst de algemene inleiding de omvang en het breder juridische en operationele kader van de thesis, terwijl in de algemene conclusies de belangrijkste bevindingen van de verschillende hoofdstukken worden opgesomd.

De eerste stap van deze thesis was het vinden van een wetenschappelijk onderbouwde methode voor de monitoring van scheepsemissies vanuit de lucht. Daarom wordt het onderwerp in dit eerste deel vanuit een meer technische context benaderd in drie hoofdstukken. Voortbouwend op de wetenschappelijke bevindingen van eerder onderzoek is een methode voor de monitoring van zowel SO_x- als NO_x-emissies vanuit de lucht voorgesteld. In de eerste drie hoofdstukken worden niet alleen de ontwikkelde methodologieën beschreven, maar worden ook de meetresultaten gegeven. In het algemeen toont dit eerste deel aan dat de uitgewerkte technieken nu wetenschappelijk onderbouwd zijn.

In het eerste hoofdstuk wordt het algemene concept van de methodiek gepresenteerd en wordt aangetoond dat de internationale SO_2-emissie regelgeving doeltreffend kan worden gemonitord vanuit de lucht. Daarnaast toonden de monitoringsresultaten aan dat de internationale regels inzake SO_2 relatief goed worden nageleefd en derhalve daadwerkelijk hebben bijgedragen tot een aanzienlijke vermindering van de SO_2-emissies. Anderzijds blijkt uit het tweede hoofdstuk ook dat deze vermindering niet werd bereikt voor NO_x. Integendeel, de studie heeft enkele verontrustende conclusies opgeleverd, aangezien is gebleken dat de gemiddelde NO_x-emissies van recenter gebouwde schepen aanzienlijk hoger zijn dan die van oudere schepen. Bovendien werd vastgesteld dat de Tier III-regelgeving, die erop gericht is de NO_x-emissies drastisch verder te beperken, slechts zeer langzaam ingang vindt als gevolg van de manier waarop deze regelgeving is opgesteld.

In het derde hoofdstuk wordt de aanzienlijk verbeterde methodiek beschreven die werd ontwikkeld voor SO_x. Deze werd verkregen door het ontwikkelen van verschillende innovaties. De studie toonde ook voor het eerst aan dat schepen met nabehandelingssystemen, de zogenaamde *scrubbers*, een aanzienlijk groter deel van de emissieovertredingen voor hun rekening nemen. Een belangrijk aspect van deze drie artikelen is de uitgebreide handleiding die steeds werd bijgewerkt en toegevoegd in bijlage bij de verschillende publicaties. Deze handleiding waarborgt de uniformiteit en de kwaliteit van de uitgevoerde metingen. Deze handleiding kan derhalve als uitgangspunt dienen voor het opzetten van een monitoringprogramma in andere landen.

Na deze meer technisch georiënteerde hoofdstukken, werd in de volgende stap van deze thesis de toegevoegde waarde van de monitoring vanuit de lucht voor de haveninspectiediensten nagegaan, dit is beschreven in het tweede deel van deze dissertatie. Het vierde hoofdstuk toont aan dat het uitgewerkte monitoringprogramma in België een positieve invloed heeft gehad op de opvolging en sanctionering van emissieovertredingen van schepen. Zo is aangetoond dat de haveninspectiediensten in België en andere Europese lidstaten een groot deel van de gerapporteerde potentiële overtredingen konden opvolgen en sanctioneren. Via een kosten-batenanalyse toont dit artikel bovendien aan dat toezicht vanuit de lucht financieel loont.

Voor de volgende stap van deze thesis werd, op basis van de monitoringsresultaten, nagegaan in hoeverre de internationale regels hun doelstelling kunnen waarmaken. In deel 3 wordt het effect van de regelgeving op de luchtkwaliteit beschreven in twee hoofdstukken. Hoofdstuk 5 richt zich op België, terwijl hoofdstuk 6 ingaat op de luchtkwaliteit in het Noordzee en Baltische Zee emissie controle gebied.

Voor de analyse van de impact voor België werden eerst de Belgische luchtmonitoringsresultaten van 2015-2019 gecorrigeerd om ze samen met de gegevens van 2020-2022 te analyseren. Daarnaast werden de gegevens van de Vlaamse luchtkwaliteit meetstations van 2000-2022 geanalyseerd. Hieruit blijkt dat de internationale regelgeving zeer doeltreffend was om de SO_2-verontreiniging in België te verminderen. De reductie in SO_2 komt bovendien goed overeen met de invoering van verschillende SO_2-uitstoot regels voor schepen. Er werd echter ook vastgesteld dat de SO_2-uitstoot van scrubbers een toenemende reden tot bezorgdheid vormen. Zo werd aangetoond dat, hoewel de *global sulfur cap* de gemiddelde SO_2-uitstoot en het aantal overtredingen in de Belgische wateren verminderde, deze ook zorgde voor een toename van het aantal scrubberschepen, welke een aanzienlijk hogere gehalte aan SO_2 bleken uit te stoten. Deze ontwikkeling, in combinatie met de toename van de scheepvaart, zal onvermijdelijk leiden tot een toename van de SO_2 uitstoot door de scheepvaart.

Terwijl de SO_2-emissies van andere bronnen (zoals energieproductie, wegvervoer, enz.) een dalende trend volgen, zal de SO_2-uitstoot van de scheepvaart naar alle verwachtingen toenemen. Hierdoor zal de scheepvaart de komende jaren relatief een groter aandeel innemen van de totale SO_2-uitstoot, zo zal tegen 2030 de scheepvaart naar verwachting 7% bijdragen aan de totale SO_2-uitstoot in Vlaanderen, terwijl dat in 2020 nog slechts 3% was. Bovendien is aangetoond dat de internationale NO_x-uitstoot regels geen effect hebben gehad op de toch al historisch hoge NO_x-vervuiling in Vlaanderen. Er is zelfs aangetoond dat de scheepvaartsector tegen 2025 de grootste uitstoter van NO_x in Vlaanderen zal zijn en tegen 2030 zelf zal zorgen voor 40% van alle NO_x-uitstoot in Vlaanderen.

Het zesde hoofdstuk van dit proefschrift beschrijft de impact van de regelgeving op de luchtkwaliteit in het gehele emissie controle gebied. Hiervoor werden de Belgische resultaten van de luchtmonitoring en haveninspecties aangevuld met de monitoringsresultaten van de andere partijen van het Akkoord van Bonn. Bovendien werd een analyse gemaakt op basis van satellietbeelden. Uit deze analyses blijkt dat de verschillende internationale regels in uiteenlopende mate hebben bijgedragen aan de verbetering van de luchtkwaliteit. De resultaten tonen aan dat, net als in België, de SO_2-uitstoot door schepen in de andere landen sinds 2015 aanzienlijk is gedaald, al werd ook vastgesteld dat ze nu weer in stijgende lijn zijn. Voorts is bevestigd dat de invoering van NO_x regels in de Noordzee en de Baltische zee nog niet hebben bijgedragen tot de verhoopte vermindering van de NO_x-uitstoot door de scheepvaart.

De laatste stap van het doctoraatsonderzoek bestond uit het beschrijven van de internationale samenwerking en het formuleren van aanbevelingen voor beleidsmakers op basis van de opgedane ervaring. In deel 4 beschrijft het zevende hoofdstuk de samenwerking met de andere partijen van het Bonn Akkoord met betrekking tot Bijlage VI van MARPOL. In dit hoofdstuk wordt een overzicht gegeven van de inspanningen die reeds werden geleverd en zijn gepland in het kader van het Bonn Akkoord om een doeltreffende en geharmoniseerde monitoring strategie te ontwikkelen. Het achtste en laatste hoofdstuk beschrijft de juridische aspecten van het luchttoezicht. Daartoe werden de relevante juridische instrumenten geanalyseerd om onder andere na te gaan of luchttoezicht aanvaardbaar bewijsmateriaal kan aanleveren voor een juridische follow-up. Voorts worden een aantal aanbevelingen gedaan voor bijkomende regelgeving die op het terrein een effectieve bijdrage kunnen leveren voor de vermindering van de luchtverontreiniging door de scheepvaart. Deze aanbevelingen zijn reeds besproken binnen het Akkoord van Bonn en de IMO hulporganen en zullen, zij het langzaam, hun weg vinden naar de IMO besluitsorganen.

List of Abbreviations

A: Amplitude
AC: Aircraft
AFS: Anti-Fouling Systems
AIS: Automatic Identification System for Ships
ANIP: Common Emmergency and Intervention Plan (in dutch: Algemene Nood en Interventie Plannen)
AOH: Aerial Operations Handbook
ARINC: Aeronautical Radio INC
b: bias
BA: Bonn Agreement
BAOAC: Bonn Agreement Oil Appearance Code
BAQZJR: Bonn Agreement Quadripartite Zone of Joint Responsibility
BASAP: Bonn Agreement Strategic Action Plan
BC: Black Carbon
BDC: Biodiversity Committee
BE-AWARE: Bonn Agreement: Area-Wide Assessment of Risk Evaluations
BELSPO: Belgian Science Policy
BHP: Brake Horse Power
BIM: Brussels Institute for Environmental Management (Leefmilieu Brussel)
BIRA: Royal Belgian Institute for Space Aeronomy
BN2: Britten Norman Islander
BS: Baltic Sea
BS: Belgisch Staatsblad (Belgian Notifications)
BSH: Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie)
BWM: Ballast Water and Sediments
C: Concentration
CEF: Connecting Europe Facility
CEMS: Continuous Emission Measurement System
CG: Coast Guard
CH_4: Methane
CI: Confidence Interval
COG: COordination group
CompMon: Compliance Monitoring Project
CP: Contracting Party
CPM: Counter Pollution Manual
CS: Cross Sensitivity
CSN: Clean Sea Net
CV: Intra-assay coefficients of variability
CvC: Committee of Chairmen and Vice- Chairmen
CVRW: Intra-Assay Coefficients of Variability
DAB: Independent Management Service (Dienst Azonderlijk Beheer (Vloot))
DECA: Domestic Emission Control Area
DG-ECHO: Directorate General for European Civil Protection and Humanitarian Aid Operations
DG-MOVE: European Directorate General for Mobility and Transport
DWT: Dead Weight Tonnage
EAP: Aerial surveillance Experts Assessment Panel
EASA: European Aviation Safety Agency

EC: European Commission
ECA: Emission Control Area
EEA: European Environment Agency
EEDI: Energy Efficiency Design Index
EEXI: Energy Efficiency Existing Ship Index
EEZ: Exclusive Economic Zone
EF: Emission factor
EGCS: Exhaust Gas Cleaning System
EGR: Exhaust Gas Reintroduction
EIAPP: Engine International Air Pollution Prevention Certificate
EIHA: Environmental Impact of Human Activities Committee
EL: Engine Load
EMSA: European Maritime Safety Agency
EP: Emergency Plan
EPA: (Danish) Environmental Protection Age
EPL: Egine Power Limitation
EQSD: Environmental Quality Standards Directive
ERS: Engine Rated Speed
ESA: European Space Agency
ETS: Emission Trading Scheme
EU LRIT CDC: EU Long Range identification System Cooperative Data Centre
EU: European Union
EUROSTAT: Directorate General for European Statistics
FMI: Finish Meteorological Institute
FMS: Flight Management System
FPS: Federal Public Service (Mobility and Transportation)
FSC: Fuel Sulphur Content
g: gram
GDP: Gross Domestic Product
GHG: GreenHouse Gas
GPS: Global Positioning System
GSC: Global Sulfur Cap
GT: Gross Tonnage
GWP: Global Warming Potential
HASEC: Hazardous Substances and Eutrophication Committee
HC: Hydro Carbon
HELOM: Helsinki Commission
HFO: Heavy Fuel Oil
HNS-MS: (Improving Member States preparedness to face an) Harmfull Noxious Substance pollution of the Marine System
HOD: Head Of Delegation
HP: Horse Power
IAPP: International air pollution prevention Certificate
ICCT: Internation Council on Clean Transportation
ICS: International Chamber of Shipping
IEA: International Energy Agency
IFO380: Intermediate Fuel Oil (with viscosity of 380 mm^2/s)

IGPS: Identification of Gross Pollution Ships (software)
ILO: International Labour Organization
ILT: Inspectorate of the Ministry of Infrastructure and Water Management of the Netherlands (Inspectie Leefomgeving en Transport)
IMAROS: Improving response capacities and understanding the environmental impacts of new generation low sulphur MARine fuel Oil Spills
IMO: International Maritime Organization
IMS: Integrated Maritime Services
IPCC: Intergovernmental Panel on Climate Change
IPSS: International Ship and Port Facility Security
IR: Infra-Red
ISR: In Stack Ratio
IWT: European Inland Waterway Transport Platform
KB: Koninklijk Besluit (Royal Decree)
KBRV: Royal Belgian Shipowners' Association (Koninklijke Belgische Reders Vereniging)
Khd: humidity correction
KLD: Keel Laying Date
KLY: Keel Laying Year
kts: knots
kWh: kilo What hour
L: Limit
l: liter
LCA: Life Cycle Assessment
LNG: Liquified Natural Gas
LOA: Limits of Agreement
LOSC: United Nations Convention on the Law of the Sea
LRIT: Long-Range Identification and Tracking
LSFO: Low Sulfur Fuel Oil
LSMGO: Low Sulfur Marine Gas Oil
m: meter
MAD: Maximum Allowable Difference
MANIFESTS: MANaging risks and Impacts From Evaporating and gaseous Substances To population Safety
MAP: Map (function of IGPS)
MARPOL: Convention for the Prevention of Marine Pollution from Ships
MAVIEWS: MARPOL Annex VI Experts Work Shop
MDK: Agentschap Maritieme Dienstverlening en Kust (Agency for Maritime Services and the Coast)
MEP: Main Engine Power
MEPC: Marine Environmental Protection Committee
MEOP: Multiple Engine Operational Profiles
MGO: Marine Gas Oil
MIK: Maritime Information Centre (Maritiem Informatie Kruispunt)
MoU: Memorandum of Understanding (Paris MoU)
MS: Member State
MSFD: Marine Strategy Framework Directive
MSP: Marine Spatial Plan
MUMM: Management Unit of the Mathematical Model of the North Sea

n: Degrees of freedom
N_2O: Nitrous Oxide
NCA: National Competent Authority
NDIR: NonDispersive InfraRed
NEBA: Net Environmental Benefit Analysis
NECA: NOx Emission Control Area
NESTRA: Netherlands Expert Group for Sustainable TRAnsport and Logistics
NGO: Non-Governemental Organisation
NH_3: Ammonia
NHTSS: North Hinder Traffic Separation Scheme
nm: Nautical Miles
NO_2: Nitrogen Dioxide
NO_x: Nitrogen Oxides
NS: North Sea
NSN: North Sea Network on Prosecuters
NTE: Not To Exceed Limit
OC: Organic Carbon
OD: Operational Directorate (Nature)
OGV: Ocean Going Vessel
OIC: Offshore Industry Committee
OPS: Operations Manual
OSINet: Oil Spill Identification Network
OSPAR: Oslo and Paris Convention
OTSOPA: Working Group on Operational, Technical and Scientific Questions Concerning Counter-Pollution Activities
PAH: Polycyclic Aromatic Hydrocarbon
PM: Particle Matter
PoC: Point of Contact
PPB: Parts Per Billion
PPM: Parts Per Million
PPR: Pollution Prevention and Response
PRF: Port Reception Facilities
PSC: Port State Control
PTFE: Polytetrafluoroethylene
PVC: Polyvinyl Chloride
QA: Quality Assurance
QPZJR: Quadripartite Zone of Joint Responsibility
R or r: Correlation
RBINS: Royal Belgian Institute of Natural Sciences
RH: Relative Humidity
RoRo: Roll on Roll off vessel
RPAS: Remotely Piloted Airborne Vehicles
RPM: Rotations Per Minute
RSC: Radioactive Substances Committee
RSD: Relative Standard Deviation
RTM: Rotterdam
RV: Research Vessel

s: second
S: Sulfur limit
SAGRA: SAnd and GRAvel extraction
SCIPPER: Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations
SCR: Selective Catalytic Reduction
SD: Standard Deviation
SECA: Sulphur Emission Control Area
SEG: SafeSeaNet Ecosystem Graphical User Interface
SFC: Specific Fuel Consumption
SFOC: Specific Fuel Oil Consumption
SLAR: Side-Looking Airborne Radar
SNF: Sniffer (function of IGPS)
SNR: Signal To Noise Ratio
SO_2: Sulfur Dioxide
SOLAS: International Convention for the Safety of Life at Sea
SOP: Standard Operating Procedures
SOWG: Strategic Operational Working Group
SOx: Sulphur Oxides
SPN: Directie van de scheepvaartpolitie (Shipping Police)
SQMS: Sniffer Quality Management System
SSN: Safe Sea Net
SSPD: Ship Source Pollution Directive
STOL: Short Take Off and Landing
T or t: Temperature
T: Threshold
t: time
T90: 90% Response Time
TDH: Tour de Horizon
TEU: Twenty-foot Equivalent Unit
TROPOMI: TROPOspheric Monitoring Instrument
TWG: Technical Working Group
U: Uncertainty
ULSFO: Ultra Low Sulfur Fuel Oil
UMAS: University Maritime Advisory Services
UN: United Nations
UNCLOS: United Nations Convention on the Law of the Sea
UNCTAD: United Nations Conference on Trade and Development
UNFCCC: United Nations Framework Convention on Climate Change
UV: UltraViolet
VCD: Vertical Column Density
VLIZ: Vlaams Institute voor de Zee (Flemish Institute for the Sea)
VLSFO: Very Lowe Sulfur Fuel Oil
VMM: Flanders Environment Agency (Vlaamse Milieumaatschappij)
VOC: Volatile Organic Compound
WF: Weighting Factor
WFD: Water Framework Directive
WH: West Hinder (anchorage Area)

WHO: World Health Organization
WHTSS: West Hinder Traffic Separation Scheme
WS: Westerscheldt
WTTC: World travel and Tourism Council
XRF: X-Ray Fluorescence
σ: Sigma

General Introduction



RBINS -MUMM © picture taken during flight 17085 (20/06/2017)

General Introduction

1. Outlining of the dissertation

The key subject of this doctoral dissertation is air pollution caused by international shipping and, more specifically, how international regulations established to reduce ship emissions and thus air pollution, can be monitored and enforced via airborne monitoring techniques. This thesis includes various chapters that look at the use of airborne monitoring techniques to establish effective monitoring and enforcement practices with regard to the ship emission regulations and their impact on air quality. This general introduction provides a comprehensive background to the subject matter to shed light on the research objectives of the thesis. This introduction starts by outlining the broader picture of the importance of emissions regulations for ships, how these regulations came about, who is responsible for enforcing these regulations and how this is achieved. In addition, relevant previous studies and monitoring activities on this topic are discussed. Next, the research area and the methods used in this thesis are presented. Finally, the structure of the thesis and the main research questions are defined.

2. Background on air pollution from shipping

This section describes the general background on air pollution from international shipping, emphasizing the importance of regulating ship emissions. This can be particularly helpful for readers who are unfamiliar with the subject as it provides context for the rationale behind implementing and enforcing emissions regulations.

2.1. Economic importance of shipping

The shipping industry is responsible for the transportation of over 80% of the world's trade goods, making it an essential component of international trade [1]. For the European Union (EU), shipping accounts for 80% of total exports and imports by volume, and 50% by value, as of 2019 [2]. With 11 billion tons of transported goods, the total value of the annual world shipping trade accounted to more than 14 trillion US Dollars in 2022 [3]. International shipping is therefore intricately linked to the global gross domestic product (GDP.) By 2030 international shipping is expected to increase *ca.* 2.5-3% annually [1,4,5].

The main importance of the shipping industry is transporting raw materials and finished goods between countries. This movement of goods between different parts of the world has led to the development of a global market that is interconnected and interdependent. The shipping industry has enabled certain countries to export raw materials they have in abundance and other countries to specialize in the production of finished goods they have a comparative advantage in, leading to increased productivity and economic growth [2].

In addition, international shipping is essential for the global food supply chain. The world's population is projected to reach 9.8 billion by 2050 [6]. Without international shipping, it would be challenging to meet the food demands of the world's growing population.

Further, the shipping industry is essential for the transportation of energy resources. The transportation of crude oil and natural gas is critical for the worldwide energy security. In 2021 energy products were responsible for 36% of all seaborne trade [7].

The shipping industry also plays a crucial role in the transportation of renewable energy resources such as wind turbines and solar panels [8]. The transportation of these resources is essential for meeting the growing demand for clean energy and reducing reliance on fossil fuels.

Finally international shipping is also essential for passenger transport and the global tourism industry. In the EU annually *ca.* 400 million people embark on passenger vessels annually, with exception for 2020 due to global Covid-19 pandemic [9]. In addition, the tourism industry is a significant contributor to the global economy, and international shipping plays a crucial role in transporting tourists from one part of the world to another [10]. The shipping industry also plays a crucial role in transporting goods and supplies to tourist destinations, ensuring that tourists have access to the services and products they need.

2.2. Environmental impact from shipping

The shipping sector is known for its use of heavy fuel oils (HFO). These fuel oils were introduced in the maritime sector in the second half of the previous century to provide use for the residual fuels after refinery [11]. However, its use has been leading to extensive and persistent marine pollution of the ocean surface, water column, seabed, and global atmosphere [12–14]. The act of utilizing fuel oil for ship propulsion inevitably causes diverse environmental impacts, given that it entails a combustion process that produces a range of air pollutants, such as sulfur oxides (SO_x), nitrogen oxides (NO_x), particulate matter (PM), black carbon (BC), and volatile organic compounds (VOCs), which have significant indirect and direct effects on the environment. When SO_x and NO_x dissolve in water, they generate H_2SO_4 (sulfuric acid) and HNO_3 (nitric acid), respectively, leading to the formation of acid rain and ocean acidification [15,16].

High concentrations of gaseous SO_x can have detrimental effects on trees and plants, leading to foliage damage and reduced growth [15]. To reduce SO_x emission and comply with emission regulations (see Section 3 for the legal framework), ships can choose to use exhaust gas cleaning system (EGCS), also known as "scrubbers". These EGCS work by spraying a solution of seawater and alkaline into the exhaust stream, which dissolves the SO_x. The EGCS wash water is afterwards either discharged overboard (open loop) or stored on board (closed loop). This process may reduce the airborne emission of SO_x, but when used in an open loop system, leads inherently to ocean acidification, which in specific locations can take on significant levels. Dulière et al. have demonstrated that in the shallow areas of the North Sea, the acidification potential of the EGCS wash water is several times higher than the current ocean acidification caused by carbon dioxide (CO_2) emissions [17]. In addition, the high concentrations of several heavy metals and other pollutants like poly aromatic hydrocarbons (PAHs) in the discharged washwater are a reason for concern, especially in the shallow waters of the Baltic Sea which suffers already from historic high concentrations of heavy metals [18–20].

Apart from contributing to the formation of acid rain, NO_x emissions have been observed to have adverse effects on foliage, resulting in decreased growth and reduced crop yields [15]. In addition, Nitrate radicals (NO_3^*) are highly reactive oxidants that, when combined with VOCs, play a crucial role in the process of ozone depletion, and contribute to the formation of the ozone hole [21]. To reduce NO_x emissions, ship owners may opt to use an after-treatment system such as selective catalytic reduction (SCR). However, it must be noted that these systems have been prone to slips of ammonia (NH_3) and the formation of nitrous oxide (N_2O) [22,23]. NH_3 pollution can have a significant impact on biodiversity, particularly through the accumulation of nitrogen, which affects plant species diversity and composition in affected habitats. Additionally, ammonia pollution influences species composition by causing soil acidification and direct toxic damage to leaves [23].

2.3. Climate change impact

When burned, fossil fuels generate greenhouse gases (GHGs) such as CO_2, NO_x, N_2O, methane (CH_4) and BC. It's commonly known that the main GHG responsible for global climate change is CO_2. Being responsible for only 3% of global CO_2 emissions [24], seaborne trade emits low amounts of CO_2 per unit

of goods transported per kilometer when compared to other freight modes [25,26], making it an efficient means of transport (Figure 1) [7]. Moreover, due to the ample space available on ships, maritime transport is highly suitable for the adoption of sustainable energy sources such as green hydrogen and ammonia [7,27]. International shipping can therefore play a pivotal role in climate change mitigation.

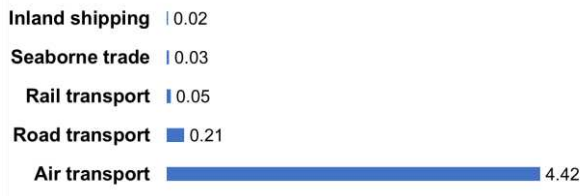


Figure 1. CO_2 emissions per kg transported goods expressed in kg CO_2 /1000 km [25,26].

However, when looking at the impact of the shipping industry it's important to take a more comprehensive approach, thus it is inevitable for all transported goods to follow primary and secondary transportation via road or rail in order to reach ports or the next distribution stage. Such primary and secondary transportation often leads to greater CO_2 emissions compared to the seaborne phase. Nevertheless, given the inherent connection between these two transportation phases, it is imperative to include both in any comprehensive life cycle impact assessment (LCA) of the shipping industry. A mere transition to alternative energy sources for ships would be insufficient in achieving a sustainable economy and transportation mechanism. Instead, a shift towards a sustainable economy which emphasizes high-quality production rather than high quantity is necessary for achieving net zero emissions.

Another important GHG from shipping is NO_x. Even though its effect on global warming is not direct, but rather indirect through the formation of ozone, it is a more potent GHG than CO_2. Nevertheless, the extent of its global warming potential (GWP), i.e. the thermal radiating capacity expressed in CO_2 equivalent (CO_2-eq), is highly dependent on the location and altitude of its emission [28,29]. Lasek et al. provide a comprehensive literature overview of NO_x as GHG [29]. Lamel et al. calculated a 20-year GWP for NO_x at sea level of ca. 31.5 CO_2-eq and 8.5 CO2-eq for a 100-year period [28]. As demonstrated in Chapter 6, this accounts to the 45% and 12% of the GWP of shipping related CO_2 emissions over a 20-year and 100-year period respectively. Johnson and Derwent determined a comparable GWP of 5 CO2-eq for a 100-year period for surface Northern Hemisphere sources, however for the Southern Hemisphere the impact is lower. However, for certain areas the GWP may be substantially higher, with the highest impact in the area of Brazil [30]. Additionally, Skowron et al. demonstrated that NO_x is a very short-lived GHG [31], reducing its emissions from ships would therefore lead to an immediate reduction of the climate impact of international shipping.

While shipping is not typically a major contributor to high N_2O emissions [24], N_2O is considered as one of the most potent GHGs, with a GWP of 280 and 300 CO_2-eq on a respective 20- and 100-year basis [22,32]. Overall, the climate change impact of N_2O emitted from ships accounts for 0.5% of their overall climate change impact [33,34]. It should be noted that the use of an SCR system can potentially result in significant emission of N_2O [22].

CH_4 is recognized as a highly potent GHG, with a GWP of 30 CO_2-eq over a 100-year period [35]. Conventional fuel oil-powered ships generally have limited emissions of CH_4. However, incomplete combustion of hydrocarbons (HCs) in fuels can lead to the generation of small amounts of CH_4. Several factors, such as the CH_4 content of the fuel, engine type, presence of non-combusted hydrocarbons in the engine, and effectiveness of emission abatement systems, can affect CH_4 emissions. Gas-powered

ships, mainly liquefied natural gas (LNG), emit drastically less SO_x and NO_x emissions, but are a major source of CH_4 [35].

Although strictly speaking not a gas, BC also contributes significantly to climate change via its capacity to absorb sunlight and cover sea ice, reducing its reflective capacity, an effect called "blacking" of sea-ice [36–38]. The importance of BC emissions cannot be understated as it is considered the second most important contributor to climate change after CO_2 [39]. This is mainly a result of BC's very high GWP. For a 20-year period the GWP of BC is 4470 CO_2-eq and 1647 CO_2-eq for a 20-year basis [39–42]. Accounting to a GWP of 21% over a 20-year period and 7% over a 100-year period, compared to shipping related CO_2 emissions [38]. BC is also a short-lived climate pollutant [39–41], which means that regulating BC emissions would lead to an immediate reduction of its impact on climate change.

While SO_2 itself is not considered a GHG, its emissions can indirectly impact global warming. Sulfur particles released to the atmosphere during combustion processes can contribute to the formation of sulfate aerosols, which have a cooling effect by reflecting solar radiation [43]. While this cooling effect may initially seem beneficial, it masks the primary effect of global warming. As efforts to address climate change will inherently lead to a transition away from carbon-based fuels, the cooling effect of sulfate aerosols will diminish, potentially resulting in a sudden increase in the climate forcing of other GHGs.

2.4. Health impact

Apart from the harmful impact of burning fossil fuels in the shipping industry on the environment and climate, the impact of emissions from shipping on human health may be the most concerning, posing a severe burden on our society. With air pollution being acknowledged as the primary cause of fatalities worldwide, [44–48] the human toll of ship-source air pollution has become of rising concern.

Numerous studies have been conducted to assess the health effects of international shipping on global and regional level. Mueller et al. made a comprehensive overview of the research done in this area [49]. In one of the more recent studies, Sofiev et al. estimated the global number of premature deaths caused by ship-source air pollution at between 226,800 (for Scenario 2) and 349,000 (for Scenario 1) in 2020 [50]. On a European level, Crippa et al. estimated the number of premature deaths to be 11,569 in 2019 [51].

While most studies focus on PM, it should be noted that SO_x and NO_x particles indirectly contribute to a substantial extent to the total PM emissions caused by shipping. The consensus is that by reducing SO_x and NO_x emissions, PM emissions are also reduced. According to Sofiev et al, by reducing SO_x emissions in 2020, an estimated 122,000 premature deaths could be prevented (Scenario 2). As will be demonstrated further in this general introduction, the discussed global SO_x reduction was effectively implemented. Additionally, Zhang et al. (2020) demonstrated that the most significant progress in further reducing the health burden from shipping can be made by reducing NO_x emissions. His estimations show that the "Tier III scenario" could prevent 42% of all remaining premature deaths caused by international shipping [52].

It is important to note that this kind of research relies on modelling techniques. In addition to specialized health models, these studies utilize maritime traffic data from ships' automatic identification systems (AIS), engine databases, and plume models, as well as average emission factors. These studies use different assumptions and approaches in estimating the total health impact, often resulting in substantial differences. Emission data can affect specialized health models significantly, therefore accurate emission data should be inputted. The research conducted in this dissertation provides more insights on real-world emission factors and therefore helps in refining the health impact models. In addition, these studies

are often based solely on average emission factors and disregard non-compliance behavior, which can lead to an underestimation of the health impact.

3. Legal framework

This section presents a comprehensive overview of the legal framework regarding international and national regulations on ship emissions. The different legal instruments are discussed in a top-down approach, beginning with an examination of the international regulations, followed by EU laws and subsequently Belgian national laws. As several regulations in the bibliographies of the various chapters were subsequently amended, the section below refers to the most recent consolidated version or the version in force at the time the emission measurements were carried out. The purpose of this section is to provide readers with a detailed background on the different regulations concerning ship emissions, thereby facilitating a better understanding of the subsequent chapters of this dissertation. The purpose of this section is not to provide an exhaustive overview of all legal instruments, it is primarily intended for readers who may not possess extensive familiarity with this subject to provide some insights on the legal framework. Experienced readers may find it unnecessary to review this section and may instead choose to proceed directly to the next section.

3.1. IMO framework (MARPOL)

Multiple severe pollution incidents and the ongoing problem of chronic oil pollution in the world's oceans and seas prompted the establishment of regulations for ships under the International Convention for the Prevention of Pollution from Ships (MARPOL) by the International Maritime Organization (IMO). The MARPOL convention was adopted on 2 November 1973. In response to a series of tanker accidents in 1976-1977, the derivative Protocol of 1978 was adopted. Since the 1973 MARPOL Convention had not yet come into effect, the 1978 MARPOL Protocol assimilated the parent Convention. The merged instrument (MARPOL 73/78) became effective on 2 October 1983 [53]. Initially, these regulations focused on oil pollution (MARPOL Annex I) which became effective in 1983. Annex I was amended several times. The most recent consolidated version was adopted in 2004 [54], but was frequently amended afterwards. In addition to MARPOL Annex I, regulations on noxious liquid substances in bulk (MARPOL Annex II) came into force in 1983. Annex II was also revised and consolidated in 2004 and amended multiple times, with the most recent amendment entry into force in 2021 [55]. The Convention was extended in 1988 to deal with garbage from ships (MARPOL Annex V) as revised and consolidated in 2011 [56], and amended afterwards. The Convention was also amended in 1992 to cover pollution by harmful substances carried by sea in packaged form (MARPOL Annex III) and in 2003 to prevent pollution by sewage from ships (MARPOL Annex IV). In response to the growing global concern on air pollution from ships, the MARPOL Convention was expanded by the 1997 Protocol introducing MARPOL Annex VI on the prevention of air pollution from ships. The 1997 Protocol was revised in 2008 [57] and in 2021 [58]. Given that MARPOL Annex VI serves as the primary regulatory tool for this dissertation, a comprehensive explanation of this instrument is presented in the following section.

3.2. MARPOL Annex VI

The primary objective of MARPOL Annex VI is to reduce air pollution from shipping by regulating the emission of harmful airborne pollutants such as SO_x (Reg. 14) and NO_x (Reg. 13) from ships. In addition to regulating air pollution, MARPOL Annex VI also prohibits the intentional emission of ozone-depleting substances (Reg 12), VOCs (Reg. 15) and sets requirements for the monitoring and reporting of ships' energy efficiency in order to reduce GHG emissions, in particular CO_2 (Reg. 19-29). Furthermore, it defines Port State Control (PSC) requirements (Reg. 10) and defines that States Parties to Annex VI shall cooperate and use all practicable measures and environmental monitoring to detect violations and enforce its provisions (Reg. 11).

MARPOL Annex VI introduced Emission Control Areas (ECAs) for SO_x and NO_x in densely populated areas [59–63]. MARPOL Annex VI entered into force in 2005 and has subsequently been amended several times, with changes to the technical standards agreed by the Marine Environment Protection Committee (MEPC), the latest consolidated version was adopted in 2021 [58]. By 3 January 2023, MARPOL Annex VI had been ratified by 105 countries representing 96.8% of the gross tonnage of the global merchant fleet [64]. MARPOL Annex VI is therefore considered a crucial regulatory tool for reducing the environmental impact of air pollution from ships. In the following sections, the two primary regulations governing emission limits for SO_x and NO_x are discussed as they are the legal backbone of this dissertation.

3.2.1. SO_x Regulations

MARPOL Annex VI Regulation 14 defines the emission limits on SO_x. In 2007 the Baltic Sea and North Sea Sulfur Emission Control Area (SECA) came into effect [63] (see section 6.1). Starting from that point, ships operating in the North Sea and the Baltic Sea SECA are required to use marine fuels with a maximum fuel sulfur content (FSC) of 1.5% by mass or switch to natural gas or use an EGCS to achieve the same emission level as low sulfur fuels. On 1 January 2010, the SECA emission limits were further reduced to 1% FSC, and on 1 January 2015, the limits were tightened again to the current limit of 0.10% FSC [65]. In 2005, the sulfur limit for ships operating outside the ECAs was established at 3.5%. However, as of 1 January 2020, the IMO "global sulfur cap" came into effect, which mandates that ships can only use fuels with a maximum of 0.5% FSC outside the ECAs (Figure 2) [66]. Furthermore, on 1 March 2020, the so called “carriage ban” came into effect, prohibiting the carriage of non-compliant fuel in the bunker tanks of ships, unless equipped with an EGCS [67].

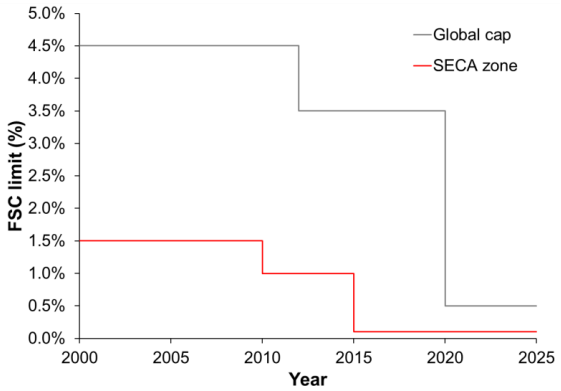


Figure 2. Regulations on the FSC of ships as of MARPOL Annex VI [65].

Table 1. Emission ratios for EGCS systems [68].

Fuel oil sulfur content (% m/m)	Ratio emission SO2(ppm)/CO2(% v/v)
4.5	195
3.5	151.7
1.5	65
1	43.3
0.5	21.7
0.1	4.3

Regarding the regulations of SO_x, dedicated guidelines for the use of EGCS have been adopted by the MEPC. The principle of these guidelines is based on the ratio of the measured concentration of SO_2 (in ppm) over CO_2 (in %) in the exhaust plume. In the ECA areas this ratio is limited to 4.3, outside the ECAs this ratio was reduced from 151.7 to 21.7 with the introduction of the global sulfur cap (Table 1). The guidelines on EGCS were first adopted in 2009 and were subsequently amended in 2015 and 2021 [68–70]. As the time period of this dissertation spans from 2015 until 2022, reference is made to both the 2015, 2019 and 2021 Guidelines. The Guidelines define among others the logging of the emission ratios and the required actions that need to be undertaken in case of failures.

At the MEPC session 79 in December 2022, a new SECA was adopted in the Mediterranean Sea, as the fourth area where sulfur emissions are more restricted. This SECA is expected to come into effect on 1 May 2024 [71]. Also, in the Atlantic Sea areas of France, Spain and Portugal an ECA is currently being considered. In addition to the international ECAs and SECAs, domestic restricted sulfur emissions that

apply to ships in coastal waters and ports have also been implemented in other countries, such as the Domestic Emission Control Areas (DECAs) in China [72–74].

3.2.2. NO_x Regulations

Regulation 13 of MARPOL Annex VI defines the NO_x emission limits for ships. In addition, it describes dedicated NO_x Emission Control Areas (NECAs) where stricter NOx emission limits apply. A North American and US Caribbean Sea NECA came into force on 1 January 2016 [60]. As of 1 January 2021, the North Sea and Baltic Sea became NECAs [61], expanding the existing SECAs. As a result, the SECAs were renamed to ECAs.

MARPOL Annex VI Regulation 13 defines the NO_x emission limits for ships in grams of NO_x emitted per kilowatt hour (kWh) of brake horsepower (BHP). The merchant fleet is categorized into four tiers based on their keel laying date (KLD) (Reg. 2.19). Tier 0 relates to ships with a KLD before 2000 (Reg. 13.7), Tier I applies to ships with a KLD from 2000 until 2011 (Reg. 13.3), Tier II concerns ships with a KLD from 2011 until 2021 (Reg. 13.4) and Tier III is for ships with a KLD from 2021 onwards (Reg. 13.5). The emission limits for each tier decrease in function of the ships' Engine Rated Speed (ERS or n), which is measured in rotations per minute (rpm) (Figure 3). Tier I regulations also cover all Tier 0 ships that have a KLD after 1990 and either a main engine (ME) power greater than 5000 kWh or a displacement of at least 90 L per cylinder [58].

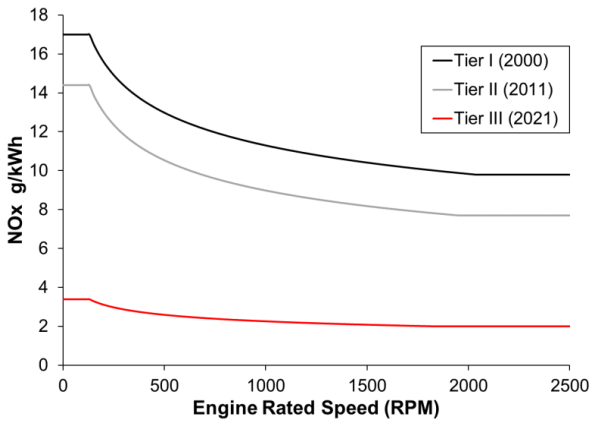


Figure 3. NOx emission limits according to MARPOL Annex VI Regulation 13 [58].

Table 2. Test cycles and weighting factors according to the NOx Technical code [75].

E2	Speed	100%	100%	100%	100%
	Power	100%	75%	50%	25%
	WF	0.2	0.5	0.15	0.15
E3	Speed	100%	91%	80%	63%
	Power	100%	75%	50%	25%
	WF	0.2	0.5	0.15	0.15

In order to provide the requirements to comply with MARPOL Annex VI Regulation 13, the NO_x Technical code was adopted in 2005 and amended in 2008, describing in detail all technical standards and compliance verification tests with the purpose of the certification of the engines [75]. The verification tests are based on five different engine test cycles with four to five engine loads and corresponding weighting factors (WF). For the main engines, two cycles are described, E2 is used for constant-speed marine diesel engines and E3 for propeller law operated engines. However, both are based on the same WFs per engine load (Power) (Table 2). Only for Tier III a "not-to-exceed" limit (NTE) is defined, which stipulates that the NO_x emission limit may not be exceeded with more than 50% for any of the individual engine loads [58]. For none of the four tiers, emission limits are currently defined under a main engine load of 25%.

3.2.3. Port inspections

Regulation 10 of Annex VI defines the procedures for port inspection authorities to verify if ships comply with the operational requirements of Annex VI. A ship may be inspected in a port or offshore terminal by duly authorized or appointed officers to verify whether the ship has emitted a substance in violation of the provisions of Annex VI (Reg. 10.2).

Regulation 11 describes that States shall use all appropriate and practicable measures for the detection of violations and environmental monitoring, thus providing a clear incentive for carrying out remote compliance monitoring (Reg. 11.1). Furthermore, MARPOL Annex VI requires that in addition to the Party that reported the alleged violation, the IMO is also notified of the measures taken by the flag State (Reg. 11.4).

In 2019, the MEPC adopted new Guidelines for Port State Control under Annex VI [76], defining which documents should be checked by port inspection authorities and when a more detailed inspection is required, such as the verification of the proper functioning of the EGCS. The Guidelines also specify detainable deficiencies (Art. 2.7.2.6).

3.2.4. Energy efficiency

In 2018, the IMO adopted its initial strategy to reduce GHG emissions from international shipping [77]. The strategy aims to decrease CO_2 emissions from international shipping by 2030 with at least 40% from 2008 levels, in addition it plans to reduce absolute GHG emissions by 2050 to 50% compared to 2008 levels. As mentioned in the Fourth IMO Greenhouse Gas Study, as of 2018, the GHG emissions from international shipping had already decreased by 22% compared to 2008 levels [24]. This development is partly due to the use of slow steaming by the whole industry due to market-based factors. [24,77]. To achieve the additional 18% reduction, required to meet the 2030 target, new regulations were adopted, such as a tightening of the Energy Efficiency Design Index (EEDI) for new ships under MARPOL Annex VI Regulation 20 [78]. For addressing GHG emissions from existing ships, the Energy Efficiency Existing Ship Index (EEXI) came into effect on 1 January 2023 under the revised MARPOL Annex VI of 2021 (Reg 23) [58]. To improve the scores of this index, shipowners can use measures that fall under two categories, being either operational or technical measures (Reg 25). The most used operational approach will be most likely the implementation of an engine power limitation (EPL). An EPL establishes a semi-permanent, overridable limit on a ship's maximum power, and therefore its speed [58]. However, the International Council on Clean Transportation (ICCT) argued that the effective impact is estimated to be limited due to the fact that slow steaming is already widely applied [77]. In the event of a hypothetical decrease in fuel costs, it can be anticipated that the cruising speed would increase once more. As a result, these indexes are commonly regarded as minimum thresholds rather than real incentives to create substantial efficiency improvements.

3.2.5. Black carbon

As mentioned in the previous section, BC is the second most significant contributor to global climate change after CO_2. Although technical solutions for the monitoring and reducing of BC emissions exist, they have not yet been introduced in the shipping industry. As the impact of BC is the most severe in the Arctic areas, due to the blackening of sea ice, measures have been proposed to regulate BC emissions in Arctic waters [37]. MEPC 79 passed a resolution urging both States and ship operators to consider using distillate or other cleaner fuel alternatives to help reduce BC emissions from ships operating in or near the Arctic. The resolution also calls on States to take steps to address the threat posed by BC emissions in the Arctic and to provide reports on BC measurements and best practices for reducing such emissions from shipping [36,79,80]. In the light of this, an HFO ban was proposed [37]. Despite the urgency to impose regulations on BC emissions from ships, the IMO so far only agreed to adopt voluntary measures and urged its members to gather data on BC emissions from ships [81].

3.3. UNCLOS

According to the United Nations Convention on the Law of the Sea (LOSC), 'States have the obligation to protect and preserve the marine environment' (Art. 192) [82]. How States can fulfil this obligation depends on whether they act as flag State, coastal State or port State. The flag State is defined as the State of registration of the ship, indicated by the flag a ship sails. The port State is the State with

jurisdiction over ships calling at the port. The coastal State is the State that has jurisdiction in the internal waters, the territorial sea and the exclusive economic zone (EEZ) in which a ship is sailing.

3.3.1. Coastal State

Coastal States are entitled to take action against ships that have polluted their territorial sea or EEZ. Those ships, when entering voluntarily in a port of the coastal State, can be investigated and that State can institute proceedings in case of violations of the applicable rules and standards for the prevention, reduction and control of pollution from ships (Art. 220(1)) [82].

In addition, if there are clear grounds to believe that the ship navigating in the territorial sea or the EEZ of a coastal State committed an Annex VI violation, the concerned ship may be asked for relevant information concerning the potential violation (Art. 220 (3)). If the ship refuses to provide information or the information provided was manifestly incorrect and there is a substantial discharge that causes or threatens to cause significant pollution, a physical inspection of the ship at sea can take place (Art. 220 (5)) [82].

3.3.2. Port State

Port State Control (PSC) may investigate any given ship entering ports on the States territory. A physical inspection of the ship always starts with a documentary inspection (certificates, records, etc.) and may be followed by a further physical inspection (Art. 226 (1)(a)), in which case foreign-flagged ships may not be delayed longer than essential for the purpose of the investigation (Art. 2018 and 220) [83].

If the investigation indicates a MARPOL violation, the ship shall be promptly released after an appropriate financial security or a deposit has been paid (Art. 226 (1)(b)), the flag State shall be notified and will receive official records of the measures taken (Art. 231). Penalties incurred by a foreign ship as a result of MARPOL violations in or outside the territorial sea of the State initiating the penalty proceedings are limited to monetary fines, except in case of a willful and serious act of pollution in the territorial sea (Art. 230 (1)(2)) [82].

3.3.3. Flag State

Any violations by foreign-flagged ships detected by a port or coastal State outside the territorial sea must be notified to the flag State. Consequently, the State that initiated the proceedings shall suspend its proceedings for six months; in the meantime, the flag State may initiate its own proceedings to impose sanctions for those violations. The flag State is obliged to inform the State that initiated the proceedings. The suspended proceedings are terminated when the flag State's proceedings are concluded. (Art. 228 (1)). A decision by the flag State to not proceed, also closes the proceedings. The initial proceedings shall not be suspended in case of major damage to the coastal State or if the flag State has repeatedly failed to fulfil its enforcement obligation with regard to violations by ships flying its flag [82,84].

3.4. EU regulations

At European level, SO_x emissions from ships are regulated by the EU Sulphur[1] Directive (Directive (EU) 2016/802) [85], and the Commission Implementing Decision ((EU) 2015/253) [86]. These

1. Please be aware that while "sul*f*ur" is the preferred spelling in scientific texts and is therefore used as the preference spelling in this dissertation, "sul*ph*ur" is still used in various regulations. Consequently, the original wording has been retained when referencing regulations.

regulations were pivotal for the monitoring and enforcement of SO_x emission regulations from ships in EU waters and are therefore discussed in detail in the following sections.

3.4.1. EU Sulphur Directive

The sulfur content in marine fuels was first addressed at EU level by the Council Directive 1999/32/EC, which was adopted in 1999 [87]. This was in essence the implementation of the MARPOL Annex VI Protocol of 1997 in EU legislation. With the adoption of the SECA and consequent amendments to the MARPOL Annex VI regulations, this Directive was revised and codified by the EU Sulphur Directive of 2016 (Directive (EU) 2016/802) [85]. Despite being mainly an implementation of the limits on the sulfur content in marine fuel as defined under MARPOL Annex VI Regulation 13 (Art 6) and the use of EGCS (Art 8), the EU Sulphur Directive includes supplementary rules and guidelines. One of these additional rules stipulates that if ships are at berth for more than two hours in EU ports outside the SECA, a maximum FSC limit of 0.1% FSC applies for the fuel used (Art 7). In addition, the sampling procedures for port inspection authorities have been laid down (Art 13). Finally, the Directive describes the reporting of the inspection results to the European Commission (EC) (Art 14) [85].

3.4.2. Implementation decision

In addition to the EU Sulphur Directive, the EC adopted the Commission Implementing Decision (EU) 2015/253) on 17 December 2015 which came into force on 1 January 2016 [86]. This Implementing Decision outlined the mandatory number of sulfur inspections to be executed by the EU MS (Art 3). It was stipulated that MS must carry out documentary inspections on at least 10% of the total number of individual ships calling at MS' ports (Art 3.1). In addition, 40% of the inspected ships must be checked using approved (laboratory) fuel sampling methods for MS that fully border the SECA area (Art 3.2(a)). However, the number of fuel samplings can be reduced by a maximum 50%, by subtracting the number of ships that have been monitored using remote measurement techniques or with mobile X-ray fluorescence (XRF) scanners (Art 3.3(a)). The Commission Implementing Decision also provides the sampling procedures (Art 5) and the information to be included in the annual reporting format (Art 7). Finally, in the Implementing Decision it is stated that for the reporting of inspection results, MS may use the Union reporting system. This Union reporting system, was developed, and is still managed by the European Maritime Safety Agency (EMSA), initially referred to as Thetis-S and later renamed to Thetis-EU [86].

3.4.3. Water Framework Directive

The Water Framework Directive (WFD) was adopted on 23 October 2000 and came into force on 22 December 2000 [88]. The WFD aims to establish a framework for the protection and sustainable use of inland surface water, transitional waters and coastal waters within the EU. The Directive requires MS to develop management plans that address the ecological and chemical status of their water bodies and identify measures to improve them. It also includes provisions for public participation, economic analysis, and monitoring to ensure that water bodies achieve good ecological and chemical status by 2027 [88]. Regarding the ecological status, coastal waters are defined as surface waters up to one nautical mile (nm) from the baseline (coastline), however regarding the evaluation of the chemical status, coastal waters are extended to the entire territorial sea (12 nm) (art. 2.1 and 2.7). The WFD defines a list of priority substances, which must be monitored by the MS. The standards for these substances are set out in the Environmental Quality Standards Directive (EQSD) from 24 December 2008, which entered into force on 22 December 2012 [89]. MS must achieve good surface water chemical status (Art. 4 and Annex V point 1.4.3) [88–90]. Additionally, the WFD also defines a list of priority hazardous substances, all emissions of these substances should be phased out (Preamble paragraph 43 and Art 1) [88]. However, EGCS wash water contains several of the priority substances (lead and benzene) and priority hazardous substance (PAHs, cadmium, and mercury), that have proven to impact marine life [17–20,90–97].

In light of the limitations imposed on discharges under the WFD, several EU MS have invoked the WFD to prohibit the use of EGCS in their inland waters and ports. This is also the case for Belgium, where the region of Flanders, responsible for the implementation of the WFD, banned the use of EGCS in ports and inland water under the Royal Decree of 23 June 2010 establishing a framework for achieving good surface water status [98]. Due to historic pollution and industrial activities, Flanders does not achieve a good ecological and chemical status in any of its ports and must therefore limit the additional sources of priority substances. Flanders only achieves good environmental status in 0.2% of its waters, while it attains bad status for more than 90% of its coastal waters [99]. Coastal and territorial waters fall under the jurisdiction of the federal Belgian authority, which banned the use of EGCS within 3 nm of the territorial waters. Nonetheless, it should be noted that the WFD is technically applicable for the entire the territorial waters (12 nm) with regard to the chemical status. Belgium is not the sole EU MS which is not able to achieve a good chemical status in the coastal waters. According to the European Environmental Agency (EEA), up to 45% of the territorial seas of the EU MS do not achieve a good chemical status [100] and up to 40% of the coastal waters do not meet a good ecological status (Figure 4) [101]. Therefore, an overall ban of EGCS in the territorial seas of the EU MS would be a step forward towards improving the chemical quality status of the coastal waters and territorial seas of the EU MS.

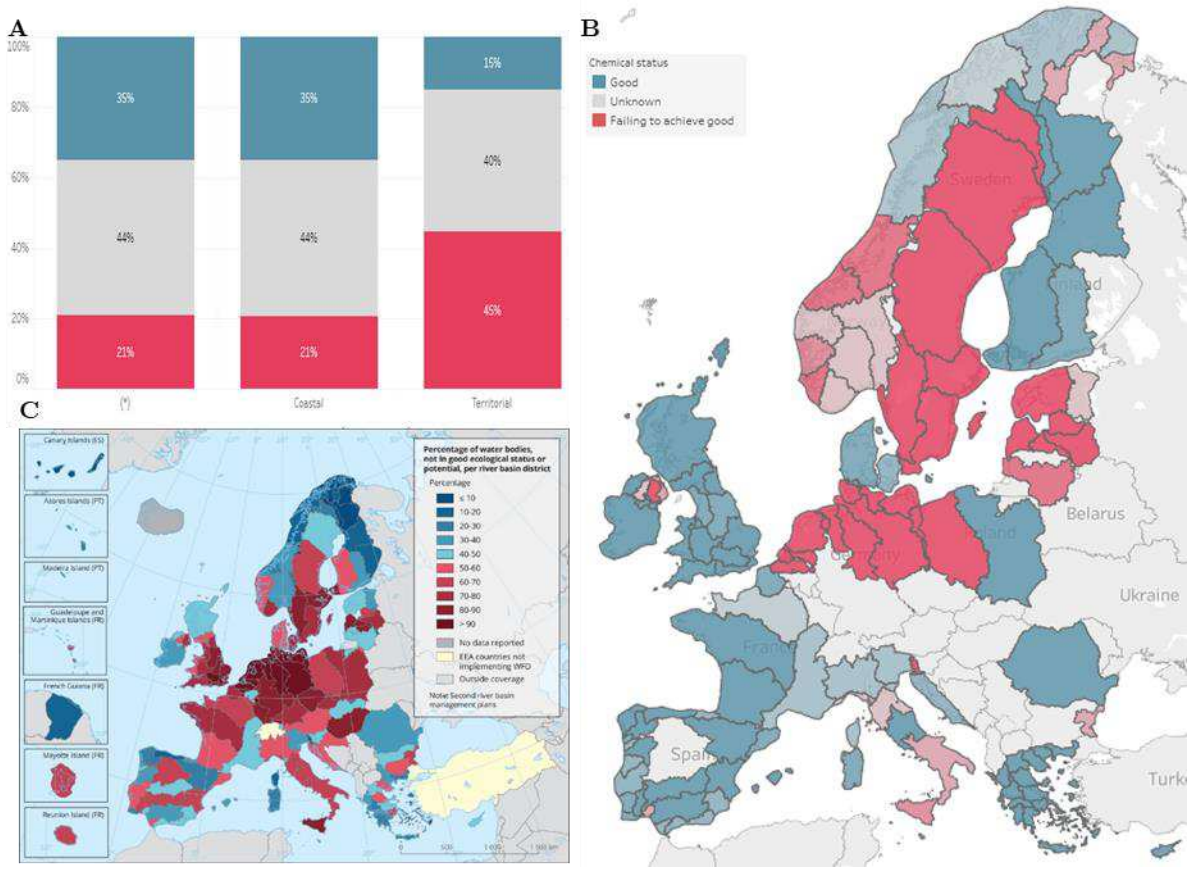


Figure 4. Chemical status of the EU coastal and territorial seas in percentage (A) and EU chart (B) [100]. EU chart of water bodies that are not in good ecological status (C) [101].

3.4.4. Marine Strategy Framework directive

The Marine Strategy Framework Directive (MSFD) was adopted on 17 June 2008 and came into force on 26 June 2008 [102]. The MSFD aims to achieve a good environmental status for all EU marine waters and to ensure that the economic activities dependent on the marine environment are sustainable. The strategy sets out a range of objectives, targets and indicators to assess the environmental status of marine waters and to address the main pressures on the marine environment. The strategy is

underpinned by the principles of ecosystem-based management and the precautionary approach, which prioritize the protection and preservation of marine ecosystems and the services they provide to society [103].

Even though the MSFD does include atmospheric deposition it does not cover airborne emissions. Nevertheless, it contains certain descriptors that are applicable to MARPOL Annex VI, particularly with respect to the effluent from EGCS washwater. One such MSFD descriptor to achieve a good environmental status is that concentrations of substances should be at levels not giving rise to pollution effects (Annex I.8) [102]. However, research has demonstrated that the use of EGCS in the Baltic Sea may increase the concentration of certain heavy metals. They can therefore be considered under the MSFD [18,90–95,104]. With regard to substances that are considered within coastal waters by the WFD, the MSFD defines that when discharges outside the territorial waters lead to increased concentrations in coastal and territorial waters (Preamble 13 and Annex III) [102]. Thus, for the priority hazardous substances, MS must take measures to monitor and reduce releases of these substances if they can result in increased levels in territorial waters. However, under the MFD, MS can currently not prohibit the use of EGCS outside territorial coastal waters as this would conflict with the IMO regulations. Nevertheless, the significance of a potential EU wide EGCS ban for the European, marine environment cannot be understated, in particularly for the environmental management strategies of the Baltic Sea States, as the Baltic Sea is distinguished by shallow depths and restricted mixing of water bodies and therefore especially prone to pollution effects from EGCS.

3.4.5. Ship Source Pollution Directive

The Ship Source Pollution Directive (SSPD) (Directive 2005/35/EC on ship-source pollution) [105] ensures that ship-source discharges of polluting substances at sea are regarded as infringements. The directive also sets out a common framework on how to deal with penalties, including criminal sanctions, for illegal discharges from ships. Initially, the Directive was limited to discharges of oil and chemical pollution. However, the Directive is currently being reviewed. The revised directive is foreseen to include among others all MARPOL Annexes. However, for MARPOL Annex VI only the discharges to the sea, i.e. the discharges of wash water from EGCS ships, are currently considered [106]. The rationale for this is that the EU Sulfur Directive already regulates SO_x air emissions, and incorporating airborne emissions under the SSPD would lead to duplicate regulation. However, this explanation may appear inconsistent, given that discharges from EGCS are also covered by the EU Sulfur Directive, as well as the WFD (for inland waters only).

3.4.6. NOx emissions under EU regulations

NO_x emissions from ships are currently not regulated by an additional EU NO_x directive. EU officials have stated at several official meetings that it is currently unlikely that a NO_x directive will be considered at EU level in the foreseeable future. However, some opportunities are still present to include NO_x under other EU regulations.

The first one worth mentioning is the SSPD. As mentioned before, regarding MARPOL Annex VI, the revised version currently only includes discharges to the sea. It will not include air emissions as it was argued that they are already included under other Directives. However, this reasoning is only applicable to SO_x emissions, and it would therefore technically still be feasible to solely incorporate airborne emission related to Regulation 13 of MARPOL Annex VI under the revised SSPD.

Alternatively, NO_x could have been incorporated in the reformed Emissions Trading Scheme (ETS) under the new FuelEU Maritime regulations as part of the Fit for 55 package. Under the reform of the ETS system, besides CO_2, also non-CO_2 GHGs and particles can be considered [107–109]. At this stage only N_2O and CH_4 have been included. Although it is stated that other gases and particles could be

considered in the future, with a decision on this expected by the end of 2023 [110]. As explained in Section 2, NO_x is also a very potent GHG, therefore NO_x would have been a worthy candidate to be considered under ETS. By including NO_x under ETS, a powerful incentive for businesses and industries would be created to reduce their emissions.

In addition to the aforementioned Directives, there are ongoing discussions at the EU level regarding a new directive on ambient air quality (revision of Directive 2008/50/EC) [111]. This regulatory framework would establish specific standards aligned with the guidelines set by the WHO by 2030, with the ultimate goal of achieving zero air pollution by 2050 [112]. However, it is doubtful whether these targets can be attained without addressing the impact of ship emissions on air quality.

Legal and environmental experts from several EU MS have expressed in several fora and research projects that it would be a missed opportunity for not including NO_x in ETS under current or new EU regulations [113]. It is deeply concerning that 15 years after the adoption of MARPOL Annex VI, still no EU vision exists for developing a EU NO_x legal framework for ships. This subject is further elaborated in depth in Chapter 8 of this dissertation.

3.5. Belgian laws

MARPOL and its Annexes were implemented in Belgian laws soon after their creation. In this section an historic overview of the most relevant national Belgium laws are provided.

3.5.1. MARPOL law

The law for the prevention of pollution by ships, also known as the MARPOL law, was initially adopted on 6 April 1995. Although at that moment air pollution from ships was not yet mentioned in MARPOL, the law was fundamental for the legal follow-up of MARPOL violations in Belgium. It implemented MARPOL Annexes I and II, described financial and criminal penalties and provided an overview of the competent legal authorities. Furthermore, this law stipulated that any evidence could be used as proof that illegal pollution had taken place. This law was amended several times after its adoption and is later replaced by the law introducing the Belgian Shipping Code (2019) and further implemented by the Royal Decree concerning environmental friendly shipping (2020) which are discussed further in this section [114,115].

3.5.2. MMM Law

The law on the protection of the marine environment of 20 January 1999, provided for a much broader scope than the original MARPOL law, including the definition of protected areas and the introduction of marine spatial planning. Furthermore, this law provided an update of the sanctions for environmental offences, described additional legal competent authorities and established the rules for reporting environmental offences. This law was also amended several times after its adoption and is replaced by the law of 11 December 2022 on the protection of the marine environment and the organization of marine spatial planning in the Belgian sea areas. [116]. The 2022 MMM Law does not introduce changes to the 1999 MMM Law relevant for the topic of air pollution from ships.

3.5.3. Exclusive Economic Zone

The EEZ of Belgium was established by the law concerning the Exclusive Economic Zone of Belgium in the North Sea of April [117] (see section 6.1).

3.5.4. Sulfur implementation: law on the Belgian Shipping Code

Belgium implemented the MARPOL Annex VI regulations and the EU Directive 2005/33/EC in 2007 by Royal Decree of 27 April 2007 concerning the prevention of air pollution from ships and the reduction

of the sulfur content of certain marine fuels [118]. This Royal Decree was also later replaced by the Royal Decree of 15 July 2020 concerning environmentally shipping [115].

The law on the Belgian Shipping Code of 1 August 2019, replaced all relevant former laws related to shipping, which are now merged into one single law dealing with the prevention of operational pollution from ships and facilitates the application of administrative penalties. Under this law a broad range of international, EU and national maritime rules are defined, such as the International Convention for the Safety of Life at Sea (SOLAS), the Convention on the International Regulations for Preventing Collisions at Sea (COLREG), etc. Furthermore, the competent legal authorities are defined [114].

3.5.5. Royal Decree concerning environmental friendly shipping

The Royal Decree concerning environmental friendly shipping was adopted on 15 July 2020, with the aim to combine all relevant regulations on the prevention of marine pollution from ships into one single regulation [115]. With the creation of the NECA, the Royal Decree concerning environmental friendly was amended by a Royal Decree of 4 November 2020 that implemented the NO_x emission limitation of MARPOL Annex VI regulation 13 into Belgian legislation [115].

3.5.6. Law on administrative penalties

The law establishing administrative fines applicable in case of violations of shipping laws was adopted on 25 December 2016 [119]. This law authorizes the Federal Public Service (FPS) Mobility and Transport to impose administrative sanctions for violations by ships, including navigation violations, COLREG offences, port state violations and MARPOL violations. In addition, according to this law MARPOL violations are depanelized, meaning that when administrative fines are challenged, the case will be referred to a civil court instead of a criminal court [119].

4. Operational and strategic framework

This section provides an overview of the Belgian and international organizations, legal bodies and international mechanisms involved in the monitoring and enforcement of MARPOL and related ship emission regulations. A bottom-up approach is used to examine the various actors, commencing from the national level, and progressing to the regional, EU, and global levels.

4.1. Belgian coastguard structure

The Belgian coastguard structure plays a critical role in ensuring the safety and security in the Belgian part of the North Sea. The Belgian coastguard is responsible for a wide range of activities, including search and rescue operations, maritime security and environmental protection. The Belgian coastguard structure is a collaboration of 17 partners, being different national and regional governmental agencies with competences at sea (Figure 5). The Belgian coastguard structure was founded by the Cooperation Agreement of 8 July 2005 between the Federal State and the Region of Flanders [120], and is chaired by the governor of the province of West Flanders.

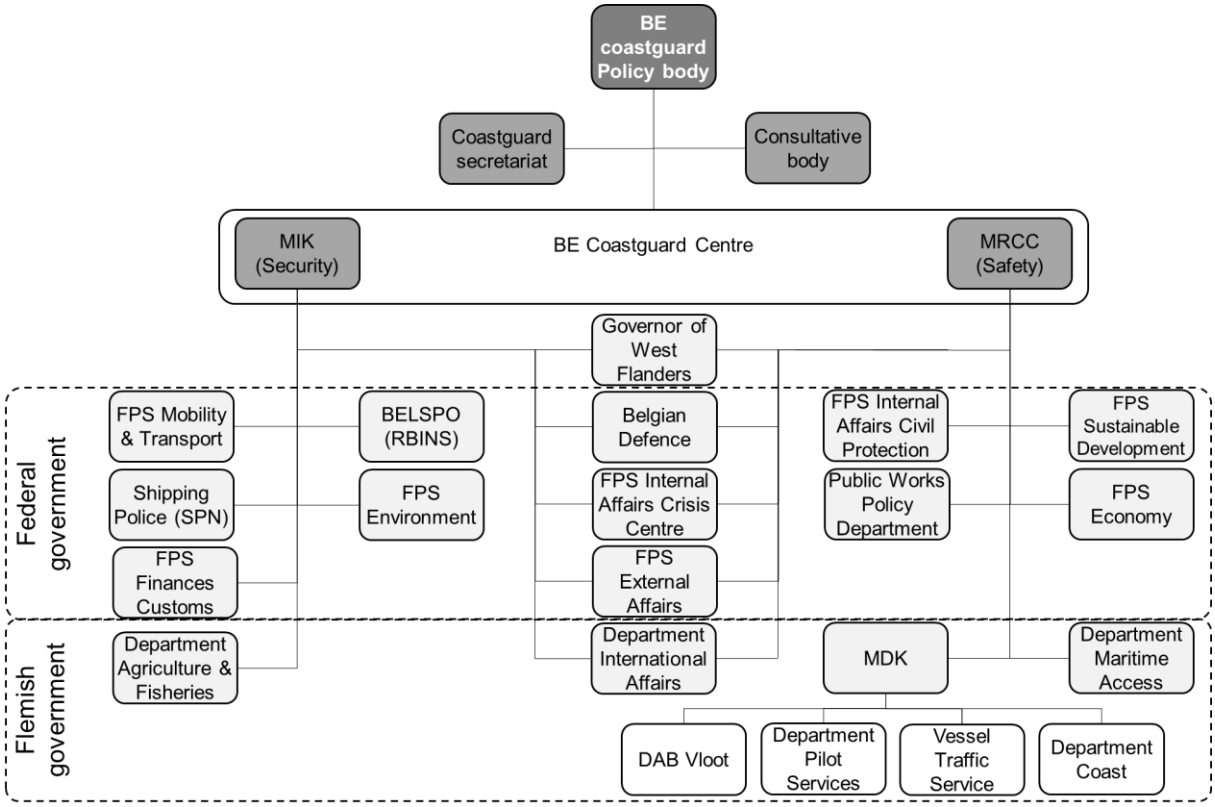


Figure 5. Organigram representing the Belgian coastguard structure. The 17 partners from both federal and Flanders government levels are categorized based on their primary responsibilities, namely safety or security. However, it is important to note that all partners are capable of operating under both responsibilities.

The main objective of the Belgian coast guard structure is to ensure good cooperation between the different agencies and to provide a more efficient deployment of actions at sea. The three main principles of the Belgian coastguard structure are: ensuring equality between the different partners, having respect for each other's competences, and making optimal use of resources to avoid additional costs [120]. An important milestone for the development of the Belgian coastguard structure was the creation of the Maritime Security Centre (MIK) in Zeebrugge in 2007. Together with the Maritime Rescue and Coordination Centre (MRCC) in Ostend, the MIK forms the coastguard center. Whereas MRCC is responsible for safety related aspects and acts as the first point of contact for ships in distress, MIK is responsible for security related tasks at sea, it is 24/7 operated by the Belgian Navy and includes representatives of the Shipping Police (SPN), customs and FPS Mobility and Transport [121].

4.1.1. Scientific Service MUMM

The Royal Belgian Institute of Natural Sciences (RBINS) is one of the partners of the Belgian coastguard structure and represent the Federal Public Service (FPS) of the Belgian Science Policy (BELSPO) in the Belgian coastguard structure. The duties of the RBINS within the Belgian coastguard structure are taken up by the Scientific Service Management Unit of the Mathematical Model of the North Sea (MUMM) of the Operational Directorate (OD) Nature. The tasks of MUMM within the Belgian coastguard structure include environmental monitoring of human activities at sea that impact the marine environment. Flight reports of observations made by MUMM at sea, are sent to the MIK responsible for forwarding the report to the competent legal authority. MUMM is also responsible for data collection, including the continuous monitoring of the quality of the marine environment, monitoring sand and gravel (SAGRA) extraction, dumping sites of dredged material, offshore wind farms, aquaculture at sea and most importantly for this dissertation, the prevention of pollution from

ships. In case of environmental catastrophes at sea, the common emergency and intervention plan (ANIP) will be activated, which involves the setting up of a crisis committee — MUMM, as part of this crisis committee, will provide scientific advice to the crisis committee to act accordingly [122]. During an environmental emergency, MUMM coordinates the scientific work, particularly in the case of strandings of animals. MUMM is also the competent authority to authorize the use of chemical dispersants to combat oil spills after a net environmental benefit analysis (NEBA). In addition, MUMM is responsible for the federally managed descriptors relating to the MSFD and the WFD applicable to the North Sea [123].

In order to fulfil its legal commitments, MUMM started airborne surveillance operations in 1991. At that time an aircraft of the Belgian Defense was equipped with a remote sensing system. MUMM conducts airborne surveillance operations in the Belgian part of the North Sea area (as coastal State) and neighboring waters, in the so-called Bonn Agreement (BA) Quadripartite Zone of Joint Responsibility (QPZJR). MUMM has long been recognized by Belgian law as one of the legally competent authorities to monitor and enforce MARPOL regulations at sea [114–116,124]. In 2015 MUMM started with the monitoring of MARPOL Annex VI.

4.1.2. Federal Public Service Mobility and Transport

The FPS Mobility and Transport, partner of the Belgian coastguard is responsible for the flag State inspection of Belgian ships and PSC of all flags in Belgian ports. With regard to the inspection of sulfur regulations, a dedicated Department for Dangerous Goods and Sulfur was created [125]. This department operates separately from the PSC. Unlike PSC, this service does not operate under the Paris MoU, but under the EU Sulphur Directive. This provides more operational flexibility, but also has disadvantages, such as the fact that the inspectors of this department do not have access to the Paris MoU THETIS database (PSC), only to the Thetis-EU database (see later in this section).

FPS Mobility and Transport is mainly enforcing the international sulfur emissions regulations through on-board inspections. If a violation is found during or after an on-board inspection, inspectors have the authority to issue a public statement. This public statement is sent to the shipowner who may choose to respond to clarify or question the findings of the public statement. Also the flag State will be informed to provide the flag state the opportunity to initiate its own proceedings. If after six months the flag State did not start its own proceedings, the FPS Mobility and Transport can impose administrative fines taking into account the response of the shipowner. The amount of the fine will be based on various factors, such as the level of the violation, the economic benefits in terms of revenue made from being in non-compliance (in Belgian waters), recidivism, etc. The offender has the right to appeal against the administrative fine, after which the case is referred to a civil court and the lawyer representing the Belgian government is appointed by the FPS Mobility and Transport [119].

4.2. Bonn Agreement

As a reaction to the Torrey Canyon oil spill which occurred in 1967, the first "Agreement for Cooperation in Dealing with Pollution of the North Sea by Oil" was signed in 1969 by the eight North Sea coastal States. However, the Agreement was not activated until the late 1970s, after two major pollution incidents, namely the 1977 "EKOFISK" blow-out and the 1978 "AMOCO CADIZ" ship disaster. The original 1969 agreement was replaced in 1983 by a new Bonn Agreement (BA) that also covered "other harmful substances" in addition to oil [126]. In 1989, the BA was amended to include aerial surveillance for detecting operational and illegal discharges, which became effective on 1 April 1994. In the mid-1990s, there was a key debate on prosecuting pollution offenses at sea [127]. Despite aerial surveillance of oil spills, there were no sanctions with regard to MARPOL violations. Several seminars were organized to consider various perspectives on the acceptability of evidence obtained from aerial surveillance and

oil fingerprinting. An important evolution in this respect was the creation of the Bonn Agreement Oil Appearance Code (BAOAC) [128–130].

Today the BA consists of eleven Contracting Parties (CPs), being the Governments of the Kingdom of Belgium, the Kingdom of Denmark, the French Republic, the Federal Republic of Germany, the Republic of Ireland, the Kingdom of the Netherlands, the Kingdom of Norway, the Kingdom of Sweden, the United Kingdom of Great Britain and Northern Ireland and the European Union[127]. The Kingdom of Spain became the latest member of the BA [131]. The BA covers the Greater North Sea and its Wider Approaches. This area includes the North Sea proper, the Skagerrak, the English Channel and its approaches and other waters comprising the Irish Sea, the Celtic Sea, the Malin Sea, the Great Minch, the Little Minch, part of the Norwegian Sea, and parts of the North East Atlantic Ocean (see section 6.1) [127,132].

The BA holds annual meetings to discuss work done in working groups and to decide on work to come. For this the BA develops Bonn Agreement Strategic Action Plans (BASAPs) and Bonn Agreement Joint Action Programs (BAJAPs). These documents are updated and implemented annually. For each task a lead country or the BA Secretariat is identified, responsible to take forward the work. When found necessary, BA workshops may be convened by a CP to examine a particular subject. The BA may also undertake projects funded by the EU (Figure 6) [127,133].

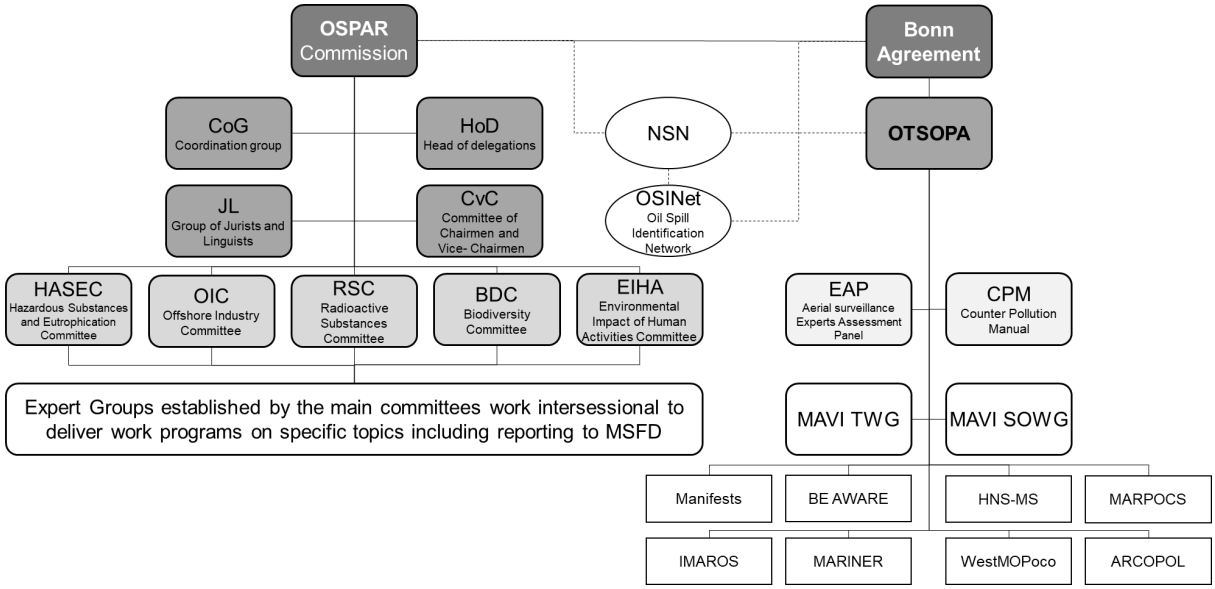


Figure 6. Organigram of the OSPAR Commission with its committees, the Bonn Agreement, NSN, OTSOPA, the SWOG and TWG and the recent BA projects [127].

4.2.1. OTSOPA

Work to implement the BASAP is taken forward through the Working Group on Operational, Technical and Scientific Questions Concerning Counter-Pollution Activities (OTSOPA). OTSOPA meets on annual basis to discuss and prepare documents for the annual BA meeting of the CPs. In preparation of the OTSOPA meeting, CPs report their annual monitoring data and submit working documents. During the OTSOPA meeting the BASAP is discussed and updated where needed. In addition, an update is made on the organization of the BAJAP, which includes the Tour de Horizon (TDH) missions for the monitoring of oil producing platforms, the Coordinated Extended Pollution Control Operations (CEPCO) and national or regional pollution exercises (POLEX or BONEX). Furthermore, lead CPs will report on the results of working groups (WGs) on specific subjects and funded projects. In addition, the organization of seminars to address certain topics are to be discussed [127]. During OTSOPA, CPs have also the opportunity to present recent work or issues that were observed regarding pollution from

ships and share best practices. In light of this, Ward Van Roy presented several times the results of the Belgian MARPOL Annex VI emission monitoring activities and the results of the Compliance Monitoring (CompMon) project (see section 5.3). Finally recent pollution cases are presented by CPs and discussed within this forum.

4.2.2. MARPOL Annex VI under the BA

The incorporation of Marpol Annex VI in the BA is described in detail in Chapter 7. At the ministerial meeting of September 2019 in Bonn, the BA CPs formally adopted MARPOL Annex VI under the BA jurisdication [131]. In the BASAP 2019-2025 it was agreed to organize a MARPOL Annex VI workshop and start-up a MARPOL Annex VI project. Belgium (Ward Van Roy) agreed to co-lead the organization of the workshop together with the EU (EMSA) and Germany. In 2021, the MARPOL Annex VI expert workshop was held to develop a common strategy and operational procedures on monitoring of ship emissions in the Bonn Agreement area. The Workshop concluded with a set of recommendations to be further explored by creating two working groups dealing with (1) strategic and operational aspects (MAVI-SOWG) and (2) technical aspects (MAVI-TWG) under the umbrella of OTSOPA.

BONN21 agreed on the Terms of References (ToRs) of both working groups. Belgium and Denmark agreed to co-convene the TWG. However, no co-convenors were found for the SOWG, which delayed the start of the WGs. At OTSOPA22 France and the Netherlands volunteered to co-convene the SOWG and in September 22 the WGs were started up. Since then ten meetings have taken place, of which four of the TWG, three of the SOWG, two joint sessions on NOx and 1 final Joint session. One of the co-conveners of the WGs (Ward Van Roy) presented the status of the work conducted within the WGs during the first intersessional reporting at Nort Sea Network of Prosecutors (NSN) on 25 April 2023 and at OTSOPA on 24 May 2023.

4.2.3. Counter Pollution Manual

The Bonn Agreement Counter Pollution Manual (CPM) contains practical information and standard procedures in dealing with pollution, including joint operations to combat pollution agreed by the BA. The manual is periodically reviewed by OTSOPA to ensure the use of the most effective technologies available [134]. One of the objectives of the SOWG and TWG is to update the CPM with information regarding the monitoring of MARPOL Annex VI within the BA.

4.2.4. Aerial Operations Handbook

After the decision of the BA in 1989 to include aerial surveillance for pollution detection, the BA CPM was extended with the Aerial Surveillance Handbook (AOH). The AOH was developed to provide best practice information on how to conduct aerial surveillance operations within the BA area [127,134].

The AOH is designed to be a useful reference for crews and operators during flights. It covers remote sensing techniques, flight coordination, standardized forms for reporting pollution and national points of contact (PoCs). A designated lead country (Norway) regularly reviews and updates the AOH. With the adoption of the BAOAC in 2004, the AOH was reviewed in 2008 [129]. The AOH is accompanied by the BAOAC Photo Atlas, which features exemplary photos of different types of oil slicks from accidental or illegal discharges, including Side Looking Airborne Radar (SLAR) images and IR/UV images [135]. Also this AOH is foreseen to be reviewed by the SOWG and TWG.

4.2.5. OSPAR Commission

The OSPAR Convention facilitates cooperation among 15 governments and the EU for the protection of the marine environment of the North-East Atlantic. OSPAR traces back to the Oslo Convention of 1972, which aimed to restrict the dumping of waste at sea, and the Paris Convention of 1974 concerning land-based sources of marine pollution. In 1992, the two Conventions were merged into the OSPAR

Convention. In 1998, the scope was extended to biodiversity and ecosystems, covering also non-polluting human activities that can have a detrimental effect on the sea. The 15 OSPAR countries include Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom [136].

The MSFD stipulates that EU MS sharing a marine region, should cooperate to ensure that the Directive's objectives are achieved. The coordination of the MSFD implementation for the wider North Sea is done under OSPAR ,with the regular publication of Quality Status Reports [137].

The BA and OSPAR are closely related because they share common objectives and have complementary roles in protecting the marine environment. The BA operates in the context of OSPAR and provides a framework for cooperation between the contracting parties in response to oil pollution incidents in the North-East Atlantic. In addition, both agreements share the same Secretariat, located in London UK. In this way, OSPAR and the BA work closely together to ensure that the marine environment is protected against various forms of pollution, including oil spills and air pollution. Therefore, both Agreements play an essential role in safeguarding the marine environment and ensuring the sustainable use of marine resources [127,136].

4.2.6. Nort Sea Network of Prosecutors

NSN was set up in 2002 by the Ministers at the Fifth North Sea Conference to fulfil their commitment to: 1) create a greater co-operation between North Sea States and the EU; 2) enforce internationally agreed rules and standards for the prevention, control and reduction of pollution from ships; 3) increase detection of illegal discharges; and 4) improve the investigation and prosecution of offenders [127].

NSN is an informal network that meets on annual basis and organizes seminars together with OTSOPA for the exchange of expertise and best practices [127]. NSN also collects a list of interesting cases on voluntary basis. These cases are presented during the annual meetings and contain successful and non-successful legal cases. The objective is to learn more about legal proceedings occurring in other CPs rather than providing a basis for statistical analysis. The cases are afterwards added to a database which is managed by the BA.

NSN is neither strictly linked to the BA nor to OSPAR, but can be located in between as it concerns legal follow up of all types of violations in the marine environment. However, as most cases discussed concern MARPOL cases, NSN is more closely linked to the BA.

4.3. European Maritime Safety Agency

The European Maritime Safety Agency (EMSA) was established in 2002 by the EU to ensure the maritime safety and the protection of the marine environment in the EU [138]. EMSA's responsibilities include the provision of technical and scientific assistance to the EU and its Member States (MS) on maritime safety, security, and pollution prevention. For this purpose EMSA developed several tools, like Safe Sea Net (SSN) Ecosystem Graphical User Interface (SEG), the Clean Sea Net (CSN) satellite services for the detection of oil pollution in EU waters, the EU Long Range identification System Cooperative Data Centre (EU LRIT CDC) and finally the portal most relevant for this dissertation, Thetis-EU [139]. All these tools are accessible online (Figure 7).

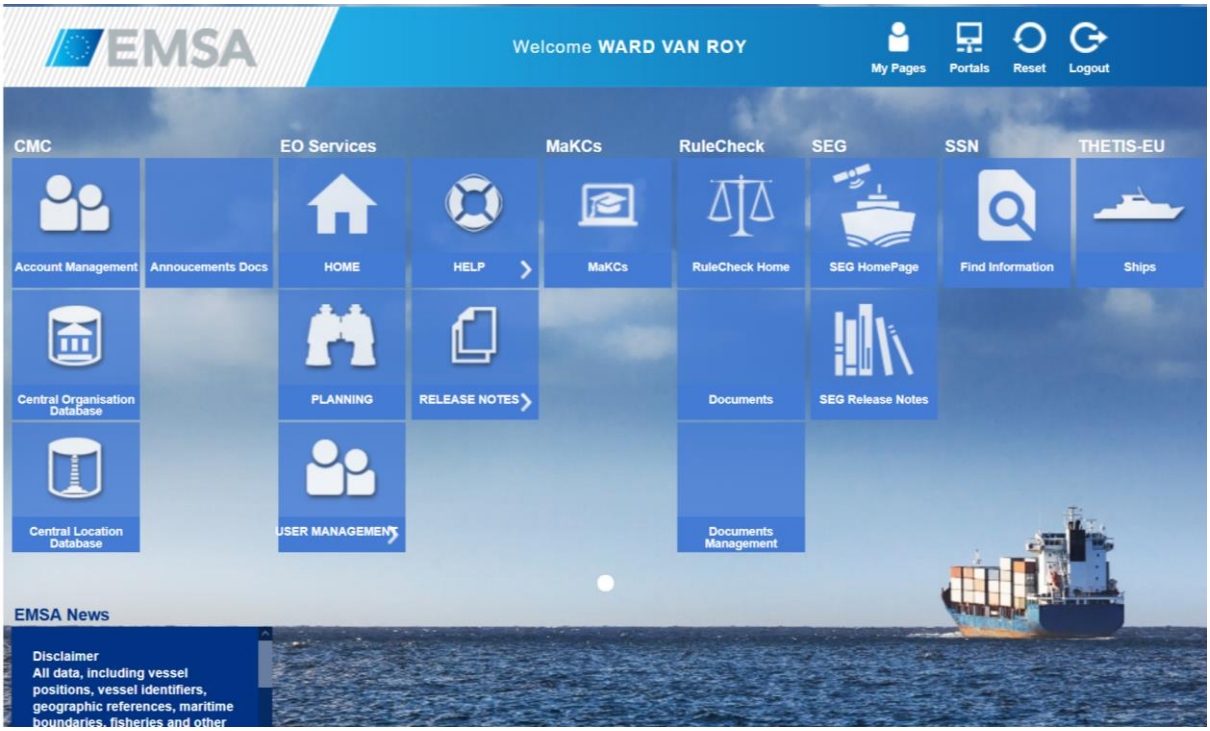


Figure 7. Several EMSA portals currently availabe to MUMM [138].

Furthermore, EMSA facilitates the cooperation between MS and between the EU and its MS to ensure an effective implementation of EU maritime legislation and related international regulations. For this purpose, EMSA organizes workshops and seminars, and conducts visits to the MS. In light of this, EMSA also developed the Rule Check which provides a comprehensive overview of all maritime EU legislation and related international regulations [139].

EMSA also assists in the response and coordination in the event of maritime accidents and incidents at sea within the EU. For this purpose, EMSA has built up a stock of oil spill combating equipment and established a network of standby oil spill response vessels through contracts with commercial vessel operators. These resources are at the disposal of the EU MS in case of accidents involving oil spills at sea [139].

EMSA also supports the development of EU policies related to maritime transport and maritime affairs and reports to the EC about the data collected by EMSA and the MS regarding EU maritime laws [139].

4.3.1. Integrated Maritime Services

In order to integrate the different tools and portals under the scope of EMSA, the agency developed the Integrated Maritime Services (IMS). IMS provides a comprehensive strategic maritime overview, responding directly to the specific needs of more than 4000 users across the different maritime authorities throughout the EU (Figure 8) [139]. RBINS is one of the National Competent Authorities (NCAs) for CSN. For other functionalities like SSN and Thetis-EU the responsibility lies with other agencies in Belgium. To access these tools a request needs to be made to the relevant NCA. The Belgian NCA for Thetis-EU is FPS Mobility and Transport.

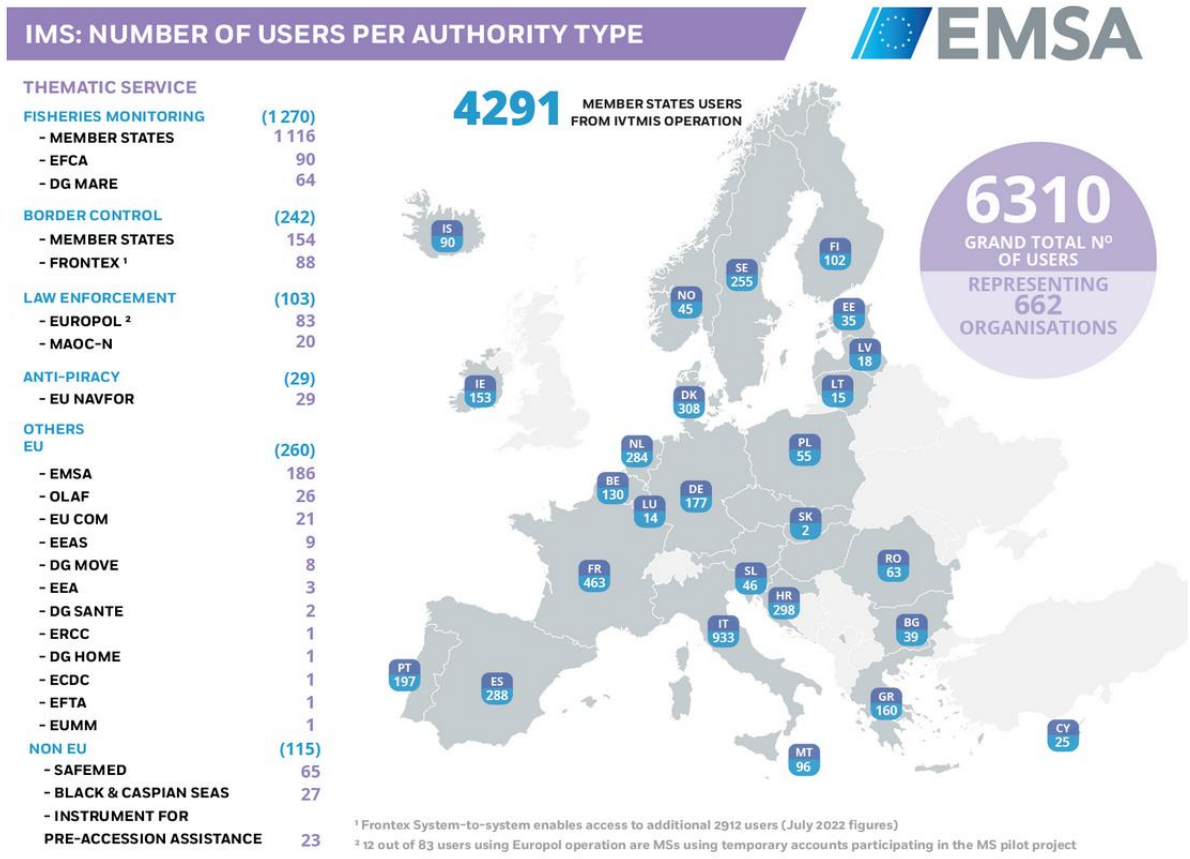


Figure 8. IMS users across the EU, Norway and Iceland [139].

4.3.2. Thetis-EU

The implementation of the EU Sulphur Directive and the Commission Implementing Decision led to the creation of the data reporting system of the Union [85,86]. To achieve this, EMSA was put in charge of the development of an inspection database and reporting tool. This tool was initially called Thetis-S, but was later renamed to Thetis-EU to include other international and EU related maritime regulations like Port Reception Facility (PRF) regulations. As of today, EMSA manages and hosts the database. Thetis-EU is accessible to inspectors across all EU MS, including Norway and Iceland. However, due to Brexit, the UK has no longer access to the database [85,140]. Although, in accordance with the EU Sulphur Directive and the Commission Implementing Decision the use of Thetis-EU is voluntary, all MS in the BA are actively using Thetis-EU. Considering the privacy and sensitivity of the collected data, Thetis-EU is not accessible to the public, however, certain statistics are available to the public and updated on a daily basis [140,141]. For approved users, Thetis-EU provides a tool to monitor ships going to national ports. Ship particulars can be looked up like the KLD, presence of EGCS, active alerts, etc. Inspection results on the different regulations can be uploaded, including remote measurement data and fuel sampling results (Figure 9) [140]. MUMM has access to Thetis-EU since the start of its airborne monitoring operations and data from Thetis-EU was vital for this dissertation (see section 6.5).

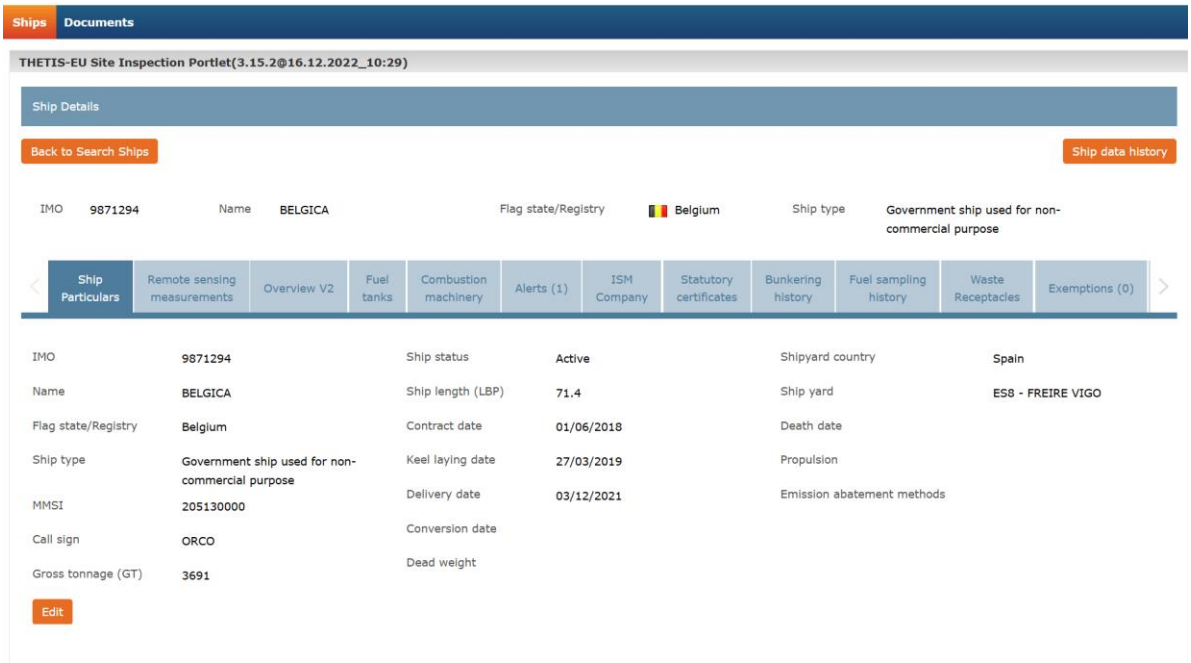


Figure 9. Thetis-EU with ship details of the research vessel (RV) BELGICA of the RBINS [140].

4.3.3. Reporting to the European Commission

EMSA is responsible for the analyses and reporting of the overall implementation of maritime legislation to the EC and the EU MS [138]. For this purpose EMSA produces regular and ad hoc statistics based on 1) data from its own tools and applications, and 2) data collected by the MS to be reported to the EC. Furthermore, EMSA drafts annual summaries in cooperation with the relevant EMSA units, MS and other agencies on the status of the national authorities and the follow up of research projects in which EMSA is actively involved in [139]. With regard to the EU Sulphur Directive, EMSA provides statistics on among others the number of executed inspections, fuel samples taken, the executed penalties and the data provided in Thetis-EU [141].

4.4. Paris MoU on Port State Control

In 1978, several maritime authorities in Western Europe adopted the 'Hague Memorandum,' which focused on enforcing shipboard living and working conditions regulated by the ILO Convention no. 147. However, after the "AMOCA CADIZ" oil spill disaster of March 1978, a more impactful memorandum was needed [142]. This new Memorandum of Understanding (MoU) on Port State Control was signed by fourteen European countries during a Ministerial Conference on 26 January 1982 in Paris, France. The Paris MoU on PSC entered into operation on 1 July 1982 [143].

Today the Paris MoU involves 27 States that oversee waters in European coastal States and the North Atlantic coastal States. Its Parties include Belgium, Bulgaria, Canada, Croatia, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Latvia, Lithuania, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Slovenia, Spain, Sweden and the United Kingdom. The Russian Federation is currently suspended due to its invasion of Ukraine [142].

The main goal of the Paris MoU is to implement a uniform system of PSC by its Parties. Every year, over 17,000 inspections are conducted on foreign ships in Paris MoU ports to ensure that they meet international safety, security and environmental standards, as well as to ensure that crew members have satisfactory living and working conditions. The Paris MoU operates under the principle that shipowners are primarily responsible for complying with the requirements outlined in international maritime

conventions, while the flag State is responsible for ensuring the compliance of the ships sailing under its flag and the port State is only responsible for regular compliance checks [142,143].

Since the Paris MoU encompasses MARPOL in the inspection regime, the Paris MoU also extends to MARPOL Annex VI. As a result, in most Parties of the Paris MoU, PSC inspectors are responsible for executing port inspections regarding MARPOL Annex VI. However, in some other countries, such as Belgium and Germany, other government agencies are responsible for enforcing sulfur regulations. In Belgium, this responsibility lies with the Department for Dangerous Goods and Sulfur, which is part of the FPS Mobility and Transport, the same agency that oversees PSC and flag State inspections. Nevertheless, inspectors from this department are not accredited as PSC inspectors and do not have access to the Paris MoU information database (THETIS) (Figure 10).

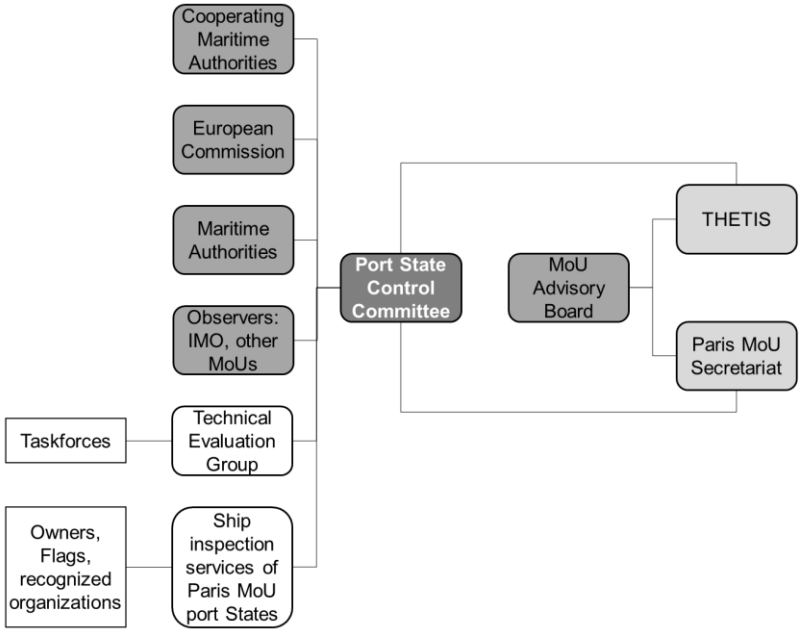


Figure 10. Paris MoU organization structure [142].

4.4.1. THETIS

THETIS, which should not be confused with Thetis-EU, is the database that stores the inspection results of Paris MoU port States. Like Thetis-EU, the database is hosted by EMSA. However, THETIS is designed to facilitate the inspection of regulations falling under the LOSC and the IMO, in contrast to Thetis-EU, which is specifically developed for the inspections in accordance with EU Directives. One of the crucial features of THETIS is its ship inspection prioritization system, which assigns ships a priority index based on several criteria, such as the time elapsed since the last inspection, past deficiencies, and flags of convenience. If a ship is suspected of polluting the waters of a coastal State, the affected State can request an ad-hoc inspection, resulting in a higher priority level for the vessel. This prioritization system does not exist in Thetis-EU.

Since MARPOL Annex VI is part of the PSC inspections regime, inspection results for MARPOL Annex VI can be transmitted via THETIS. Nevertheless, since THETIS and Thetis-EU are currently not interconnected, this entails additional work for PSC officers. Moreover, in several States, like Belgium, the responsible authorities for sulfur inspections differ from those of PSC, which implies that inspectors in charge of MARPOL Annex VI in some cases only have access to Thetis-EU and not to THETIS

4.5. International Maritime Organization

The IMO is a specialized agency resorting to the United Nations (UN). The IMO was originally established by the Convention on the Intergovernmental Maritime Consultative Organization (IMCO) of 6 March 1948 in Geneva [144,145]. The IMCO came into force on 17 March 1958 and was later renamed to IMO. As of today, the IMO has 175 States Parties [145]. The IMO is responsible for developing and maintaining international regulations and standards for maritime safety, security, and environmental protection [145]. The organization has adopted several conventions of great importance, such as SOLAS, MARPOL, and the International Ship and Port Facility Security (ISPS) Code. The IMO also plays an essential role in facilitating international cooperation and coordination on maritime issues. The organization works closely with other international organizations, such as the International Labor Organization (ILO) and the United Nations Framework Convention on Climate Change (UNFCCC), to ensure that shipping policies are consistent and coherent [145].

The development of new regulations is prepared in committees or subcommittees in IMO's subsidiary bodies (like MEPC and PPR), after which they are formally adopted (Figure 11).

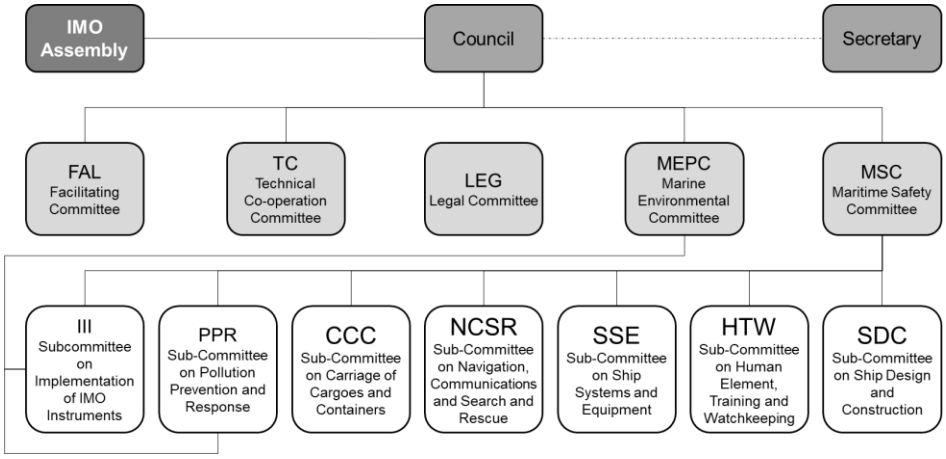


Figure 11. Organigram of IMO, with the position of MEPC and PPR [145].

4.5.1. Marine Environment Protection Committee

The Marine Environment Protection Committee (MEPC) is a subsidiary body of the IMO responsible for developing and overseeing the implementation of international regulations and guidelines for the prevention of pollution from ships. The MEPC was established in 1973 and meets on annual basis to review and update the regulatory framework for the protection of the marine environment. This includes the MARPOL Convention and the designation of special areas and ECAs. Another important instrument for which the MEPC is responsible is the International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM) of 2004, which entered into force on 8 September 2017 [146]. Furthermore the MEPC also deals with anti-fouling systems (AFS) as defined by the International Convention on the Control of Harmful Anti-fouling Systems on Ships of 5 October 2001, entered into force on 17 September 2008 [147]. Finally, the MEPC also includes ship recycling. In this regard the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships was adopted on 15 May 2009. However, as of today not all ratification requirement have been met and as a result this important Convention is not yet in force [148].

Another important responsibility of the MEPC is to monitor the implementation of international regulations and guidelines related to marine environmental protection. The Committee reviews reports from MS and takes action to address any non-compliance issues. Finally, the MEPC also coordinates with other international organizations and stakeholders to promote awareness and understanding of the importance of marine environmental protection [145,149].

4.5.2. Sub-Committee on Pollution Prevention and Response

The Sub-Committee on Pollution Prevention and Response (PPR) is another IMO's subsidiary body that deals with issues related to the prevention of marine pollution and responses to marine pollution incidents caused by ships. The PPR generally meets annually to review and develop guidelines and regulations related to the prevention and control of marine pollution. The PPR has a wide range of responsibilities related to pollution prevention and response. One of the key tasks of the sub-committee is to develop and update MARPOL regulations and guidelines. For this purpose PPR and MEPC work closely together, generally a proposal for new regulation is first addressed at PPR after which an output at MEPC can be requested.

4.6. Overall enforcement chain

To visualize how all the different actors of the operational and strategic framework act together, an organigram is provided about the enforcement chain for MARPOL Annex VI violations in Belgium (Figure 12). Remote measurement alerts are reported to Thetis-EU, accessible to the whole EU. If the ship, inspected by the Belgian FOD Mobility, appears to be non-compliant, a public statement will be sent. If the ship owner does not object to this public statement, a periodic penalty payment will be sent to the ship owner. If the ship owner refuses to pay this penalty, the case will be transferred to a civil court of justice. Data is collected annually on the number of ships inspected and violations found. This data is sent to EMSA, who is responsible for reporting the latter to the EC. Violations and deficiencies are also reported to the IMO. The added value of airborne monitoring and remote alerting in the Belgian enforcement chain is the subject of Chapter 4 of this dissertation.

It must be noted that for other MS the enforcement chain might be slightly different, not all MS apply fines. For instance in the Netherlands, offenders are requested to rectify the non-compliance before leaving port, which often requires a debunkering. Other MS do not apply administrative fines but the cases are directed to the criminal court of justice, which is the case in France. For most MS the Paris MoU plays a more significant role in the enforcement chain, with priority inspections and reporting of inspection results to THETIS. With thousands of remote measurements, remote measurements alerts and access to inspection results. The role of Thetis-EU is key in providing a successful and efficient enforcement mechanism for all EU MS.

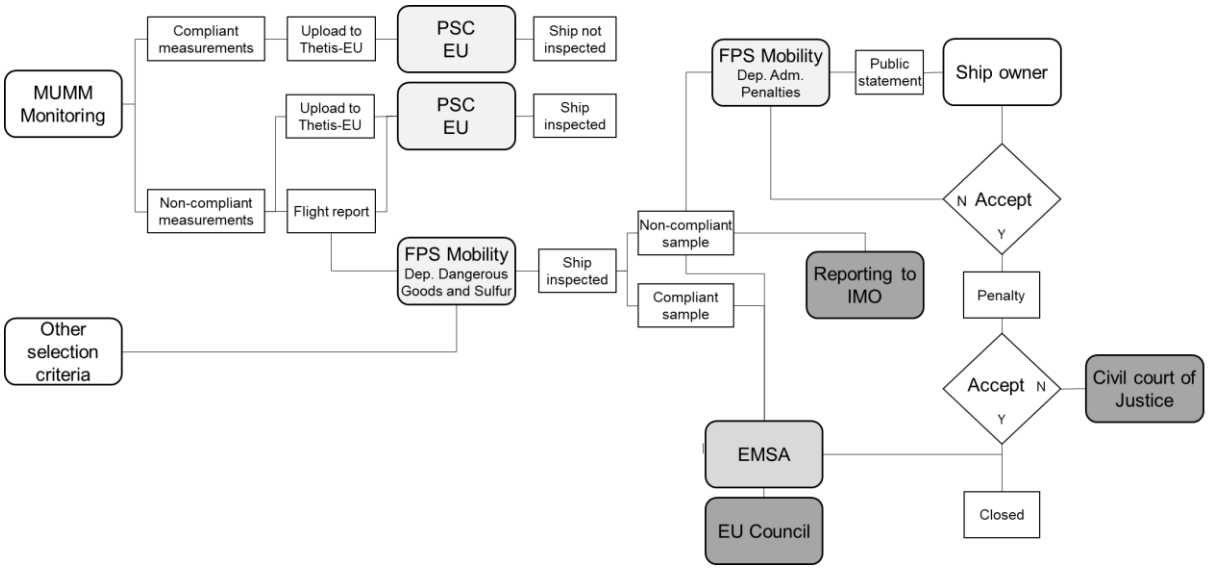


Figure 12. Enforcement chain MARPOL Annex VI.

5. Remote ship emission monitoring

This section discusses the most relevant scientific research and previous projects related to remote monitoring of ship emissions in the North Sea and Baltic Sea ECA. It must be noted that this is not meant to be an inclusive list of all relevant research and projects. This section is drafted to reflect the research and projects that provided the foundation of this dissertation.

5.1. Academic research

Since the start of MARPOL Annex VI, researchers have been investigating the possibility for remotely measuring ship emissions. TNO (Delft, The Netherlands) [150–153] and Chalmers University (Goteborg Sweden) have been on the forefront of this research [153,154]. Chalmers was also one of the first to use remote sensors on airborne platform for ship emission measurements, with among others campaigns in Belgium in 2009 and Sint-Petersburg in 2013 [155–160]. Also Finnish and German researchers from the Finnish Meteorological Institute (FMI) (Helsinki, Finland) and Bremen University (Bremen, Germany) respectively have played a key role in the development of remote measurement techniques [91,161–170]. An important step was taken with the publication of Balzani et al. on the validation of different sensor technologies, conducted in the Netherlands in 2013 [171,172]. The extensive preceding research laid the foundation for the FSC and NO_x measurement methods further developed for this dissertation as described in Chapter 1-3.

5.2. Other sniffer operational monitoring efforts

5.2.1. Overview of remote operational ship emission monitoring in the SECA

In addition to Belgium, other coastal States of the ECA have been using remote measurements for targeting ship inspections for several years. Chalmers University, which can be considered as one of the founders of remote ship emission monitoring, has been operating fixed sniffer stations in Sweden and Denmark since 2014. The most remarkable measurement campaigns are the ones conducted at the Oresund and Great Belt bridge [173,174]. In addition, Chalmers operated an airborne sniffer on behalf of the Danish Environmental Protection Agency (EPA) from 2015-2016 [175]. Another important instigator of remote ship emission monitoring is TNO. Since 2014, TNO has been operating a fixed sniffer station at the port of Rotterdam in the Netherlands on behalf of the Human Environment and Transport Inspectorate of the Ministry of Infrastructure and Water Management of the Netherlands (ILT) [150,152]. Also Germany was an early adopter of remote measurements and has developed a vast network of measurement stations and applies a large range of techniques and sensors. BSH (Hamburg, Germany) oversees this network, with fixed sniffer stations in Hamburg, Kiel and Bremerhaven [176,177].

In addition to research and government agencies certain private companies have also been working on the remote measurements. The most successful being Explicit (Virum, Denmark) which conducted airborne measurements using helicopters equipped with dual mini-sniffers on behalf of the EPA in Denmark, and in the Netherlands, on behalf of ILT [178–182]. Explicit is also working on EMSA's Remotely Piloted Aircraft Systems (RPAS) program.

5.2.2. The RPAS program from EMSA

The RPAS program of the EMSA is a state-of-the-art technological initiative aimed at enhancing maritime safety and security in EU waters. Using advanced drone technology, EMSA's RPAS program enables the agency to gather real-time information on maritime activities, monitor and enforce compliance with international regulations, and respond to critical incidents at sea. The program is part of EMSA's broader effort to promote a safe, secure, and environmentally sustainable maritime industry in Europe (Figure 13) [183].

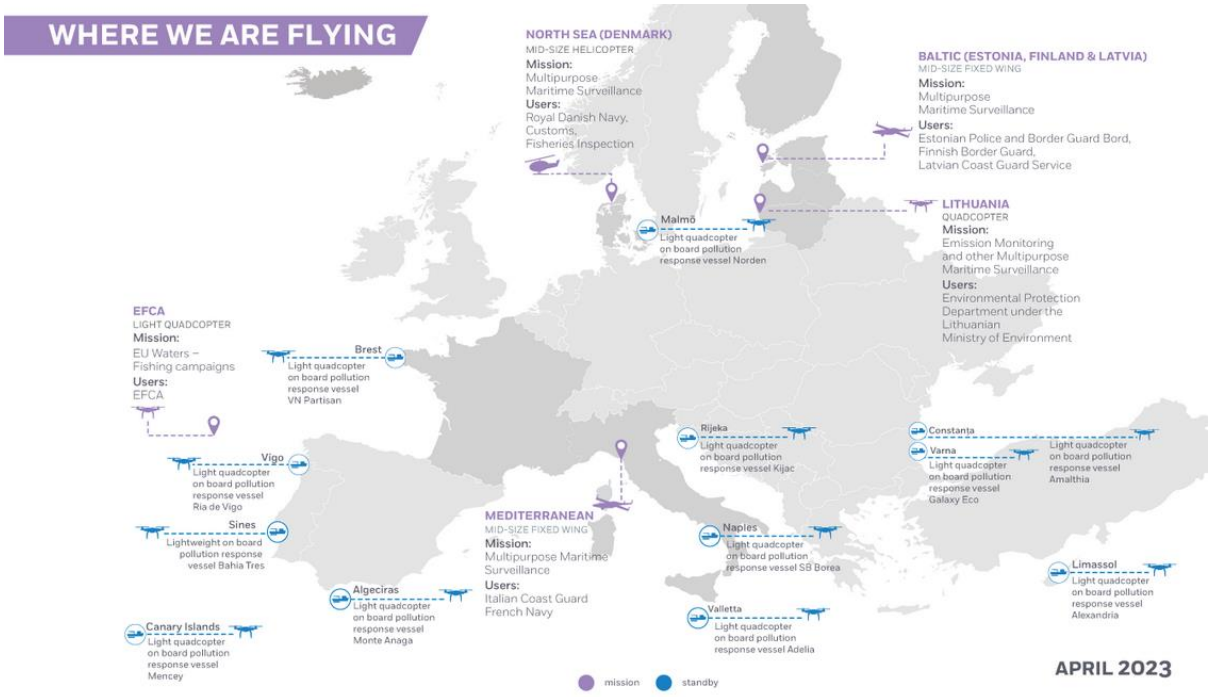


Figure 13. Deployment of EMSA's RPAS program [183].

The RPAS are not owned by EMSA but are contracted through a service contract. Several types of drones are used depending on the mission type. For MARPOL Annex VI inspections at sea, vertical take-off and landing drones with a medium range are used. Currently two service providers are contracted for the operation of the emission sensors: Explicit from Denmark and Aeromon from Norway. The drone used for MARPOL Annex VI is the Schiebel CAMCOPTER S100 operated by Nordic Unmanned and NORCE (Norway) [183]. Smaller, short-range drones are used in ports.

France, Denmark, Lithuania, Spain, and Germany have already applied for EMSA's RPAS. The results of these monitoring operations are discussed in Chapter 6 of this dissertation.

5.3. CompMon

In 2014 in a reaction to the upcoming reduction in the SECA to 0.1% FSC, a voluntary network was established. This network included EU government agencies, and specialized research institutions from Denmark, Germany, Netherlands, Belgium, Finland, and Sweden. This network received substantial funding from the EC and aimed to improve the enforcement of the 0.1% FSC limit in the North Sea and Baltic Sea SECA using innovative sensor technology and various monitoring platforms [184].

The resulting project, known as "MARPOL Annex VI Compliance Monitoring" or "CompMon" ran until the end of 2016. Its purpose was to generate monitoring information at sea and along the coast using remote sensing and to transfer that information to national port inspection authorities to conduct MARPOL Annex VI inspections on board of ships when entering EU ports in a targeted, cost-efficient way. During the CompMon project, the Belgian coastguard aircraft performed 152 flight hours, with 25 hours financed by the Netherlands (ILT) for monitoring above Dutch waters. The aircraft performed FSC measurements on 1347 ships, and 107 ships were found to have exceeding FSC values, which were systematically reported to the competent port inspection authorities [184]. Other airborne monitoring operations included operations by Chalmers University in Danish waters and at the SECA border with a fixed wing aircraft (Piper Navajo) [158] and Explicit executed measurements with a helicopter (Eurocopter Ecureuil 2, operated by Charlie 9) in order of ILT [185,186].

CompMon was successful in identifying suspicious ships through airborne monitoring above sea and making the enforcement chain considerably more efficient. The project yielded significant findings, such as higher MARPOL Annex VI offense rates at sea, the increased efficiency of port inspections by targeting ships based on remote measurements, and the observation of adaptative behavior of ships at sea, where they switched from high-sulphur to low-sulphur fuel too late or vice versa [187]. Based on these experiences, Van Roy and Scheldeman produced a Best Practices report which was presented to the BA and EMSA [72] and which was later used by other agencies involved in airborne ship emission measurements (e.g. Explicit and EMSA). Another important outcome worth mentioning was the study conducted by Ringbom, demonstrating that the international legal framework allows the execution of airborne monitoring at sea as long as they are not in conflict with the right of innocent passage at sea [83]. This subject is further elaborated in the final Chapter of this dissertation.

5.4. SCIPPER

The SCIPPER project, which stands for Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations, was an EU Horizon 2020 funded project that aimed to provide evidence on the performance and capacity of different techniques for shipping emissions monitoring and regulations' enforcement. The project was organized into eight work packages and included six measurement campaigns carried out in France, Germany, Sweden, and the UK. The project consortium comprised 17 partners from seven countries, led by the Aristotle University of Thessaloniki in Greece. The project results were published in 40 deliverables and numerous scientific papers. [188,189]

5.4.1. Cost effectiveness

One of the most relevant outcomes of the SCIPPER project was the study on the cost-effectiveness of different approaches for compliance monitoring, which includes remote sensing in the exhaust plumes of ships and on-board monitoring with sensors mounted in the exhaust stack. The study included remote sensing options with fixed stations on shore, airborne platforms, and monitoring via the TROPOMI satellite [190,191]. One of the key findings was that the economic cost of implementing the use of Continuous Emission Measurement Systems (CEMS) on board of ships, is by far inferior compared to the generated overall economic health benefits. However, it was stated that even when CEMS become mandatory, remote monitoring will still be required for verification purposes [190,192].

5.4.2. Harmonizing measurement uncertainty

To assess the quality assurance of remote monitoring systems and harmonized reporting, the data from a six-week side-by-side field sensor cross comparison campaign was used. The campaign yielded data from six fixed sniffer systems, one experimental and one operational UAV, and 65 fuel samples and bunker delivery notes, collected by the German federal police. The data showed a good agreement between the systems for measured SO_2 and NO_x emission factors. However, when comparing the calculated FSC from the remote measurements to the fuel sample analysis and bunker delivery note results, a tendency of underestimating the FSC by the fixed sniffers and the experimental UAV was observed. It was suggested that this bias might be caused by high relative humidity but that it needs further investigation. Notably, this tendency was not observed for the Danish operational UAV which operates without a filter system [191,193].

From the cross comparison, it was concluded that with the state of the art remote measurement systems, the FSC of bypassing ships can be detected with an estimated uncertainty varying between 0.03 % and 0.14 % S m/m for ships operating at the FSC level of 0.1 % S m/m (at Confidence Interval (CI) of 95 %). For NO_x, it was found that the fuel-mass specific emission (g NO_x/kg fuel) can be remotely detected with an estimated relative uncertainty (CI 95 %) of 17% to 40% [193]. These uncertainties are, although somewhat higher, in the range of the current Belgian airborne monitoring measurements, as discussed in Chapter 2 and 3 of this dissertation.

5.4.3. Recommendations

According to SCIPPER deliverable 5.5, several recommendations were given to address gaps in current legislations, identify upcoming risks based on future shipping, and improve the effectiveness of monitoring and enforcement efforts [113]. These recommendations include establishing better emission cycles and limits for NO_x, including limits on particles, ammonia, methane, and N_2O. In addition, the establishment of more NECAs was endorsed. It was suggested to use more CEMS for NO_x, SO_2, and BC on ships [192]. Finally, the development of regulations regarding the use of remote monitoring techniques for targeting and legal follow up of ship emission infringements was recommended [113]. Several of these recommendations are echoed in Chapter 7 of this dissertation.

6. Methods and Material

In this section an overview is given of the methods and materials applied for the different studies performed in this dissertation. However, every chapter of this dissertation also has an extensive methods and material section. Therefore, to avoid providing too much repetitive information this section does not give a comprehensive description of the Belgian sniffer and the airborne monitoring methodology, but rather fills the gaps not covered in the chapters of this dissertation. As the airborne sniffer operations is the key subject of this dissertation some repetition could not be avoided.

6.1. Research area

6.1.1. Belgian waters

Compared to the other BA CPs [194], Belgium has only a small sea area. The coastline is around 65 km, and its EEZ extends up to 83 km from the coast, resulting in a total surface area of 3454 km^2 [195,196]. Despite its relative small size, it is one of the busiest shipping areas in the world, with daily more than 400 movements of ships larger than 300 GT (Figure 14) [197,198]. The Belgian part of the North Sea is very active with several economic activities occurring beside shipping, such as sand and gravel extraction (SAGRA), wind energy, fisheries, aquaculture, etc. Finally, a large part of the Belgian part of the North Sea is defined as protected area (Figure 15).

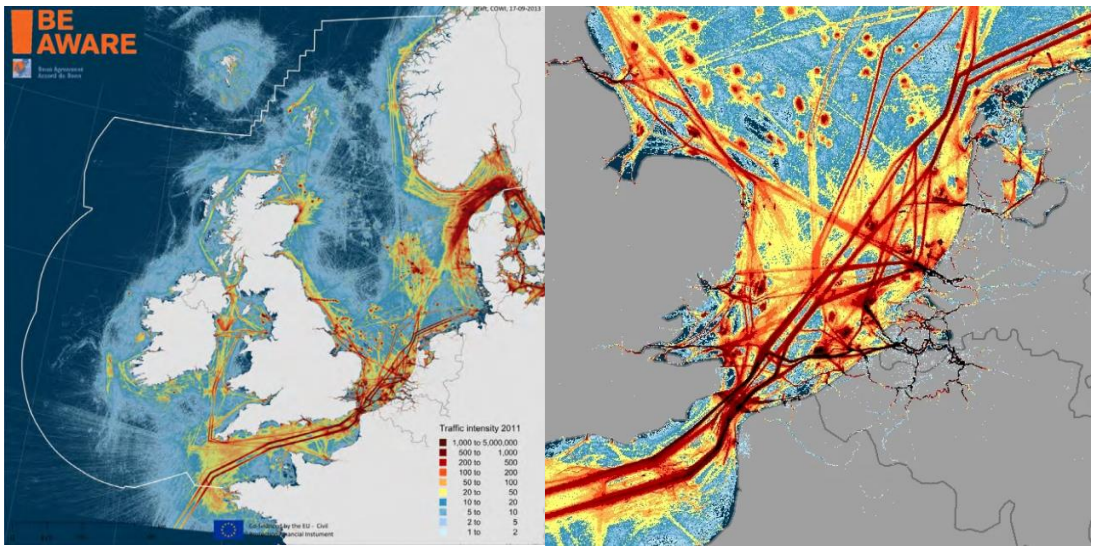


Figure 14. Traffic intensity in Bonn Agreement and Belgian Waters (figure from BE-AWARE Technical Report) [199].

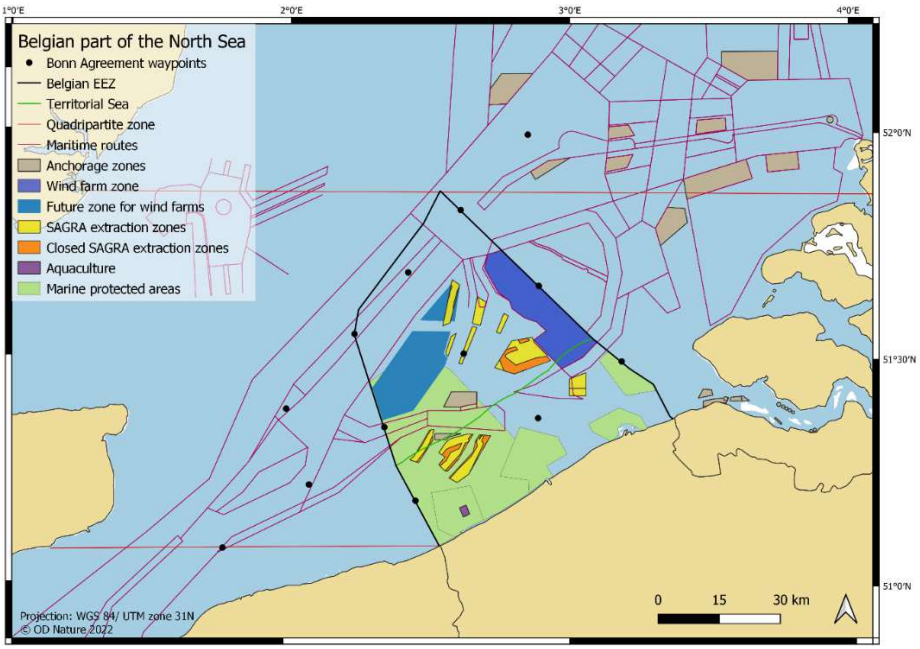


Figure 15. Belgian part of the North Sea.

6.1.2. Bonn Agreement

The Bonn Agreement area covers the Greater North Sea and its Wider Approaches [131]. The BAQPZJR covers an area of 13500 km^2 between the 51°51'52" N and 51°6'N parallels (Figure 16). [132].

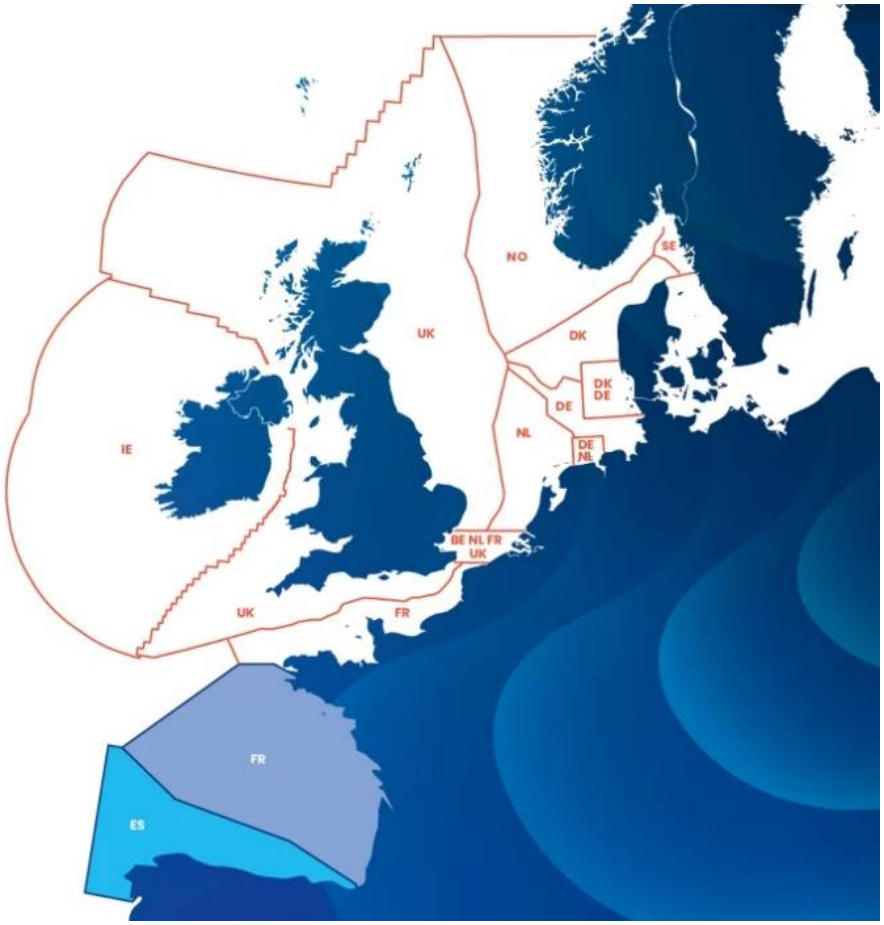


Figure 16. BA area as of 2023 [131].

6.1.3. North Sea and Baltic Sea Emission Control Areas

The North Sea (incl. the English Channel) ECA and the Baltic Sea ECA include the Skagerrak and Kattegat straits (Figure 17). The North Sea and Baltic Sea ECA is one of the four ECAs established by the IMO to control shipping emissions in specific regions worldwide. The other ECAs are the North American ECA, the United States Caribbean Sea ECA, and the Mediterranean Sea ECA (Figure 18).

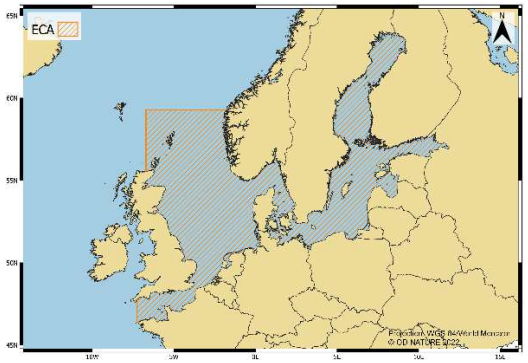


Figure 17. North and Baltic Sea ECA.

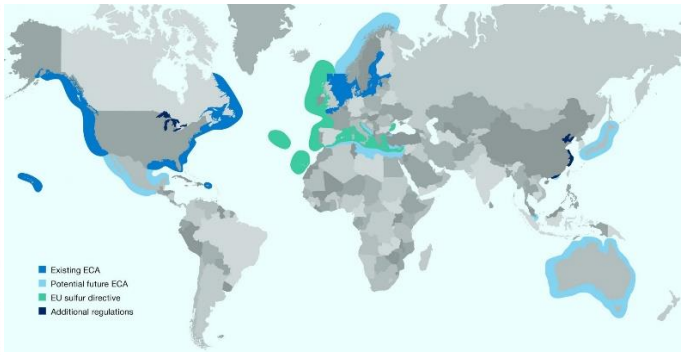


Figure 18. Different ECAs worldwide [50]. Note that the Mediterranean SECA will come into force in 2024.

6.2. Airborne sniffer sensor

6.2.1. OO-MMM Coastguard aircraft

The Belgian coastguard aircraft, owned by RBINS, was used for the airborne ship emission measurements that were utilized throughout this dissertation. The aircraft, a Britten Norman Islander (BN2), is a high wing short take-off and landing (STOL) aircraft. The aircraft is a double engine aircraft, which is considered vital for operations over sea. The aircraft dates from 1976, and can be considered at the end of its lifespan, but is currently still in good condition as it has a relatively low number of total flight hours on the aircraft structure, has been always well maintained, and was equipped with modern avionics and a remote sensing system from Optimare (Bremerhaven, Germany) in 2011. In 2015 the aircraft was equipped with a sniffer sensor system. The sniffer sensor used in this study was developed by Chalmers University and built by FluxSense (Gothenburg, Sweden).

6.2.2. Sniffer sensor

The most important units of the sniffer sensor are (i) a Thermo trace level ultraviolet fluorescence sensor, used for the measurement of SO_2 in ppb (unitless); (ii) a Bioscience Licor nondispersive infrared (NDIR) sensor, used for the measurement of CO_2 in ppm (unitless); (iii) an Ecotech Serinus chemiluminescence sensor for the measurement of NO_x (iv) a custom designed hydrocarbon (HC) kicker; (v) three powerful vacuum pumps (one for the SO_2 and CO_2 sensor, one for the HC kicker and one for the NO_x sensor; (vi) pressure and flow regulators; (vii) a log computer; (viii) a combined automatic identification system (AIS) and global positioning system (GPS) receiver, (ix) an Aeronautical Radio Inc. (ARINC) module and (x) a particle filter (1 µm) installed at the air-inlet of the sniffer sensor and on the other side connected to a stainless-steel sampling tube (3/8") probe installed on the bottom of the aircraft.

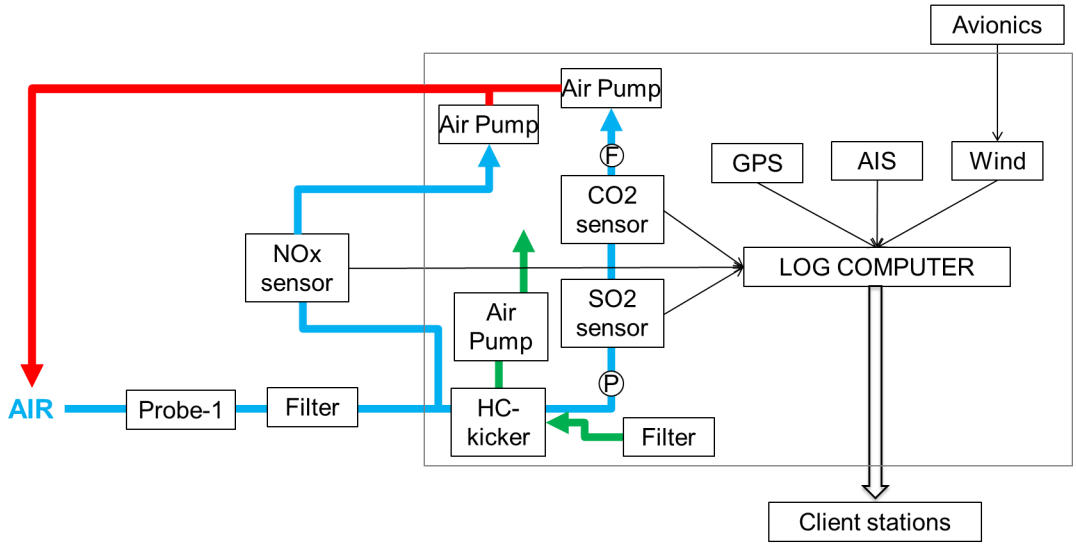


Figure 19. Schematic overview of the sniffer sensor system used on board of the Belgian coastguard aircraft.

6.2.3. IGPS software

This is the main software application for the collection of sniffer measurements. The system consists of different views, the "MAP view" allows the operators to display the AIS information on the chart together with the position and heading of the aircraft. It is important to note that ships can be displayed regarding their size, this is important as otherwise the map is overloaded with navigation of small vessels. In addition, ships can be marked for inspection, the pilots have their own display in the cockpit which visualizes the marked ships. In addition, the exhaust plumes are modelled based on the vessel's and wind's speed and direction (Figure 20).

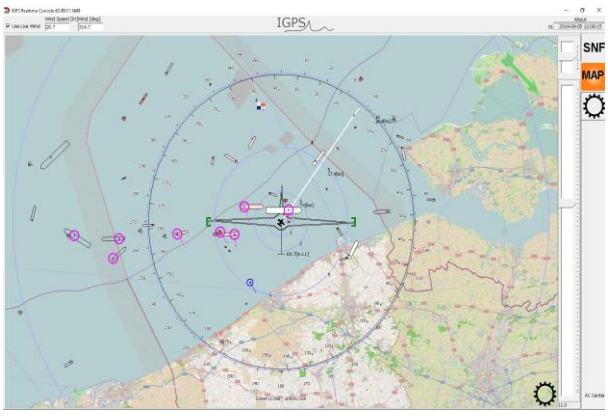


Figure 20. MAP view of the IGPS software.

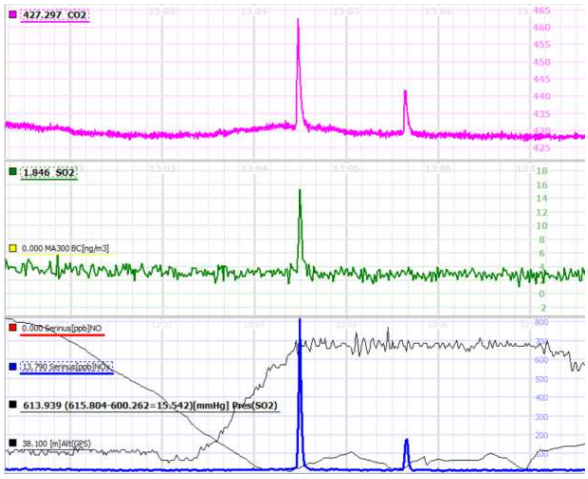


Figure 21. SNF view of the IGPS software

The "SNF view" displays the measured gas concentrations and allows to conduct an emission measurement and allocate the measurement to a specific ship (Figure 21). Several updates of the IGPS were done in over the time span of this dissertation. The most important update was the inclusion of NO_x and BC in 2020 and 2021 respectively. In addition, in 2020 a database containing the KLD of the world fleet was added to the software.

6.3. Measurement methodology

6.3.1. Ship approaches

To conduct high quality measurements the aircraft needs to fly through the ship exhaust at a close proximity from the ship (*ca.* 100-500 m) at a low altitude (*ca.* 30-100 m). It's imperative that the correct measurements are linked to the measured ships. For airborne operations this is not an issue as the measurements are conducted close to the vessels, in case there is a reason for doubt a second measurement will be conducted (Figure 22).

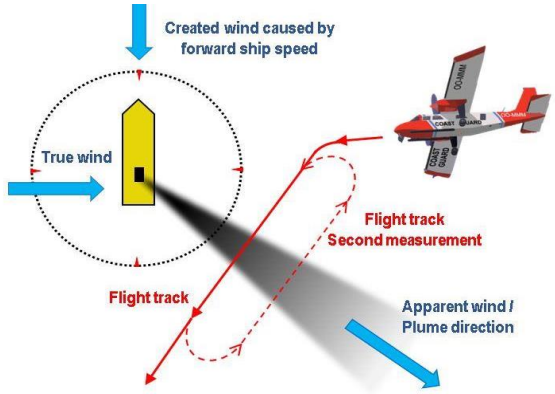


Figure 22. Monitoring methodology

6.3.2. FSC measurement

The FSC can be calculated based on the SO_2 and CO_2 concentration before and in the plume. The amount of sulfur (S) can be derived from the amount of SO_2 observed in the plume. Similarly, the amount of carbon (C) can be derived from the amount of CO_2 in the plume. To calculate the amount of kg burned fuel, the amount of C needs to be multiplied with the average C-content in the fuel. For marine fuels an average C-content of 87% was used [156,157]. The methodology for the measurement of FSC is explained in more detail in Chapters 1. However, several SO_2 sensors demonstrate a cross sensitivity to NO, if this is the case it is advisable to subtract this NO effect from the measured SO_2. This is further elaborated in Chapter 3 of this dissertation.

6.3.3. NO_x measurement

The emission factor (EF) of NO_x can be calculated using a similar approach compared to the FSC measurement. The main difference is that the NO_x limits are expressed per BHP. To transform the EFs information is required about the specific fuel consumption (SFC). This information can be obtained through marine VHF radio communication, by using a default value or by using dedicated models based on ship characteristics. This is the subject of the research described in Chapter 2. With the IGPS software, the calculation of the FSC and the NO_x emissions is done simultaneously (Figure 23).

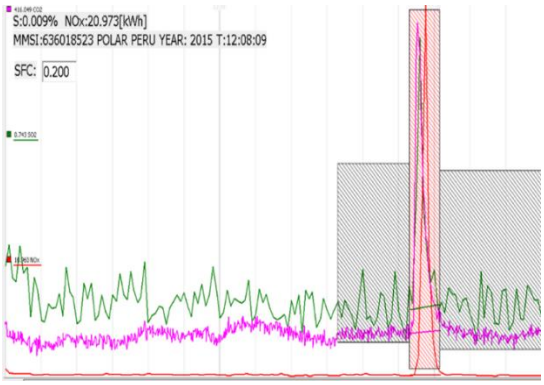


Figure 23. Measurement of FSC and NO_x on the IGPS software, the green line represents the SO_2 concentration, the magenta line represents CO_2 and the red line NO_x.

6.3.4. Reporting and use of thresholds

Chapters 1-3 delve deeper into the uncertainty and quality of the measurements. Based on the uncertainty of the remote measurements combined with the different emission limits, thresholds were defined for FSC and NO_x based on four different colors. The principle is that a balance is sought between the certainty of the possible violation and the provision of useful alerts. The provisions of highest alerts with beyond doubt of non-compliance is the most important, however if only this type of alerts would be provided, only a very low number of reports would be sent to port inspection authorities. For this reason, alerts with a lower level of certainty are also submitted for further inspection.

6.3.5. Sniffer Quality Management System

The Sniffer Quality Management System (SQMS) was developed by Van Roy et al. to be used in combination with the sniffer installation on board of the Belgian coastguard aircraft. This extensive SQMS consists of in total three sections. Section 1 describes the operational aspects of the airborne monitoring. Section 2 describes the Quality Assurance protocols and maintenance aspects and Section 3 describes all aspects related to data management. For every section a detailed manual is developed, all combined in a comprehensive SQMS document. The sections can be used as stand-alone guides during the different operations and interventions in the field. All sniffer related tasks are whittled down to a list of standard operational procedures (SOPs). The SOPs-list, together with shortcuts and links throughout the document, make scrolling and finding information throughout the manual easier and faster, which is important as the document is used as the main reference during the airborne monitoring operations.

In Section 1 of the SQMS, the Sniffer Operations Manual, detailed information and step by step instructions are provided about the operation of the sniffer sensor pre-, during and post-flight. The manual is organized in five chapters and is purposefully kept concise. Chapter 1 briefly describes the sniffer sensor set-up on board of the aircraft. Chapter 2 describes all aspects of the preparations of a surveillance flight. Chapter 3 provides the procedures on how to conduct ship emission measurements in flight. Chapter 4 describes all reporting and post flight operation procedures. The final Chapter 5 includes basic post flight reprocessing procedures. Some operational annexes were included, of which the radio communication checklist for NO_x is the most important one.

The second section of the SMQS is the Quality Assurance manual, which is more extensive than the first section. In this section, detailed information and step by step instructions are provided about the installation, calibration, and servicing of the sniffer sensor system. The manual is organized in seven chapters. Chapter 1 describes the installation on board of the aircraft and the main components of the sniffer sensor. Chapter 2 provides a detailed overview and schedule of the required maintenance interventions and preventive service. Chapter 3 provides all the information to perform software calibrations. Chapter 4 provides all the information to perform hardware calibrations. Chapter 5 describes all practical aspects of the management and calibration of reference gases. Chapter 6 provides detailed maintenance instructions for preventive servicing. Chapter 7 presents trouble shooting.

The last Section of the SQMS is the data management manual. This provides detailed information and step by step instructions about the collecting, processing and storage of the measurement data and other relevant data that is used during the missions. This section consists of seven chapters, Chapter 1 describes the data structure of sniffer sensor. Chapter 2 provides a detailed overview for the calculation of the FSC and NO_x uncertainty. Chapter 3 provides the procedures to determine the thresholds for reporting. Chapter 4 consists of all relevant information for the reporting of non-compliance data to PSC and Thetis-EU. Chapter 5 describes all practical aspects of the reporting of compliant data to Thetis-EU and to third parties. Chapter 6 describes the procedures for the collection of data for the annual reporting. Chapter 7 describes the procedures for the backup of the data.

The SQMS is added to the Supplementary material of this doctoral dissertation and may help understand the complex system of sensors and equipment that create the sniffer sensor system. This is a living document that is updated when methodologies are changed and when new techniques or sensors are added to the sniffer sensor. For the methodology a large set of excel files have been created which are used for logging and planning calibrations and other maintenance tasks. In addition, dedicated import macros were created to import measurements and process them for data-upload to among others Thetis-EU (see section 6.5.4). Although these excel files are not provided as supplementary material, they can always be provided on request.

In addition, the main operational sniffer procedures are added to the SURV OPS Manual, which consists of all operational procedures for the execution of all types of surveillance flights with the Belgian coastguard aircraft. It must be noted that this OPS manual does not contain the level of detail as the SQMS, but rather focusses on the operational tasks, before flight, inflight and after flight.

6.4. Port inspections

6.4.1. Sulfur

On board inspections in port are executed by port inspection authorities in accordance with the IMO and EU guidelines, whereby a fuel sample is collected from a location in the fuel supply lines as close as possible to the main engine(s). This location is always decided in cooperation with the chief engineer and is most often either from a dedicated sampling point or close to the last booster filter. A fuel sample will be collected in one sampling bottle (1 l) and after mixing is dispersed over two additional bottles, each containing *ca.* 0.3 l, one of the three bottles remains on-board to be used as counter-expertise if necessary. The other two bottles will be taken along by the inspector, one of them will be sent to an accredited laboratory for a fuel analysis using laboratory XRF techniques and the other will be stored by the environmental administration and kept as a reference sample [18,45].

6.4.2. NO_x inspections

In contrast to sulfur inspections, NO_x inspection executed by port inspection authorities are limited to documentary inspections. The NO_x Technical file is an essential document that must be kept on board to demonstrate compliance with NO_x emission regulations. This NO_x technical file includes 1) a list of the components and engine parameters which influence the NO_x emissions; 2) a list of the adjustments or alternatives for the components of the engine; 3) an overview of the engine's parameters, including ERS; 4) a system of on-board NO_x verification procedures; 5) a copy of the test report provided in Appendix 5 of the NO_x Technical Code (Art 5.10); 6) if applicable, the restrictions for the engine; 7) the specifications of spare parts/components that would not impact the engine's compliance; and 8) the Engine International Air Pollution Prevention (EIAPP) Certificate (Art 2.4.1) [75].

Along with the NOx technical file, the International Air Pollution Prevention (IAPP) certificate should also be available on board (Art. 2.4.2). The IAPP is granted after the engine has been installed on board of the ship and the on board NO_x verification procedure has been successfully carried out and demonstrated the ship's compliance (Art 2.4.4). If the emission tests were performed within three months prior to the inspection, the emission test results must also be available on board (Art. 2.3.4) [75].

As part of routine port inspections, usually only a basic review of the NO_x technical file is conducted along with verification of the validity and presence of engine certificates. Additionally, Appendix 5 may be reviewed to confirm the engines' compliance with the required emission limits. For Tier III ships, inspectors may examine the functioning of the emission abatement systems (Art. 2.4.5) [65], though detailed guidelines for the logging of emission values from the CEMS are currently not implemented by international regulations. As a result, port inspection authorities do not have a reliable enforcement

procedure to verify whether a ship's real world NO_x emissions meet the required emission limits. This matter will be discussed in depth in Chapter 8 of this dissertation.

It should be noted that classification societies can conduct a more comprehensive examination during an audit or engine re-certification. This involves a detailed examination of the NO_x Technical file to confirm that the engine has not been significantly altered to the extent that it no longer meets compliance or no longer reflects the specifications outlined in the NO_x Technical file. This type of inspection would be beyond the scope and expertise of port inspection authorities.

6.5. Data management

6.5.1. Belgian airborne monitoring data

Throughout the process of writing this dissertation, a considerable amount of data was gathered, processed and analyzed. As this data is regarded as sensitive information, the data is kept on RBINS' servers that are password-protected and are only accessible by authorized personnel. The processed remote measurement data collected by the Belgian coastguard aircraft are available through a DOI, but the identity of the ships has been concealed. However, for specific purposes, an unmasked dataset can be accessed via a secure server after obtaining clearance by providing valid credentials, along with a motivation letter and signing a non-disclosure agreement. So far, only two requests have been received so far to obtain access, which have both been granted. One was made by La Libre, a Belgian newspaper that published a series of articles on ship emissions [200], and the other by the International Council on Clean Transportation (ICCT), which is currently working on a dedicated report on NO_x emissions from ships.

6.5.2. Other remote measurement results

In addition to the data collected by the Belgian coastguard aircraft, compliance levels from other BA CPs were obtained based on remote measurements conducted by the BA CPs between 2015 and 2022. While some BA CPs, like Denmark, had already published these results, data from Germany and the Netherlands, as well as the data collected by the RPAS service provided by EMSA, was not publicly available. To access this information, permission was sought from the national competent authorities (NCAs) of the involved BA CPs for the use of the data for the BA and for scientific research purposes. Permission was granted, and since the BA CPs provided only overall compliance levels based on different cut-off levels, no sensitive information, such as the identification of possible violators, was collected. Therefore, the management and processing of the data did not require any special treatment.

6.5.3. Port inspection results

FPS Mobility and Transport provided information on inspections conducted in Belgian ports for the enforcement of ships' compliance with the international and national emission regulations. However, this information is the property of the FPS Mobility and Transport and cannot be shared without their explicit permission. Any inquiries regarding access to this information should therefore be directed to the FPS Mobility and Transport. The BA CPs also provided data on sulfur and NO_x inspections, which are collected by EMSA for reporting to the EC on an annual basis. Since EMSA was unable to share this information without written consent from the EU MS, the BA CPs were contacted directly and provided the data in preparation for the NSN23 and OTSOPA23 meetings. To avoid confidentiality issues, the identification of the found non-compliant ships was not requested, and only the total number of found violations and sanctions for the BA CPs were included for the research conducted in Chapter 6.

6.5.4. Thetis-EU

Starting from 2016, when the Belgian airborne monitoring became fully operational, ships with high measured FSC levels were observed and reported to Thetis-EU. For measurements conducted over Belgian waters, the FPS Mobility and Transport reported to Thetis-EU, while for those carried out over

Dutch waters, ILT was responsible for the reporting. After extensive preparatory discussions with EMSA, a protocol for the automatic transfer of emission measurement data was developed by RBINS at its own expense, the data protocol was put into use in 2019. RBINS was hereby the first MS to provide this data streaming service, and from 2019 onwards, all measurement data collected by Belgium was automatically sent to Thetis-EU. Following the initiative of Belgium also other MS, such as the Netherlands and Germany, implemented this procedure for their own monitoring operations. Ward Van Roy and the RBINS IT department (SWAP) organized several meetings with the IT departments of other MS to support them in setting up their own streaming protocol. This automatic streaming of remote measurements has made over 20,000 measurements per year available to the entire port inspection community within the EU, Norway, and Iceland. However, due to the Brexit proceedings, the UK currently no longer has access to Thetis-EU, but is negotiating to restore access.

7. Structure of the dissertation and research questions

7.1. Presentation of articles

The doctoral dissertation is divided into four parts, which serve as the undertaken subsequent steps in exploring the use and effectiveness of airborne measurements for the monitoring and enforcement of MARPOL Annex VI (Figure 24). These parts expand from the technical level of induvial measurements to strategic cooperation at regional level, with airborne monitoring acting as the common thread that connects the entire dissertation. In total eight chapters were composed, every chapter represents a published or submitted paper, the papers included for Chapters 1-5 are peer-reviewed and published in scientific journals. The papers included in Chapters 6-8 are submitted, but are still under peer review process at the date of the submission of this dissertation.

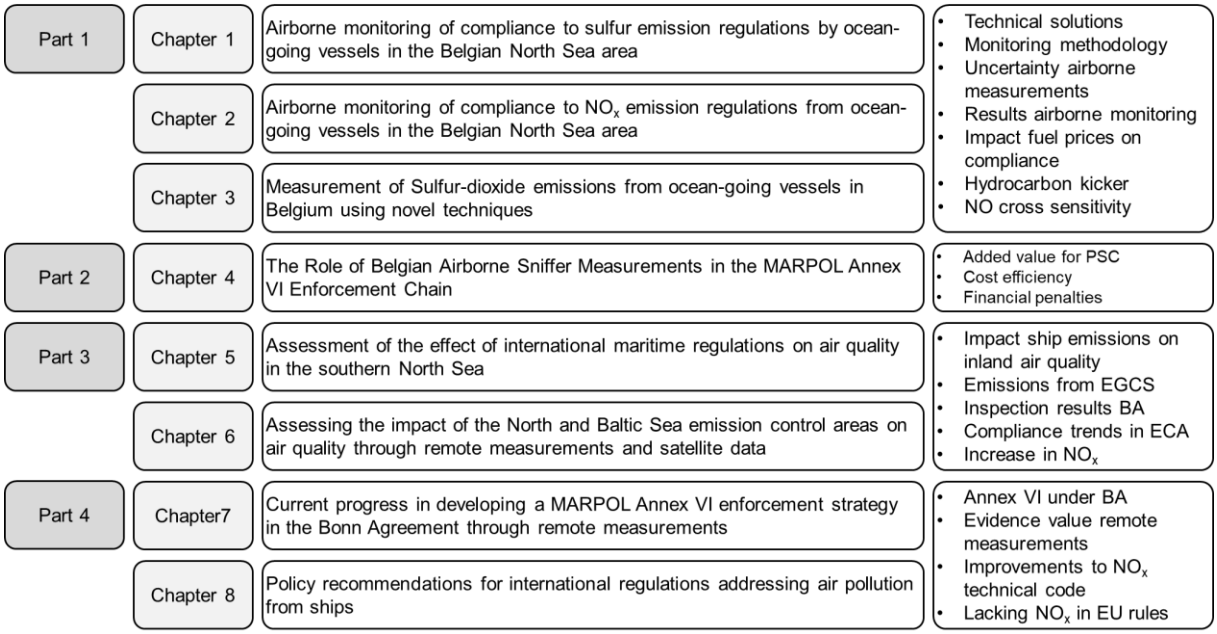


Figure 24. Structure of the dissertation

7.1.1. Part 1 Technical solutions and methodologies

The first part of this disseratation comprises three chapters that provide a comprehensive overview of the technical solutions and remote measurement methodologies that have been developed to monitor and enforce compliance with SO_x and NO_x emission regulations from ships in Belgium. The three chapters provide significant and informative insights into the establishment of an airborne monitoring and enforcement mechanism and its unique characteristics. These chapters shed light on the processes involved in setting up this mechanism and detail its specific features and attributes, or in other words

this part focuses on the "HOW" and "WHAT" of the dissertation, how are airborne operations executed, how are the measurements conducted, what techniques are applied and what are the results and findings at sea.

Chapter 1 of this thesis focuses on the execution of airborne operations and provides a comprehensive explanation of the methodologies employed. The chapter aims to define the basic approach of the airborne monitoring methodology for the monitoring and enforcement of SO_x emission regulations. In addition, the chapter describes the methodology for the assessment of the measurement uncertainty and the establishment of non-compliance alerting thresholds. This chapter lays the foundation for the subsequent chapters and provides a clear understanding of the monitoring methodology and its intended purpose. Furthermore, it provides insights on ships' compliance behavior at sea and their average SO_2 emission factors.

Chapter 2 expands on the monitoring methodology introduced in Chapter 1 and applies it to NO_x emissions. This chapter delves deeper into the methodology and provides an explanation of the process for monitoring NO_x emissions. This chapter presents a thorough analysis of the NO_x monitoring methodology regarding the specifications of the NO_x emission regulations and the associated challenges. Furthermore, this Chapter aimed to provide highly needed insights on NO_x compliance levels at sea and average NO_x emission factors of ships sailing in the ECA.

In Chapter 3, the research seeks to improve the reliability of the SO_x emission monitoring practice introduced in Chapter 1. This chapter sought to find a solution to remove the NO cross-sensitivities of the SO_2 sensor and the impact of volatile organic compounds (VOCs) on the SO_2 measurement process This was achieved by applying novel techniques that eliminate the NO cross-sensitivity and the VOC influence, resulting in a significant improvement of the measurement sensitivity for assigning potential non-compliance. This chapter provides a detailed explanation of the techniques employed and presents the results of their analysis. This chapter presents an important contribution to the study by improving the reliability of the monitoring methodology and enhancing the accuracy of the results obtained. In Chapter 3, also the link between fuel prices, non-compliance rates, and average FSC values is investigated.

Overall, these three chapters offer insights into the execution of airborne monitoring operations and the methodologies employed for the monitoring and enforcement of SO_x and NO_x emission regulations. The main research questions addressed in these chapters focused on the feasibility of setting up an airborne monitoring system to verify compliance with international emission regulations and the reliability of the measurements obtained. The research also examined the thresholds beyond which non-compliance alerts could be generated and sought to gain insights into the compliance situation at sea. In addition to identifying the number of non-compliant ships and average emission levels, the research attempted to identify non-compliant profiles and determine whether location and routing played a role in non-compliance behavior. To answer these research questions, previous studies were examined, statistical analyses on the collected data was performed, and the methodology for measuring SO_x and NO_x was solidified. The updated methodology was also described in detail in the SQMS.

7.1.2. Part 2 Impact on PSC

Part 2 of this dissertation includes only one chapter, the research described in Chapter 4 was dedicated to exploring the link between airborne monitoring operations and on board sulfur inspections. The overall objective of this chapter was to establish the reasoning behind the use of airborne measurements, or in other words, the "WHY" behind the implementation of this technology. This part seeks to answer the key question of whether airborne monitoring operations are useful to the MARPOL Annex enforcement chain on an operational level or if their value remains more academic in nature.

To answer this question, the results of the port inspections conducted by the Belgian port inspection authorities were analyzed and compared to the airborne monitoring results. The goal was to determine if the conducted airborne measurements led to an improvement in the port inspection results and, if so, whether they did so in a cost-efficient manner.

In addition, data was obtained on the penalties imposed as a result of non-compliance in Belgium. By comparing the results of the port inspections to the airborne monitoring data, the researchers were able to determine if there was a correlation between the two and if the use of airborne monitoring operations provided a substantial improvement of the overall port inspection efficiency.

For this chapter data was collected from the ships that were targeted for inspection and were alerted in Thetis-EU, to examine if and when they were followed up by port inspection authorities in the EU and what the results were of the on-board inspections.

Finally, this chapter seeks to address the question of whether the real-world measurement uncertainty of the airborne measurements is consistent with the results from previous research. To answer this question, a validation analysis was conducted using reference data from fuel samples and ships equipped with an EGCS.

Overall, this chapter provides an important contribution to the study by exploring the practical implications of using airborne monitoring operations for the enforcement of MARPOL Annex regulations. Valuable insights are given into the effectiveness of this technology and whether it provides a cost-efficient means of improving compliance with sulfur regulations.

7.1.3. Part 3 Impact of regulations on air quality

This part of the dissertation delved into the "WHERE" and "WHEN" aspects of international ship emission regulations. In two chapters, the thesis attempts to answer questions such as where the impact of these regulations has been most significant and when this impact could be observed, to determine the extent to which the regulations have led to improved air quality or not. Additionally, this part aims to identify the areas where non-compliance is most prevalent, to optimize monitoring operations.

One of the main objectives of these chapters was to evaluate the effectiveness of the international ship emission regulations in improving air quality in Belgium (Chapter 5) and the broader ECA (Chapter 6). To this end, remote monitoring results and port inspection results from Belgium and other BA CPs were employed, as well as satellite data.

Furthermore, Chapter 5 also examines the impact of EGCS ships, which are designed to reduce emissions by cleaning the exhaust gases before they are released into the atmosphere. This is an important area of investigation since these ships are becoming increasingly prevalent in the maritime industry and could have a significant impact on compliance monitoring and enforcement. For this purpose and extensive dataset on EGCS ships was collected from EMSA and linked to remote measurement data to evaluate if the use of EGCS impacts the SO_x and NO_x emissions and the ships' compliance to SO_x and NO_x emission regulations.

Overall, the two chapters provide valuable insights into the spatial and temporal patterns of compliance with international ship emission regulations, as well as the impact of these regulations on air quality in Belgium and the broader ECA region. The results of this part is especially relevant for policy makers and other stakeholders responsible for environmental regulation and enforcement, as they can offer valuable guidance in developing more efficient regulations and strategies for monitoring and enforcing of compliance to emission regulations at sea and in port.

7.1.4. Part 4 Regional cooperation and legal recommendations

The concluding part of the thesis shifts its attention towards the "WHO," exploring the various regional and international actors and their corresponding legal instruments in two chapters. These chapters emphasize on the roles and responsibilities of different entities, highlighting both ongoing activities and regulatory gaps requiring attention. Furthermore, these chapters address the future steps that need to be taken to further improve the enforcement capacity and monitoring efforts. It highlights the need for continuous development of more efficient compliance monitoring strategies and suggests ways to make regulations more effective in achieving the goal of reducing ship emissions.

The key focus of Chapter 7 is the future rolling out of a monitoring strategy for MARPOL Annex VI within the BA region. The chapter details the various actions that have been taken by the BA CPs to address the MARPOL Annex VI regulations at a coordinated regional level. The implementation of a coordinated and harmonized monitoring strategy would require significant collaboration among the different BA CPs to ensure the successful harmonization of monitoring, enforcement and reporting efforts. Therefore, the adoption of this harmonized strategy is expected to take several years. Up until now, Belgium has been instrumental and at the forefront of this effort, contributing its expertise and motivation towards the creation of a harmonized monitoring strategy.

Chapter 8 explores the entities responsible for implementing legal instruments regarding ship emission regulations and the enforcement mechanisms for verifying complying to these regulations by port State and coast State authorities. This closing chapter offers recommendations for policymakers involved in implementing ship emission regulation and their enforcement to ensure that they are on the right track towards the implementation of more efficient regulations to enforce the current emission limits and further reduce ship emissions.

Furthermore, this chapter also reflects on the lessons learned from the previous chapters and how they can be used to push the development of more effective regulations. It emphasizes the importance of involving all relevant stakeholders, including the monitoring agencies, environmental researchers, and the shipping industry, in the decision-making process to ensure that the regulations and enforcement strategies are practical, effective, and feasible.

7.2. Individual contributions of co-authored publications

This dissertation can be considered as the culmination of my gained experiences and expertise, particularly drawing upon my extensive year-long operational experience as an operator and instrumentation manager of the coastguard aircraft. Additionally, my efforts as co-organizer of the BA Marpol Annex VI Experts Workshop and my role as a co-convener of the BA Marpol Annex VI Technical Working Group contributed substantially to the writing of this thesis.

However, it cannot be stressed enough that the research presented in the different chapters of this doctoral dissertation is the result of a collective effort. Conducting aerial surveillance is not possible to do singlehandedly. For this reason, the operators involved in the airborne monitoring operations were listed as co-authors. In addition, all manuscripts were proofread by all co-authors, their insights greatly improved the work. The insights of the SURV team coordinator, Ronny Schallier and HoD from OTSOPA were especially valuable on all matters regarding the Bonn Agreement. The geographic visualizations of the monitoring efforts and results of the satellite analyses for the different papers were provided by Laurence Vigin and Benjamin Van Roozendael, both former operators on board of the coastguard aircraft and experienced GIS experts. For Chapter 3, Prof. Dr. Johan Mellqvist was mentioned for his technical advice in constructing the hydrocarbon kicker, in addition the sniffer and IGPS software are his brainchild and he deserves therefore all credit. For Chapter 6, fellow researchers and remote monitoring experts Dr. Andreas Weigelt, Prof Dr. Johan Mellqvist, Dr Jörg Beecken, PhD

student Jasper Van Vliet, Dr. Danielle van Dinther, Dr. Frederik Tack and Dr. Nicolas Theys co-authored the publication for their provision of remote measurement data. Invariably, the greatest contribution in proofreading and improving the manuscripts were made by Prof. Dr. Frank Maes, promotor of this doctoral dissertation. Aside from this, all draft manuscripts, all presented graphs and figures, described methods and protocols were composed by Ward Van Roy, the first author of all publications and author of this dissertation.

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Part I

Chapter 1: Airborne monitoring of compliance to sulfur emission regulations by ocean-going vessels in the Belgian North Sea area.



Personal picture taken during flight 23053 (12/04/23)

Airborne monitoring of compliance to sulfur emission regulations by ocean-going vessels in the Belgian North Sea area.

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Abstract

Air pollution from fossil fuel powered ocean-going vessels (OGVs) is responsible for various environmental and human health issues worldwide. Specifically for sulfur oxides (SO_x), from 2010 onwards, stricter standards came into force regarding the maximum allowable fuel sulfur content (FSC) in marine fuels in the European Sulfur Emission Control Area (SECA). A method was developed for the airborne monitoring of OGVs to evaluate their compliance by equipping the Belgian coastguard aircraft with a sniffer sensor. The sensor allows a highly accurate FSC determination based on real-time CO_2 and SO_2 measurements in the smoke plume of OGVs. For 5 years the aircraft collected the largest set of airborne emission measurement data from OGVs as of today. This article demonstrates the effectiveness and reliability of the airborne monitoring methodology in an operational setup for targeting ship inspections in ports and a more efficient impact monitoring of shipping on air quality.

1. Introduction

1.1. Sulfur regulations

The international environmental standards for Ocean Going Vessels (OGVs) are laid down by the International Maritime Organization (IMO) under the MARPOL Convention for the prevention of pollution from ships as modified by the Protocol of 1978 (MARPOL 1973/78) [1]. The MARPOL convention was amended by the protocol of 1997 (MARPOL PROT 1997) revised in 2008 [2] and several times amended. As of 2021, Annex VI was ratified by 101 countries representing 96.57% of the gross tonnage of the world merchant fleet [3]. MARPOL Annex VI, regulation 14 envisaged a gradual decrease of emissions of SO_x and introduced Emission Control Areas (ECAs) where more stringent emission limits for air pollutants (SO_x, NO_x, PM) from OGVs apply. As of 2008 the Baltic Sea was designated as a Sulfur Emission Control Area (SECA), followed by the North Sea [4] which became ECAs [5,6]. In 2010 the 200 nautical mile zone adjacent to North American waters became an ECA [7] and the US Caribbean Sea in 2011 [8,9]. On European level, SO_x emissions from OGVs are furthermore regulated by the EU Sulfur Directive, which in general is a translation of the MARPOL Annex VI regulation in European legislation, but some additional requirements were introduced, for example, the allowed fuel used in European Union ports [10–12]. The EU has also set out minimum quota on the number of ship inspections to be executed by the member states. Important to note is that the use of remote sensing techniques may result in a reduction of 50% of the number of such mandatory inspections in port [13]. At national level, Belgium implemented MARPOL Annex VI and EU Directive 2005/33/EC in 2007 [14].

The North Sea and the English Channel became Sulfur Emission Control Areas (SECAs) in 2006 [4,5,7] (Figure 1, left). This implied that from 2008, OGVs in the North Sea SECA could only use (i) Low Sulfur Fuel Oil (LSFO) or Marine Gas Oil (MGO) with a Fuel Sulfur Content (FSC) of 1.5% mass percentage, (ii) use natural gas, mostly Liquified Natural Gas (LNG) or (iii) use approved exhaust gas-

cleaning systems (EGCS), the so-called 'Scrubbers', to filter out the sulfur compounds from the exhaust gasses in order to achieve the same emission level as with low sulfur fuels [15–18]. On the 1'st of January 2010, the emissions limits in the North Sea and Baltic Sea SECA were tightened to 1% FSC [4]. On the 1'st of January 2015, the emissions limits were further tightened to 0.10% FSC [7]. This strengthened limit in the SECAs was 35-times lower as the limit outside the SECAs at that time, where the limit for the sulfur content in ship fuels was until December 31, 2019 still 3.5% FSC, although the effective global average was closer to 2.5% [19,20]. From January 1, 2020, the maximum sulfur content worldwide is limited to 0.5% FSC by the so-called 'Global Sulfur Cap' from MARPOL Annex VI [21] (Figure 1, right). Moreover, since March 1, 2020, the carriage of non-compliant fuel oil for combustion purposes for propulsion or operation on board OGVs is prohibited unless the OGV is equipped with an EGCS [22].

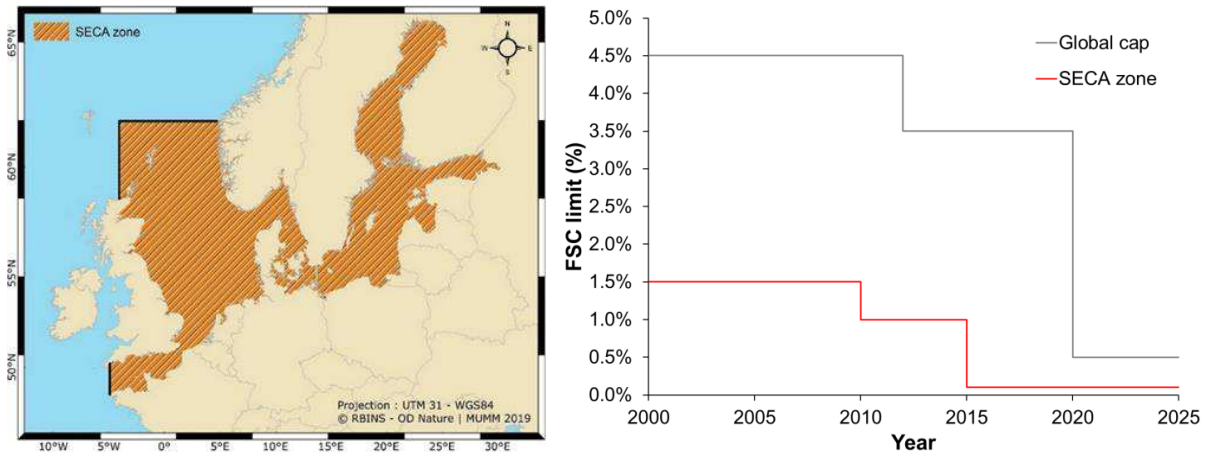


Figure 1. Left: Sulfur Emission Control Area (SECA) as defined by MARPOL Annex VI. Right: Limits on the Fuel Sulfur Content of marine fuels according to the MARPOL Annex VI regulation 14.

1.2. SO_x emissions from maritime transport

The main pollutants in the exhaust gases from OGVs are sulfur oxides (SO_x), nitrogen oxides (NO_x), particle matter (PM), Volatile Organic Compounds (VOCs), Black Carbon (BC) and Organic Carbon (OC) [23,24]. Sulfur in marine fuel is oxidized during combustion into mainly SO_2, in a lower extent to SO_3 and particulate sulphates (pSO_4^{2-}), creating sulfate aerosols [25–27].

Shipping is one of the main contributors of emissions from SO_2 on global scale [28]. For the period 2007-2012 the SO_x emission from vessels contributed to 12% of the global anthropogenic SO_2 emission, while only representing 3.1% of the CO_2 emission [24]. Even with the emission reduction regulation, it was estimated that SO_2 emission from vessels would have been responsible for up to 250.000 premature deaths per year globally without the introduction of the global cap [29]

1.3. Belgian airborne surveillance program

The Management Unit of the Mathematical Model of the North Sea (MUMM) is a Scientific Service of the Royal Belgian Institute of Natural Sciences (RBINS) is recognized by Belgian Law as one of the legally competent authorities for the monitoring and follow up of MARPOL regulations at sea. Since 1991, MUMM has been responsible for the airborne surveillance of the Belgian North Sea area [30]. From 2014 until 2016 MUMM has been involved in the CompMon project [31]. The main goal of this project was to pilot the enforcement of MARPOL Annex VI regulation in the SECA area. For this project, a sniffer sensor was acquired and installed on the Belgian Coastguard aircraft.

1.4. Surveillance area and time frame

The Belgian part of the North Sea area is relatively small, with a coastline of *ca.* 65 km and an Exclusive Economic Zone (EEZ) that stretches up to 83 km seawards, resulting in a total surface of 3454 km^2 [32,33]. At regional level MUMM is operating within the framework of the Bonn Agreement. The initial Agreement for Cooperation in Dealing with Pollution of the North Sea by Oil was signed in 1969, and later replaced by the Bonn Agreement in 1983 [34]. Within the Bonn Agreement a dedicated quadripartite zone has been defined to facilitate the contracting parties Belgium, France, the Netherlands and the UK to conduct surveillance in neighboring waters. This zone of joint responsibility is defined by the sea area between the 51°51' 52" N and 51° 6'N parallels [34]. This subregional surveillance area is with 13500 km^2 relatively small compared to maritime areas of neighboring countries (e.g., maritime area of the Netherlands consists of 58000 km^2 [35]). However, it is one of the busiest maritime areas in the world, with more than 400 vessel movements a day of OGVs larger than 300 GT [36,37] (Figure S1, upper). To visualize the air pollution from OGVs at regional level, atmospheric data from satellites were examined. Up to 2018 the OMI satellite was used for SO_2 monitoring [38], but the resolution of these data was too low and therefore the NO_2 data from EASA Copernicus Atmospheric Monitoring Services (CAMS) was used to visualize emissions from OGVs [39]. On these images individual shipping lanes in the wider North Sea, Baltic and Mediterranean area clearly visible. Shipping lanes in the Belgian part of the North sea area are less distinctive due to the concentrated maritime traffic and pollution from land sources (Figure S1, lower).

Sniffer operations started in September 2015. However, due to a ship collision that occurred in Belgian coastal waters on 6/10/2015 between the vessels FLINTERSTAR and AL-ORAIQ, resulting in a significant marine pollution [40], the sniffer campaign was interrupted as the Coastguard aircraft was requested to assist during the oil spill monitoring and response operations. For this reason the sniffer campaign in 2015 lasted only for 1 week. From 2016 until 2019 sniffer operations have been conducted all year long, apart from a winter service period from November/December until February/March.

2. Methods and Materials

2.1. Belgian coastguard aircraft

The Belgian coastguard (CG) aircraft was used for this study. The aircraft is a Britten Norman Islander (BN2), a high wing Short Take Off and Landing (STOL) aircraft, with large wing surface (14 m width for 10 m length). The aircraft is equipped with 2 Lycoming 300 HP piston engines, modern avionics and a remote sensing system from Optimare. Until today, the aircraft is used by MUMM to provide maritime environmental surveillance for the Belgian CG and the Bonn Agreement.

2.2. Sniffer sensor

The sniffer sensor is developed by Chalmers University and built by FluxSense (Gothenburg, Sweden). The sensor was initially designed to be used as a fixed sensor for autonomous measurement, e.g., at the Great Belt Bridge [41]. The fixed sensor design was further modified to enable the use on airborne platforms, by lowering the weight, increasing the airflow and improving the response time. The first model of this sniffer sensor was installed on board of a Piper PA-31 Navajo aircraft by Chalmers University and used for airborne monitoring operations over Danish waters.

The sniffer sensor consists of a set of different sensors and equipment mounted in a 19" housing (Figure 2). The most important units are (i) a Thermo Trace Level Ultraviolet fluorescence sensor, used for the measurement of SO_2 in ppb (unitless); (ii) a Bioscience Licor Nondispersive Infrared NDIR sensor, used for the measurement of CO_2 in ppm (unitless); (iii) a powerful vacuum pump; (iv) pressure and flow regulators; (v) a log computer; (vi) a combined Automatic Identification System (AIS) and Global Positioning System (GPS) receiver and (vii) an Aeronautical Radio INC. (ARINC) module. A particle

filter (1µm) is installed at the air-inlet of the sniffer sensor. The air-inlet is connected to a probe, a stainless-steel sampling tube (3/8") on the bottom of the aircraft. The AIS and GPS receivers are connected to antennas on the aircraft. The ARINC module is connected to the Flight Management System (FMS) of the aircraft avionics suite, which provides the actual wind speed and direction. The log computer is connected to an ethernet hub allowing the connection of different client stations (e.g., Console and Laptop). The video output from the log computer is connected to the avionics (FMS and cockpit display).

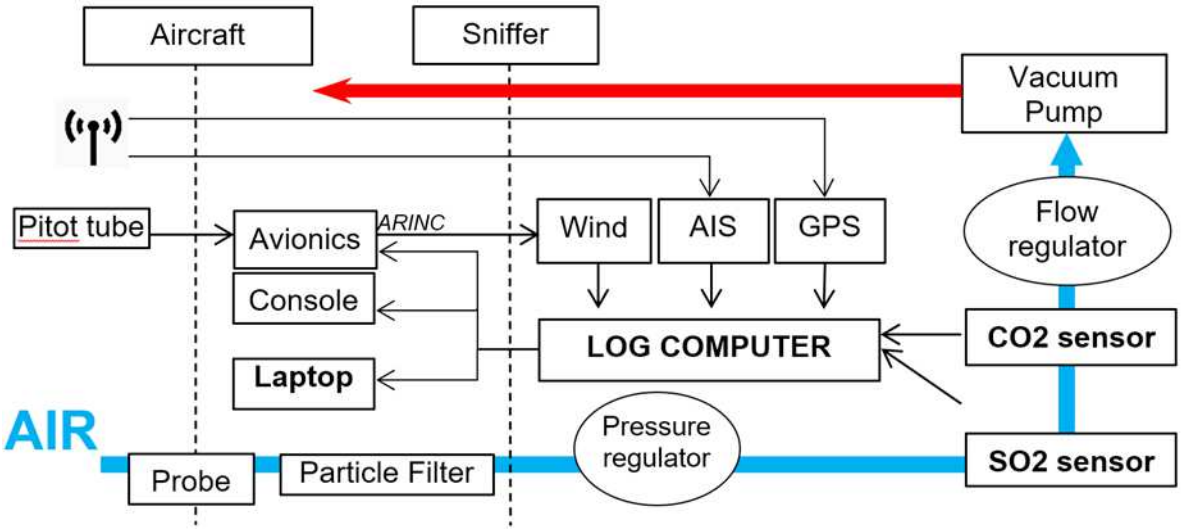


Figure 2. Schematic presentation of sniffer sensor system (dimensions are: 638x424x386 mm and weight is *ca.* 40 kg, excl. external wiring and tubing).

2.3. Sniffer sensor software

Chalmers University also developed the software for the sniffer sensor, tailored to the requests of MUMM. The gas analyzers and other equipment sent data to the log computer. Logging software (TCP) collects this data and provides the data to the client stations. The graphical user interface (IGPS Presenter) on the client stations visualizes this data. The two most important views are the MAP view and the SNF view (described below).

The MAP view shows the OGVs and AIS info, the position of the aircraft and the apparent wind direction. Based on the apparent wind direction the indicated location of the smoke plume from the OGV is plotted on the map. The MAP view allows to assign OGVs to be measured, these OGVs will be marked on all client stations. In addition, it is also possible to assign a measurement result to an OGV and indicate if the vessel was compliant or not after measurement with a tag (HIGH/LOW).

The SNF view provides plots of the CO_2, and SO_2 concentration combined with the altitude and the pressure. In operations with fixed sniffer stations, the software will automatically detect a smoke plume, calculate the FSC and link it to the OGV. Due to the high shipping density in the North Sea this software feature was not preferred by MUMM. Instead. MUMM requested to include a feature to manually assign the part of the graph that corresponds to a plume, calculate the FSC and link this to the OGV.

2.4. Sulfur emissions measurements

To calculate the FSC, the SO_2 emission factor in g SO_2/kg fuel was calculated based on the SO_2 and CO_2 concentration before and in the plume. When passing through the plume, the increased SO_2 and CO_2 compared to the background (*bkg*) was calculated by looking at the surface area under the

respective concentration plots [42]. To calculate the amount of kg burned fuel the amount of C was multiplied with the carbon content in the fuel, for marine fuels a carbon content of 87% was used [43].

$$EF_{SO_2} = \frac{MSO_2 \frac{g}{mol}}{\frac{MC \frac{g}{mol}}{0.87}} \times \frac{10^3 \times \int [SO_2 - SO_{2,bkg}]_{ppm} dt}{\int [CO_2 - CO_{2,bkg}]_{ppm} dt} \left[\frac{g}{kg\ fuel}\right] \quad (1)$$

To find the FSC, this formula was converted by using the molecular weight of S instead of using the molecular weight of SO_2 [44].

$$FSC = 0.232 \times \frac{\int [SO_2 - SO_{2,bkg}]_{ppb} dt}{\int [CO_2 - CO_{2,bkg}]_{ppm} dt} [\%\ Sulphur] \quad (2)$$

3. Sniffer Quality Management System

To guarantee a high reliability of individual FSC measurements, the spatial and temporal consistency of emission measurements and an efficient execution of the airborne monitoring missions, a Sniffer Quality Management System has been set up. This system consists of three parts, (i) the operational procedures (OPS) are described in the OPS manual, (ii) the quality assurance (QA) protocols are described in the QA manual and (iii) the data management are described in the data manual. These three parts are described in the sections below and are available as supplementary material.

3.1. Operational procedures

In flight, OGVs were selected for inspection by the operators. This selection was mainly based on an optimization of the flight pattern to maximize the number of OGV emission measurements. Vessel size was a vital decisive factor, with 100 m as arbitrary minimum length, since smaller vessels have generally emissions that are emitted at a lower altitude which lowers the success rate and increase the risk of the operations. Moreover, smaller vessels are generally operating on MGO and are therefore more prone to be compliant. The IGPS presenter software allowed to visualize the OGVs on scale, which made it straightforward to pre-select suitable vessels. Another vital decisive factor was the sailing speed. Generally OGVs that are en-route will have higher emissions, making them easier to measure. Moreover, anchored vessels in anchorage areas are generally surrounded by numerous other OGVs making it difficult to differentiate plumes from each other.

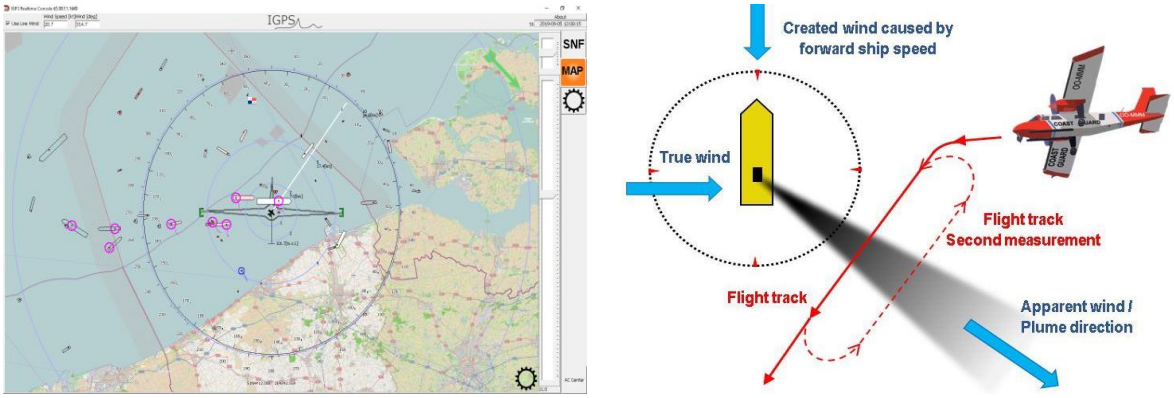


Figure 3. Left: MAP view of the IGPS software. Right: Schematic overview of the measurement approach.

The OGVs were selected by the operator and were visual for the pilots on the cockpit display (Figure 3, left). The next target was always communicated by one of the operators to the pilots. Plumes were crossed in the shortest angle possible at a cruise speed of 100-110 kts at a distance of min 100 m from the ship at an altitude of min 30 m (Figure 3, right). For these operations specially trained pilots and special Standard Operating Procedures (SOPs) are required. The Belgian Coast Guard aircraft is flown

by highly experienced military pilots in a two-pilot configuration. Special flight permission to execute these low altitude approaches are obtained from the Belgian and Dutch aviation authorities on annual basis.

As soon as the emission exhausts were sampled, measurement results were immediately plotted on the SNF graphs (Figure 4), visual to both pilots and operators. The manual calculation of the FSC by the operator took less than 2 minutes after the plume crossing. In case a high FSC was measured, a second measurement was made for confirmation. In case the initial alert was confirmed, a report was sent to the competent maritime inspection authorities of (i) the coastal state where the observation was made and (ii) of the destination of the OGV.

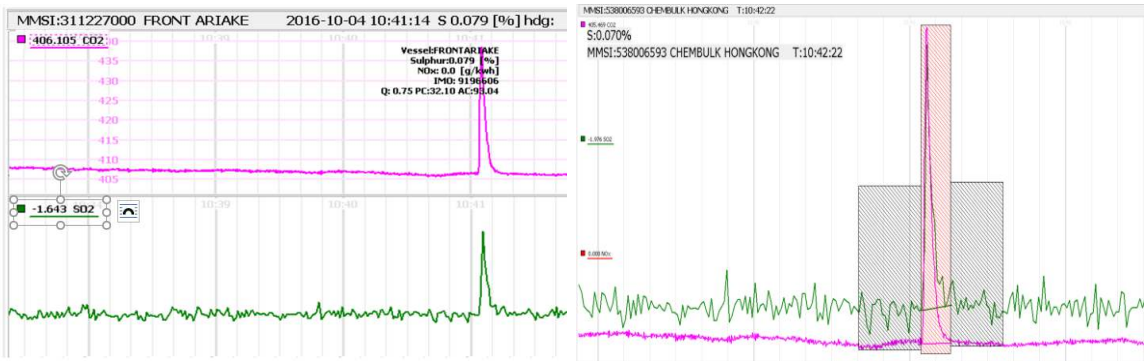


Figure 4. Left: print screen of the "SNF" view with the CO_2 concentration (in ppm) in magenta and the SO_2 concentration (in ppb) in green. Right: graph selection view, the start and end of the peak (red striped area) and the background before and after the peak (black striped areas) can be set manually by the operator. The FSC content is displayed immediately (upper left side).

3.2. Quality assurance manual

The QA manual consists of all detailed maintenance and calibration procedures. For all parts of the sniffer sensor system the service interventions were identified and all actions (e.g., service, calibrations) were logged to make sure all parts undergo the required maintenance service. One of the key parts of the QA procedures is the organization of regular calibrations. Three types of calibration procedures were included: (i) hardware calibration, (ii) software calibration and (iii) span gas calibrations. For SO_2, one span gas was used of 400 ppb. For CO_2 two span gases were used, 420 ppm and 470 ppm respectively. The span gasses were obtained from Airliquide and checked on arrival by the ISO certified air quality laboratory of the Brussels Environmental Agency (BIM). This initial check showed a difference of up to 10% from the requested concentration and was therefore deemed essential. In addition, the trace levels of SO_2 were checked for the CO_2 gas mixtures and the CO_2 trace levels were checked for the SO_2 gas mixture, this allowed to use the mixtures as zero during the calibrations.

The hardware calibration was performed on a monthly basis. During this calibration, zero and span gasses were connected to the SO_2 and CO_2 sensors directly in order to reset the sensor background (offset) and calibration factors (slope) of the sensors itself.

In addition to the hardware calibration procedure, a software calibration was executed before every mission, to account for sensor drift and drift due to meteorological conditions (humidity and temperature). For the software calibration the same span gasses were used. In this case the calibration was not done on the sensor itself but on the readings by the sniffer software.

The span gas calibration ensured that the correct span concentration was used during the hardware and software calibrations. The span gasses were therefore tested on regular intervals by the BIM. Although often a significant difference was observed with the commercial concentration, the CO_2 concentrations

were very stable over time with an average variation <1.5%. The SO_2 concentrations were notably less stable, with an average variation of 4%. Therefore, the reference gas calibration intervals were set at 3 months for SO_2 and 6 months for CO_2.

3.3. Data management

To ensure the quality of the collected data, a data management system has been created. This system includes detailed procedures on how the data needed to be collected and shared with stakeholders. Collected data was coming from 2 sources. The first being the emission measurement data from the OGVs, such as background gas concentrations, start- and ending time of the plume, and total peak area. The second source of information were target data, including tagged data by the operator (High/Low) together with the AIS data of the OGV: destination, flag, dimensions, etc. A dedicated macro was used to combine these two files into one file, which consisted of the AIS data together with the relevant emission measurement data.

As part of the data management, the calibration factors were logged to see the evolution of the sensor drift. In case the sensor drift remained within limits, no service intervention was required. During the total time frame of the monitoring activities, the sensor drift always remained within these boundaries between the service intervals.

3.4. Statistical analysis

A QQ-plot and a Kolmogorov Smirnoff test showed that the FSC dataset was not normally distributed. Therefore, two sided non-parametrical Mann-Whitney U tests were used to compare average FSC values. To determine a difference in compliance levels between two groups, two sided Chi-Squared tests were used. Statistical significance was defined as P values of < 0.05 [45,46].

4. Results and discussion

4.1. Description of the sampled OGVs

During a total of 270 flights and 417.5 operational flight hours from September 2015 until December 2019, *ca.* 9000 low passes in the exhaust plumes of 5049 OGVs were made, of which 4592 OGVs emission plumes were successfully measured. The average number of successful emission measurements was 11 OGVs per flight hour, with a total success rate of 91%. This is the percentage of the selected OGVs that could successfully be measured. The number of successfully measured OGVs per hour increased over the years, from an average of 6.7 OGVs per flight hour with a success rate of 75% in 2015, up to 12.9 OGVs per flight hour with a success rate of 97% in 2019 (Figure S2). The increase in success rate and efficiency was mainly a contribution from the gained experience of the pilots and operators in localizing the plume and focusing on OGVs with a higher probability of successful measurement.

In 2015 only 153 OGVs were measured, while from 2016 until 2019 on average 1224 OGVs were measured per year. Of the measured OGVs, 3059 consisted of distinct vessels, meaning that about 33.5% of the vessels have been monitored more than once. In total, 4787 plume measurements have been done, giving a total of 1.56 measurements per observed OGV.

The destination of the OGV was recorded from AIS for 89% of the observed OGVs, 80% concerned OGVs with a destination in the SECA (3259) and 20% concerned OGVs with a destination outside of the SECA (830). In total 66 different destination countries could be identified, with Belgium (30%) and the Netherlands (24%) covering the majority of destination countries, followed by the UK, Germany and France (Figure S3, upper). When looking at the next port of call of the observed OGVs, 531 different ports could be identified, with Antwerp and Rotterdam being the primary next port of call (39% in total) (Figure S3, middle). When looking at the flag states, there is a clear dominance of a few flag

states, with 5 flag states representing 50% of the observed OGVs, being Liberia, Panama, Malta, Marshall Islands and Hong Kong (Figure S3, lower). When looking at the type of monitored OGVs, mainly cargo OGVs (container and bulk carriers) have been observed (66%). 29% of the observed OGVs concerned tankers, 5% concerned other OGVs, passenger OGVs and Roll On Roll Off OGVs (RORO) (Figure S4).

Although anchored OGVs were observed occasionally, the monitoring was focused on OGVs that were en-route. The average ground speed of the observed OGVs was 12.6 kts (Figure S5, upper). The average observed OGV size was 209x32m (LxW) (Figure S5, middle), the smallest measured vessel was 51 m, the largest 400 m (Figure S5, lower).

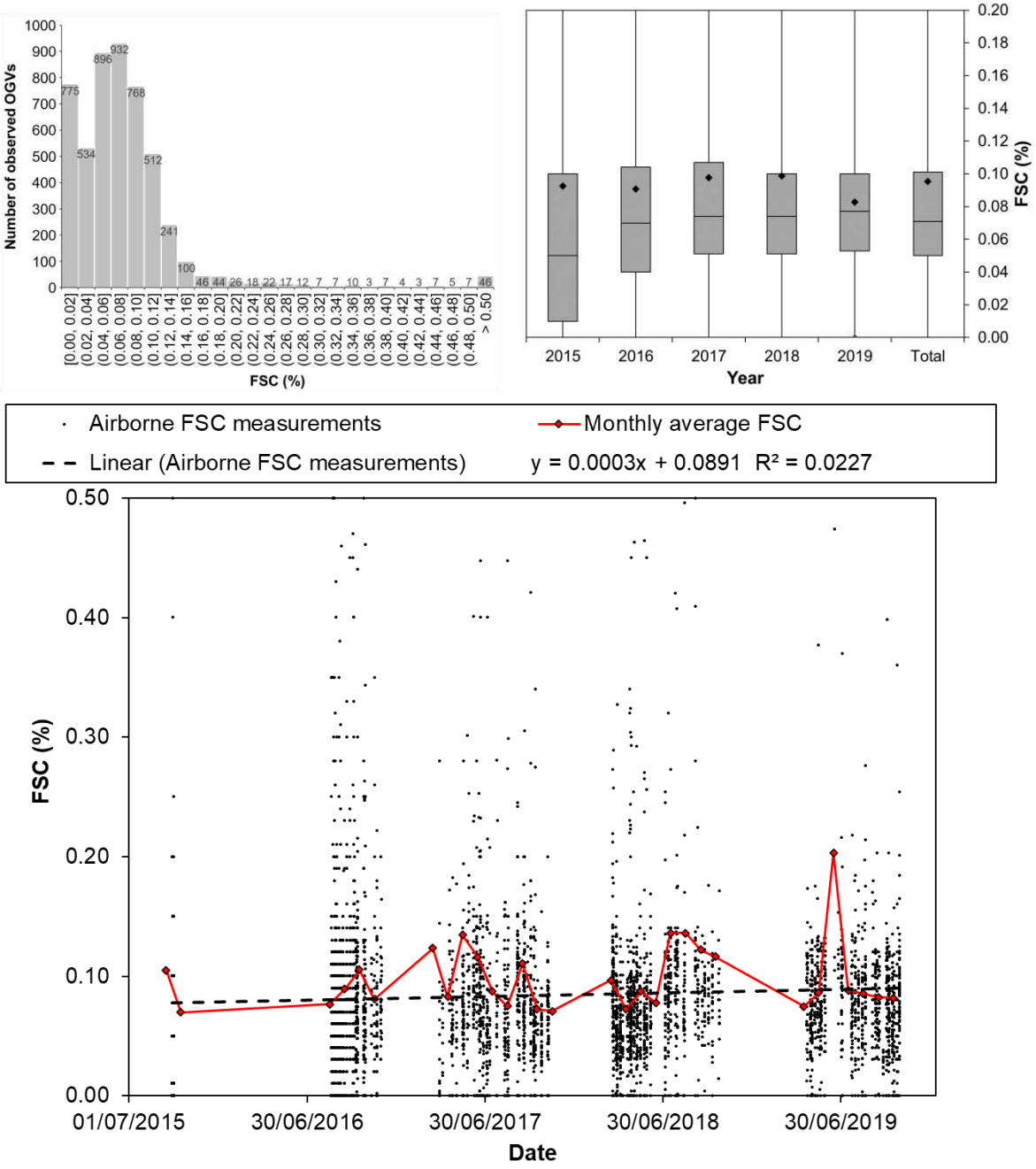


Figure 5. Upper left: histogram of FSC measurements. Upper right: Box plot with 25, 75% percentiles medians and annual average (♦) of the sampled OGVs from 2015 until 2019. Lower: Evolution in the monthly average FSC with the presentation of variation of all the observed FSC measurements.

4.2. Emission measurement results

About 3310 of the 4592 measured OGVs had an FSC value below or equal to 0.10% FSC (Figure 5, upper left). The average FSC was 0.10%. The annual average FSC did not change much during the total time frame of the measurements (Figure 5, upper right). When looking at the monthly average FSC, peaks were visual due to some high individual FSC measurements (Figure 5, lower). The linear regression of the monthly FSC showed no trend in the observed FSC (slope of 0.0003). Taking 2015 out of the equation, the median was very consistent over the time period (between 0.070% and 0.077%FSC), also the 25% and 75% percentile were stable with respectively 0.05% and 0.10% FSC when 2015 was excluded.

The mean FSC values were only significantly lower between 2016 and 2017 ($P = 0.001625$). For all other years no significant difference was observed in the average FSC value ($P > 0.05$). Average FSC was furthermore compared between vessel types. This showed a significant difference between container OGVs and the main other OGV types (oil and chemical tankers, general cargo, bulk carriers, Ro-Ros) ($P < 0.05$) (Figure S4). Average FSC was also compared between the ten most observed flag states, destination ports and destination countries, but no significant differences were observed. Also no difference was observed in average FSC between OGVs sailing inbound or outbound the SECA ($P > 0.05$).

4.3. Measurement quality

With remote OGV emission monitoring from fixed stations a quality score is often used to express the quality of the measurement [47]. The use of a mathematical quality indicator is less important with airborne measurements as the aircraft has, unlike fixed stations, the possibility of performing a second measurement. Therefore, it was chosen not to use a mathematic calculation of the measurement quality, but to define minimum quality standards for the emission measurements. This furthermore simplified the reporting of the measurement results to Port State Control (PSC). To assess a good quality measurement, the following requirements had to be met: (i) plume could be successfully linked to an OGV; (ii) response times of the SO_2 and CO_2 gas sensors were comparable; (iii) plume sampling time was sufficient; (iv) a good Signal to Noise Ratio (SNR); and (v) no interference from land pollution or other sources.

4.3.1. Linking plumes to OGV

With the software modelling of the smoke plumes, based on the actual wind conditions coming from the aircraft avionics, the ship speed and direction coming from the AIS system, the successful link with a vessel could be made in almost 100% of the cases. Only in the cases when OGVs were not emitting an AIS signal (e.g., military OGVs) or when OGVs were sailing very close to each other with the same course and speed, it could be challenging to link a vessel to a plume. In some cases when vessels were crossing each other, plumes could be mixed, and the decision was made not to sample these OGVs.

4.3.2. Response time

The pressure and flow regulators ensured a stable flow and pressure of 6 l/min with a pressure of 650 mm HG in the closed circuit of the sniffer sensor. The response time of both the CO_2 and SO_2 sensors were determined by using a SO_2 calibration gas with a concentration of 330 ppb SO_2 and 0 ppm CO_2, which corresponds to a concentration-difference (ΔC) comparable to high measurement peaks. The response time was found by determining the time difference (ΔT) between 10% of the beginning (C_b) and end concentration (C_e).

$$\Delta T = T_{90} - T_{10} \quad (3)$$

Where

$$\Delta C = C_2 - C_1 \quad (4)$$

$$C_1 = C_b + 0.1 \times \Delta C \quad (5)$$

$$C_2 = C_e - 0.1 \times \Delta C \quad (6)$$

For the determination of the T_{10} and T_{90} a linear interpolation was used based on the concentrations before and after the C_1 and C_2 concentrations.

$$C_i = C_{i-1} + \frac{C_{i+1} - C_{i-1}}{2} \quad (7)$$

$$T_i = T_{i-1} + (T_{i+1} - T_{i-1}) \times \frac{C_{i+1} - C_i}{C_{i+1} - C_{i-1}} \quad (8)$$

The curve between the start and end concentration was however not linear but follows a sigmoid curve. For CO_2 the time resolution was 0.2 Hz, whereas for the SO_2 sensor the time resolution was only 1 Hz. This means that for the CO_2 signal the curve was approximately a linear shape between 2 points. For the SO_2 signal, the time between 2 measurements was *ca.* 1 second and the error from linear interpolation could be significant. Therefore, a non-linear interpolation was used for the SO_2 sensor by using an exponential interpolation. Depending on the ΔC and the sensor, the difference between the linear and non-linear response time was different. For the CO_2 sensor the difference was negligible (Figure S6, upper). The T90 of the CO_2 sensor, based on linear interpolation, was 3.5 s. The T90 time of the SO_2 sensor was very comparable. Based on a non-linear interpolation the T90 time of the SO_2 sensor was 3.7 s.

The data was also plotted on a Richard generalized S-curve (Equation 9). The least square method was used to find the parameters m, B and v. This gave a theoretical T90 time of 2.5 s for CO_2 and 2.86 s for SO_2.

$$y(x) = A + \frac{(K-A)}{C + Q.e^{(-B.(t-m)^{\frac{1}{v}})}} \quad (9)$$

With A the lower asymptote
K the upper asymptote
C a constant = 1
Q depends on the value $y_{(0)}$
m depends on the time with maximum growth
B the growth rate
v a factor that affects near which asymptote maximum growth occurs

When the data was plotted on an S-curve (Figure S6, middle), the difference between the T90 of the SO_2 and CO_2 was minimal. This also meant that although the CO_2 and SO_2 sensor had a very comparable T90 time, the SO_2 sensor could in practice be 5-10% slower than the CO_2 sensor, which could result in an underestimation of the SO_2 concentration and therefore the FSC.

As concentrations in flight were seldom reaching these high concentrations the response time was also calculated for small ΔC differences. For CO_2 peaks, the T90 was determined for a ΔC of 111 ppm, this corresponds to the height of the majority of the peaks observed during flight. The response time of the CO_2 sensor using linear interpolation was 2.87 s, the difference with the T90 from non-linear interpolation (2.86 s) was negligible. For SO_2 a ΔC of 12.5 ppb was used.

The linear interpolation showed inaccuracy due to lower temporal measurement resolution. Therefore, the data was fitted on an S-curve (Figure S6, lower). The resulting T90 response time was 2.86 s, which was the same as the non-linear T90 of the CO_2 Sensor. This also corresponded perfectly with the S-curve based on large ΔC. Therefore, it can be concluded that both the SO_2 and CO_2 sensors have a comparable response time and react with a similar response time for both small and large peaks.

4.3.3. Plume sampling time

The plume sampling time is the time the aircraft spends in the OGV exhaust plume. Due to the airspeed and the approach angle this time is very short. For a high quality measurement it is critical that the exhaust plume is sampled for a sufficient time in relation to the sensor response time. The plume sampling time was calculated based on the start and end time of the plume that were set by the operator. The plume sampling was analyzed for 450 measurements of the 2019 data (Figure S7, upper). The average plume sampling time was 8 s, the median 7 s. The minimum time observed was 4 s and the maximum time 18 s. The very short plume sampling times of 4 and 5 s corresponded to peaks with relatively low peak concentrations (the order of magnitude $<$ 20 ppb for SO_2 and $<$ 100 ppm CO_2).

For an optimal quality measurement the plume sample time should be minimum twice the response time + 20%. This means the plume sample time should optimally be 6.5 s for normal peaks and around 10 s for very high peaks. Plume sample times longer than 10 s were observed in *ca.* 17% of the cases, plume sample times longer or equal than 7 s were observed in more than 72% of the cases. This means that for the large majority of the measurements the plume sampling time was sufficient. When looking at the relation between average FSC and plume sampling time, no significant difference was observed ($P = 0.497$) (Figure S7, lower).

As both sensors had very comparable response times, a shorter sampling time would not necessarily imply that the result had a low quality, as both sensors measured a comparable amount of the maximum concentration. To evaluate the impact of the short sample time on the quality, the peak SO_2 concentration was plotted against the sample time. This showed that short sampling time corresponded with low peak concentration, but it also showed that there was no relation between the peak concentration and the sampling time.

The graphs in Figure S.8. illustrate CO_2 and SO_2 concentrations when passing through a smoke plume for large, medium and small sized peaks. Asymmetric peaks mean that the sampling time was not sufficient to reach the final concentration, as the aircraft left the plume before levelling off. Furthermore, the graphs indicate that the height of the CO_2 peak had no impact on the response time. For plumes with low concentration, the maximum concentration was reached in 1.2 s (5-6 sensor measurements at 5 Hz), peaks with higher concentrations reached the maximum in 1.4 s. For SO_2 a comparable response time was observed: plumes with medium or high concentrations reached the maximum value in 1-2 s, peaks with low concentrations reached the maximum value in 1 s. This means that the actual time in the plume was *ca.* 1.3 s. With the obtained S-curve from the T90, the ratio of the measured amount compared to the terminal concentration could be calculated for a plume time of 1-1.3 s. For both the large SO_2 and CO_2 peaks this was 41%. For the smaller plumes this was 35% for SO_2 and 42% for CO_2. This means that both sensors measured a comparable amount of the actual concentration in the plume.

The time to return to background concentration after leaving the plume was 4.2 s for CO_2 for medium and large peaks, for smaller peaks this was 3.1 s. For SO_2 the time to reach background concentrations for medium to large peaks was 3-5 measurements (4 s) and for smaller peaks 2-3 measurements (2.5 s). The descend time was therefore very comparable to the measured response times.

Although both sensors had very comparable reaction times, in flight the assessment of the plume start and end was based on the CO_2 graph. Since the CO_2 sensor had a slightly higher response time and a higher time resolution, it was expected that a slightly higher amount of CO_2 was measured compared to SO_2. Furthermore the SO_2 sensor reached the background concentration slightly faster. As the assignment of the plume was based on the start and end times of the CO_2 sensor, some small amount of the SO_2 signal was cut. This resulted in a minor systematic underestimation of the FSC (negative bias). Overall, it can be concluded that although the sampling time was insufficient to reach terminal concentration due to comparable reaction times of both sensors, the resulted FSC had a high quality, although with a systematic underestimation.

4.3.4. Signal to noise ratio

OGV exhaust plumes dilute as soon as they leave the exhaust funnel. One of the main advantages of working with a mobile platform was the ability to sample the OGV exhaust plume close to the funnel, where the emission concentrations are still high. This provided generally large emission peaks. Often the peak concentration was rather low, resulting in a lower measurement quality. Instead of quantifying the quality based on the SNR, it was chosen to determine the minimum peak concentration; this corresponded to the amplitude of the concentration when passing through the plume (A_{bkg}), for which a reliable measurement could be made. The amplitude of the noise (A_{bkg}) of the CO_2 sensor depended on the sensor measurement resolution and the background conditions, and could be calculated by looking at the standard deviation of the background concentration over 60 measurements.

$$SNR = \frac{A_{plm}}{A_{bkg}} \tag{10}$$

Over sea the background conditions were more stable resulting in lower CO_2 noise (standard deviation SD = 0.25 ppm) as over land (SD = 1.6 ppm). The noise of the SO_2 sensor over sea was calculated accordingly (SD = 0.45 ppb). Good quality measurements are considered to have a SNR higher than 15. This corresponded to a CO_2 amplitude of 3.75 ppm. Peaks with this amplitude were considered to have a high quality. In practice, the noise might not always be the same for various reasons. Therefore, a CO_2 peak concentration of 5 ppm was used as a minimum threshold for high quality measurements. The average amplitude of the CO_2 measurements was 37.3 ppm, which means that the average SNR of the CO_2 measurements is 149.

The same method cannot be applied for SO_2, as the sulfur concentrations of MGO fuels can be very low ($\leq 0.01\%$), resulting in very low SO_2 signals. A precise FSC measurement is therefore not possible, but this is not an operational problem as it is only required if the FSC value is lower than 0.1% FSC. The minimum initial amplitude for an SO_2 peak for a vessel to be considered to be possibly non-compliant was set at 3 ppb. Although for this amplitude the SNR was only 6.7, a non-compliant measurement would always require a second measurement to ensure sufficient reliability.

In some occasions it was observed that the background conditions were unstable, resulting in more noise, although this only occurred occasionally. When these conditions were observed and the quality of the measurements could not be ensured, the missions were interrupted. Main reasons for these unstable background were, e.g., land based pollution (close to shore) and smog due to inversion layers.

Finally, operators were trained to distinguish good quality measurement from low quality measurements. The described thresholds provide some guidance but ultimately the operators could rely on their experience to assess if a measurement was acceptable or not.

4.4. Uncertainty and compliance thresholds

Initially limited information was available on the measurement uncertainty, which was estimated at 50% FSC [48]. The uncertainty of the Belgian FSC measurements (U) can be defined as a combination of the measurement bias (b) and the standard deviation (u_{tot}) derived from data from

$$U = |b| + \sigma . u_{tot} \tag{11}$$

To calculate the measurement bias, the median of the airborne emission measurements was compared to the median of a set of thirty random fuel sample analyses yearly taken by Belgian maritime inspection authorities in a certified laboratory (uncertainty <0.01%). This gave an approximate bias of 0.02% FSC. The bias was also calculated on the total datasets from all airborne measurements and all fuel samples taken between 2015 and 2019. Although this total dataset was not random and there could be some dependency expected, the difference in the median between the airborne measurements and the fuel samples was very comparable (0.018 +/- 0.005% FSC).

Previous remote OGV emission measurement campaigns observed a larger negative measurement bias (0.05-0.07) [42–44,48,49]. The smaller bias in the Belgian measurement was a result from a cross sensitivity to NO, where the bias was partially compensated. This systematic error was coming from the cross sensitivity of the SO_2 sensor to NO. As the sniffer was not equipped with a NO_x sensor, this cross sensitivity could not be eliminated. Therefore the NO cross sensitivity was included in the measurement uncertainty. The NO cross sensitivity was previously estimated to be 1.5% [43], meaning that 1.5% of the NO in the OGV exhaust was counted as SO_2. On average the absolute NO cross sensitivity could therefore have created a systematic error of 0.05% FSC (NOx EF of 12.5 g NO_x/kWh), with a maximum error of 0.1% FSC for very high NOx emissions (25 g NO_x/kWh).

The standard deviation can be calculated based on the intra-assay coefficient of variability and the sum of all additional supplementary uncertainty factors ($u_{sup,i}$). See Table S.1. for an overview of these supplementary uncertainty factors.

$$u_{tot} = \sqrt{(CV_{RW})^2 + \sum\left(u_{sup,i}\right)^2} \tag{12}$$

$$CV_{RW} = \frac{1}{\sqrt{2}} \sqrt{\frac{\sum_{i=1}^{n} \left(\frac{x_{i1} - x_{i2}}{0.5(x_{i1} + x_{i2})}\right)^2}{n}} \times 100(\%) \tag{13}$$

The CV_{RW} was calculated for 3 different arbitrary subsets of FSC values. The first subsets concerns low FSC values (< 0.2% FSC), the second subset consisting of medium FSC levels (0.2-0.4% FSC) and the last subset concerns high FSC values (>0.4% FSC). The CV_{RW} values per subset are displayed in Table 1. The higher CV_{RW} value for the > 0.4% FSC subset is caused by the lower number of measurements (n) in this subset. The supplementary uncertainty factors include all additional uncertainty factors. Some were calculated based on the observed values (e.g., drift values), others were based on description from literature or from the sensor manuals. In those cases, the used CI is 95%.

Table 1. Intra-Assay Coefficients of Variability, freedom of degrees and total uncertainty.

FSC range	<0.2%	0.2-0.4	>0.4
CV_{RW}	18.3%	11.6%	13.7%
n	109	49	29
u_{tot}	19%	13%	15%
$\|b\|$	4%	1.33%	0.66%
U (σ=1.96)	42%	27%	30%

With the bias and total uncertainty values, the combined uncertainty could be calculated for the three FSC levels, this showed to be significantly lower than the initial uncertainty from literature.

An additional reason for uncertainty is the sensitivity of the SO_2 sensor to VOCs from marine lubricants in OGV emissions [44]. In standard SO_2 analyzers VOCs are filtered out with a hydrocarbon kicker. This kicker restricts the airflow to 0.8 l/min, much lower than the required 6 l/min, and was hence not used in the airborne sniffer system. As a result, in some cases (less than 1 on 20) the SO_2 concentration did not drop back to the background levels together with the CO_2 concentration. This was probably due to an adhesive effect of the VOCs in the measurement chamber of the SO_2 sensor. In those cases the SO_2 level was cut off together with the CO_2 to avoid an overestimation of the FSC.

4.5. Compliance thresholds

The EU Sulfur Directive requires member states to conduct a fixed number of inspections and fuel samples per year. Maritime inspection authorities are in need of a targetting mechanism as they often have little indicators for selecting OGVs. For targetting, the absolute FSC values and uncertainties are less important, moreover even low FSC values with low uncertainty could be interesting in lack of other more severe violation targets. Therefore a qualitative flagging system was composed in cooperation with the Belgian maritime inspection authorities, which not only reflects the measurement uncertainty, but also the level of non-compliance.

Based on the initial measurements from 2015, three alert levels (colors) were created. For each color flag an operational reporting threshold (T_{OPS}) was defined. The yellow flag represents the lowest alert level of 0.15% FSC. The orange flag indicates a medium alert level of 0.2% FSC and red flags indicates a high non-compliance alert, set at 0.4% FSC. With increasing measurements, the combined measurement uncertainty (U) for the sniffer sensor setup in Belgian Coast Guard aircraft could be calculated. This allowed to evaluate the reporting thresholds on annual basis. The actual threshold (T_a) was defined as the FSC for which the difference with the combined measurement uncertainty exceeds a pre-defined sulfur limit (S).

$$S\ (\%FSC) = T_a(1 - \sigma \times u_{tot} - |b|) \tag{14}$$

$$T_a = \frac{S + |b|}{1 - \sigma \times u_{to}} \tag{15}$$

To emphasize the accuracy of high FSC values without losing lower alerts, different CIs were used per alert level. For the yellow color flag a CI of 68% was used ($\sigma = 1$), for the orange color flag a CI of 95% ($\sigma = 1.96$) was used, for highest alert level, a CI of 99% was used ($\sigma = 2.576$). In addition, different Sulfur limits (S) were used to reflect on the level of inspection follow-up as well. For the yellow flag, a sulfur limit of 0.10% was used. This meant that for a yellow alert there was a 68% probability that the FSC value of the OGV was more than 0.10% FSC. For the orange flag, a sulfur limit of 0.11% FSC was used, as this is the limit that can be confirmed by laboratory fuel sampling analysis. This meant that an orange alert had an FSC that was more than 0.11% FSC with a CI of 95%. For the red flags, the sulfur limit was set at 0.15% FSC, as this is the reference for charging a financial penalty by the Belgian inspection authorities. Correspondingly, for red alerts the FSC was more than 0.15% FSC with a CI of 99%. The actual resulting measurement thresholds per color flag are displayed in Table 2. The actual thresholds are all lower than the initial values, for operational reasons. The operational thresholds (T_{OPS}) were not adjusted over the period, although based on these statistics it was possible to lower the highest threshold to 0.3% FSC.

Table 2. Alert flag thresholds.

Color flag	σ	U	CI	Sulfur limit	T	T_{ops}
Yellow	1	30%	68%	0.10%	0.145%	0.15%
Orange	1.96	35%	95%	0.11%	0.174%	0.20%
Red	2.576	43%	99%	0.15%	0.275%	0.40%

4.6. Compliance data

The measurements were evaluated according to the flag colors. In case a possible non-compliant OGV was observed, a second measurement was conducted. Only in very rare occasions a second measurement could not be made. If the second attempt did not confirm the initial value, the lower of the two values was used and was therefore not reported as non-compliant. In case the second measurement confirmed the first measurement, both values were reported. If the two measurements had two different flag colors, the lower of the two was used to avoid reporting false positive alerts.

During the time frame of the operations 302 possible non-compliant OGVs were observed. The overall compliance rate was 92% (Figure 6, left) and increased from 83% in 2015 to more than 95% in 2019 (Figure 6, right).

The lower compliance levels for 2015 may not be representative, as it was only the first year of the strengthened regulations. In addition, the data was collected during a short campaign in the Belgian area with a limited number of monitored OGVs. From 2016, the monitoring efforts were increased and spread over the whole year. The compliance levels in 2016-2017 were just below 90%. It can be noted that the number of yellow and orange flags was quite comparable and the relative importance of one of the two shifted from year to year. The number of red flags was generally lower than the number of other flags, although in 2018 the number of red flags made up to 1/3 of the number of observed possible non-compliant OGVs. Until 2019 the number of red flags remained relatively stable (from 3.4% in 2015 to 2.1% in 2018). In 2019 the number of red flags decreased to 0.4%, which represents 10% of the observed possible non-compliant OGVs. Not only did the number of non-compliance decrease over the 5-year period, also the severity of non-compliance decreased.

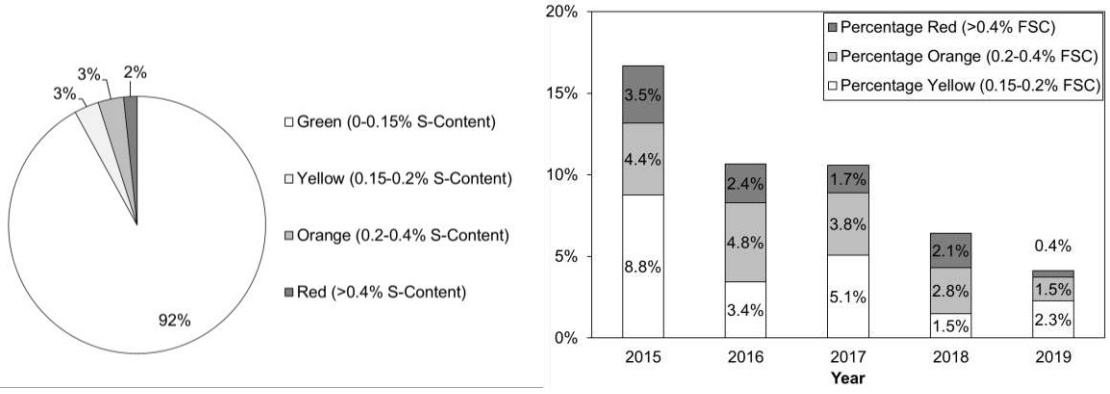


Figure 6 Left: Overall non-compliance levels between 2015-2019. Right: Compliance levels per year based on the flags.

4.7. Compliance rate comparison

When comparing compliance levels between different factors like destination, OGV type, flag state, etc., limited effects were observed. For the OGV type a significant lower compliance was observed for container OGVs compared to all other OGV types (oil and chemical tankers, Ro-Ros, general cargo and bulk carriers). Likewise, Ro-Ros had a significant lower compliance rate compared to the other OGV types (oil and chemical tanker, general cargo and bulk carriers) and finally, bulk carriers and oil tankers had a significant lower compliance rate compared to chemical tankers ($P < 0.05$) (Figure S9). The

compliance rate was also compared between the main flag states, destination ports and destination countries. Due to the large number of groups, the comparison of compliance rates was only applied on groups with $n > 100$. Significant lower compliance rates were observed for OGVs with flag states Liberia and the United Kingdom ($P < 0.05$), Malta is the only flag state that was observed with a significant higher compliance rate. When looking at the destination, it was observed that OGVs with a destination outside the SECA had a significant higher compliance rate than inbound OGVs ($P < 0.05$), which is counterintuitive as one could think as these OGVs are not close to their port of destination with therefore low risk for being sanctioned after inspection. This could be an effect of higher compliance rates in ports, OGVs that just left port are more expected to be still on compliant fuel. However, OGVs that are passing the SECA border with direction towards a SECA port may intentionally delay the initiation of the fuel changeover procedures, knowing that there is still sufficient time to complete the fuel changeover procedures before entering the port. When looking at individual ports and countries, no significant trends were observed.

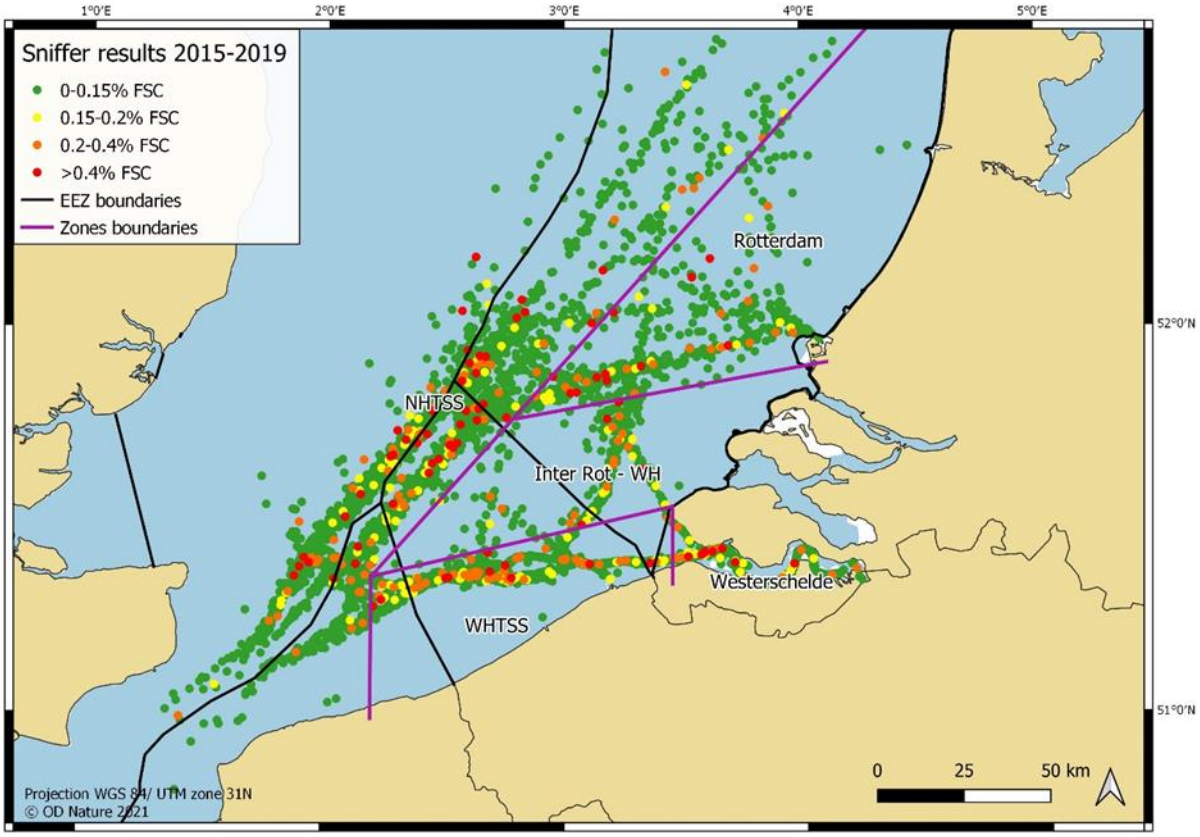


Figure 7. Geographical visualization of the monitored OGVs with the FSC color flags. The surveillance area was divided in 5 sub areas: NHTSS, WHTSS, Rotterdam, Inter Rotterdam-WHTSS and Westerschelde.

4.8. Geospatial analysis

One of the main advantages of airborne offshore monitoring using innovative sensor technology is that compliance can be monitored at sea instead of only in the ports (with fuel sample analysis) or close to shore (with fixed sniffer stations). Monitoring operations have been carried out in a large section of the southern North Sea area, from Dover Strait up to the Wadden Sea. The map in Figure 7 visualizes all monitored ships according to the flag color, the navigation patterns are clearly visible. When looking at the non-compliant OGVs on a geospatial basis, no clear patterns could be observed at first sight. Although more red flags were observed in the North-Hinder Traffic Separation Scheme (NHTSS) (Figure S10).

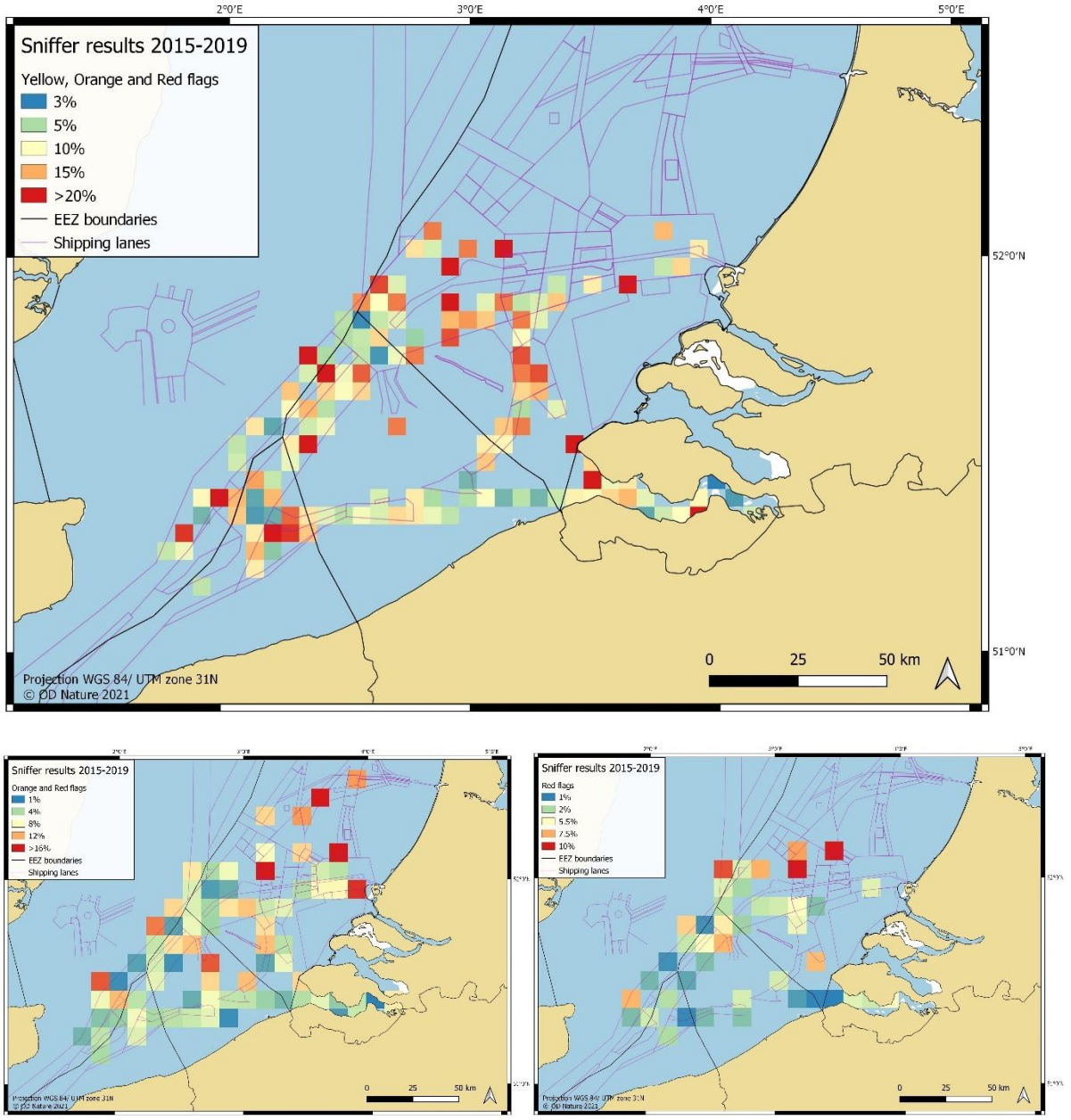


Figure 8. Upper: 5km grid map with the compliance rate per grid cell from 0.15%. Lower left :10 km grid maps with the compliance rate per grid cell from 0.2% FSC and 0.4% FSC (lower right).

To evaluate the compliance rate on spatial level, the surveillance area was divided in five subareas: Western Scheldt, Rotterdam, West-Hinder Traffic Separation Scheme (WHTSS), Inter Rotterdam-WHTSS (inter Rot-WH and NHTSS).

When comparing the average FSC between these areas, there were no significant differences. Also, the total compliance rate didn't greatly differ between the NHTSS and the other areas. However, when looking at the number of red flags only, this number was significantly higher in the NHTSS (2.1%) than in the WHTSS (0.08%) which is closer to shore ($P = 0.011$) (Table S2).

The data for the OGVs for the WS, WHTSS and Rot areas were analyzed based on their course to be able to compare inbound versus outbound traffic (Figure S.3). Although the average FSC was not significantly different for the WS ($P = 0.448$), a closer look showed a slightly higher non-compliance rate for the outbound OGVs. When focusing on the red flags, the non-compliance rate was almost

double, although this was not significant ($P = 0.36$). For the WHTSS and Rot areas, the average FSC is not significantly different, although the non-compliance rate is higher for the inbound traffic (confirming the analysis based on AIS destination), this effect is not significant ($P > 0.05$) (Table S3). The other areas are less usable as the AIS course appeared to be too unreliable to differentiate outbound from inbound traffic.

In addition, three grid maps were created with the compliance rate per grid cell, the compliance level from 0.15% (yellow, orange and red) was displayed on a 5 km grid map (Figure 8, upper). This showed a slightly higher non-compliance rate in the Western Scheldt and in the NHTSS. For the higher non-compliance levels a larger grid size was used due to the lower number of observations (Figure 8, middle and lower).

These maps show that the higher non-compliance was situated in the NHTSS and the Rotterdam area. Furthermore it was observed that the Northern lane of the NHTSS (outbound SECA direction) had a relative higher non-compliance rate.

Due to different compliance evaluation methods and other sensor techniques, it is difficult to compare compliance levels between other monitoring organizations in other regions in the SECA. In this regard, more harmonization is needed first to achieve an objective comparison of compliance levels. Nevertheless, there are signs that indicate that compliance levels do increase with distance to the SECA border [41,44,50,51].

4.9. Flight approach and health consideration

The apparent wind (resulting vector based on the wind and OGV speed and direction) played a vital role in the flight approach, as this determined the plume characteristics, such as the plume ascend, direction and diffusion. Based on the apparent wind, five flight approach scenarios were compiled (Table S4). The aircraft was able to successfully conduct measurements for all scenarios. Although for some scenarios the success rate was notably lower, for example with high diffusion or descending plumes with scenario one. Scenario four occurred when the wind direction and speed were in line with the vessel speed and direction. This was the only scenario where the aircraft conducted a measurement above the vessel. Due to very small changes in wind speed, the plume position could change instantly and these plumes were sometimes hard to find. On the other hand, the diffusion was very low, so these plumes also created the highest concentrations (e.g., up to 1500 ppm in CO_2 and 400 ppb in SO_2). Technically, these measurements might even be considered to exceed the calibrated measurement range of the gas analyzers, although this did not pose a higher non-compliant rate. These conditions only occurred in 10-15% of the time.

Concerning the wind speed limit, in the early phase of the campaign tests were done with different wind speeds. This showed that from a wind speed of 30 kts emissions tend to get more diluted, resulting in a lower chance of a successful measurement (decrease of 10-20%) and more missed approaches (+ 50%). In addition it was observed that during rainy conditions the SO_2 levels are much lower, due to increased transformation of SO_2 to sulfuric acid. Therefore, no operations are done in rainy conditions.

Furthermore, the risks of flying at low altitude increased with these conditions. When the aircraft passed through the smoke plume of a vessel it also passed through a turbulent air layer created by the impact of the vessel on the wind. With high wind speeds (from 35 kts) passing through these turbulent layers at low altitude imposed considerable risk for the aircraft and crew. The size and type of the vessel also had an impact on the created downwind turbulence. Large vessels like container and RORO vessels create more turbulence than small vessels or vessels with a low profile, such as tankers. SOPs for low altitude operations were created to limit the risks.

Another aspect was the potential health impact for the aircrew. Initially some reservation was expressed by crewmembers for flying through vessel exhausts. Therefore, BC measurements were taken with an aethalometer (model AE151) inside the cabin during OGV emission measurements. These measurements showed that, although BC peaks could clearly be seen when passing through OGV exhaust plumes, the BC levels in the cabin were much lower than the peaks observed during the time on ground and are completely insignificant when compared with BC peaks observed in traffic or in the urban environment of Brussels. This due to the very short time the aircraft spends in the smoke plume (1-2 s) and the limited air intake by the aircraft that occurs in that period.

5. Conclusions

Up to this day, airborne measurements are not used as legal evidence, but merely for targeting potential violators for port inspections. This paper demonstrates that the airborne sniffer monitoring methodology for sulfur emissions measurements in an operational setup is scientifically proven and reliable. By applying a sufficient uncertainty margin, high quality measurements of gross polluters (red flags), may even at some point in the future be taken under consideration to be recognized as legal evidence for legal prosecution or administrative sanctioning.

The measurement quality is assured based on clearly defined minimum quality standards for the emission measurements, such as the successful linking of a plume to an OGV, the comparable response times and sufficient sampling times for the SO_2 and CO_2 gas sensors, a good signal to noise ratio and no interference from land based or other pollution with the smoke plume of OGVs.

The measurement uncertainty is carefully calculated for 3 FSC levels during this research. It was chosen not to rely on the measurement uncertainty alone for reporting possible non-compliance to the PSC authorities. Instead, a color flag system was composed in cooperation with the Belgian maritime inspection authorities that indicates the different degrees of probability of violations, taking into account the calculated FSC value for a particular vessel, the level of accuracy and uncertainty of the specific measurement and the applied FSC limit based on the PSC follow up.

During the timeframe of the operations, the overall compliance rate was 92%. Over the 5-year period, the number of observed possible non-compliant OGVs decreased significantly, as well as the gravity of the non-compliance. After thorough analysis of the extensive data set, no clear profile of violators or fixed patterns could be drawn up. However, it did show that more non-compliance occurred at sea than in ports and that more non-compliance was observed further offshore.

The Belgian CG aircraft monitored sulfur emissions from OGVs in Belgian and neighboring waters at an average success rate of more than 10 OGVs per flight hour, proving to be an efficient and usable asset in the MARPOL Annex VI enforcement chain.

With approximately 92% of the OGVs off our coast that were found to be complying with the strict sulfur emission limits, the air quality for coastal communities and communities close to ports was clearly improved. At the same time, this also means that 8% of the OGVs monitored at sea were prone to be in violation. Effective enforcement and targeting of these 8% potential violators for port inspections is therefore imperative to ensure maximum and durable compliance with the emission limits.

The airborne monitoring dataset is available on: https://doi.org/10.24417/bmdc.be:dataset:2687

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Resources, Supervision, Project administration, Funding acquisition; Benjamin Van Roozendael: Investigation, Visualization, Writing - Review & Editing; Kobe. Scheldeman: Investigation, Resources, Project administration, Funding acquisition, Writing - Review & Editing; Annelore Van Nieuwenhove: Investigation, Resources, Writing - Review & Editing; Frank Maes: Supervision, Writing - Review & Editing.

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7. Supplementary figures and tables

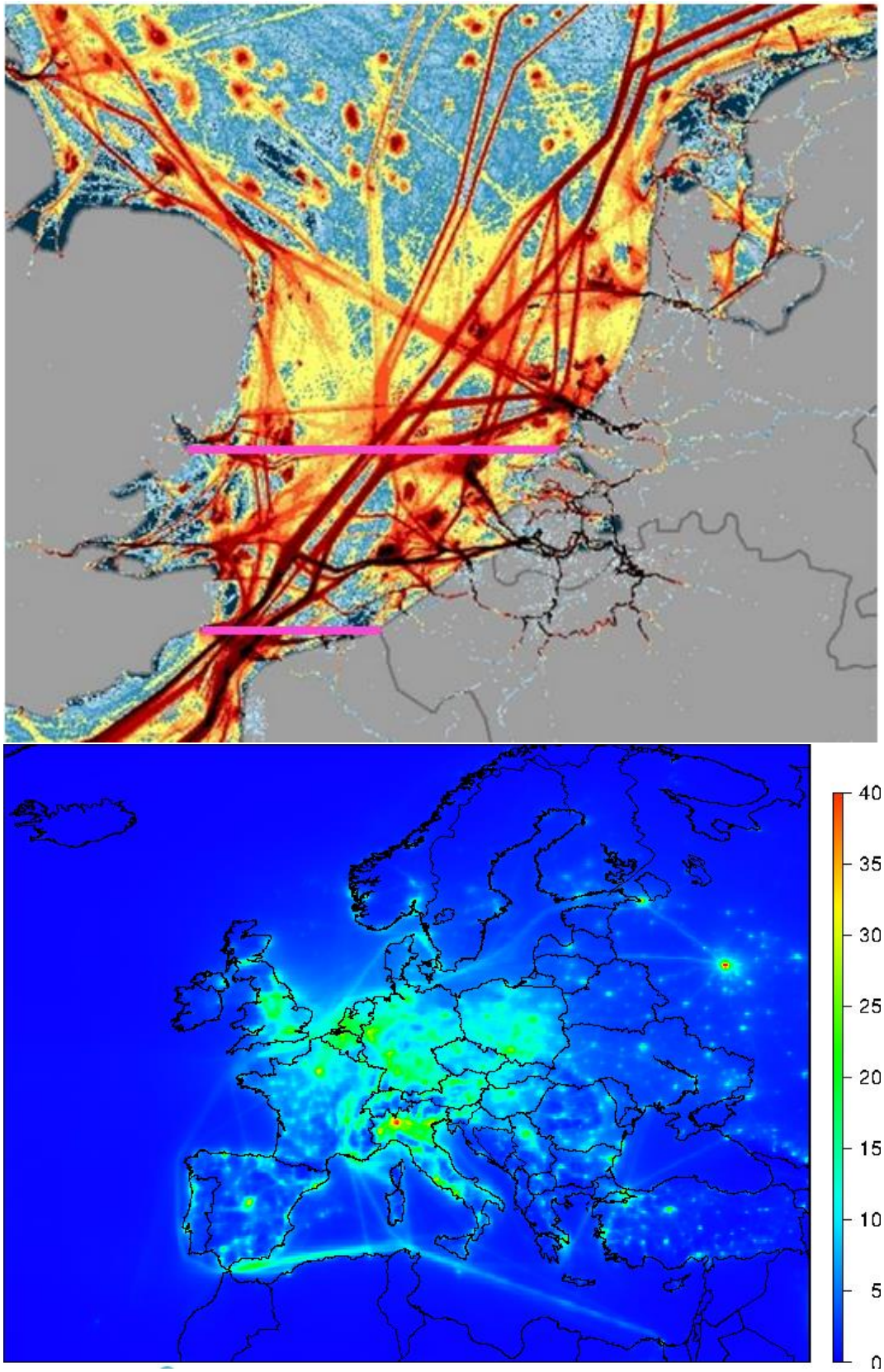


Figure S.1. Upper: Shipping density in the North Sea based on Satellite- AIS data (Bonn Agreement, 2014), the magenta lines indicate the Quadripartite zone. Lower: annual NO_2 reanalysis for 2015 (Copernicus, 2017; Tarrason, 2018).

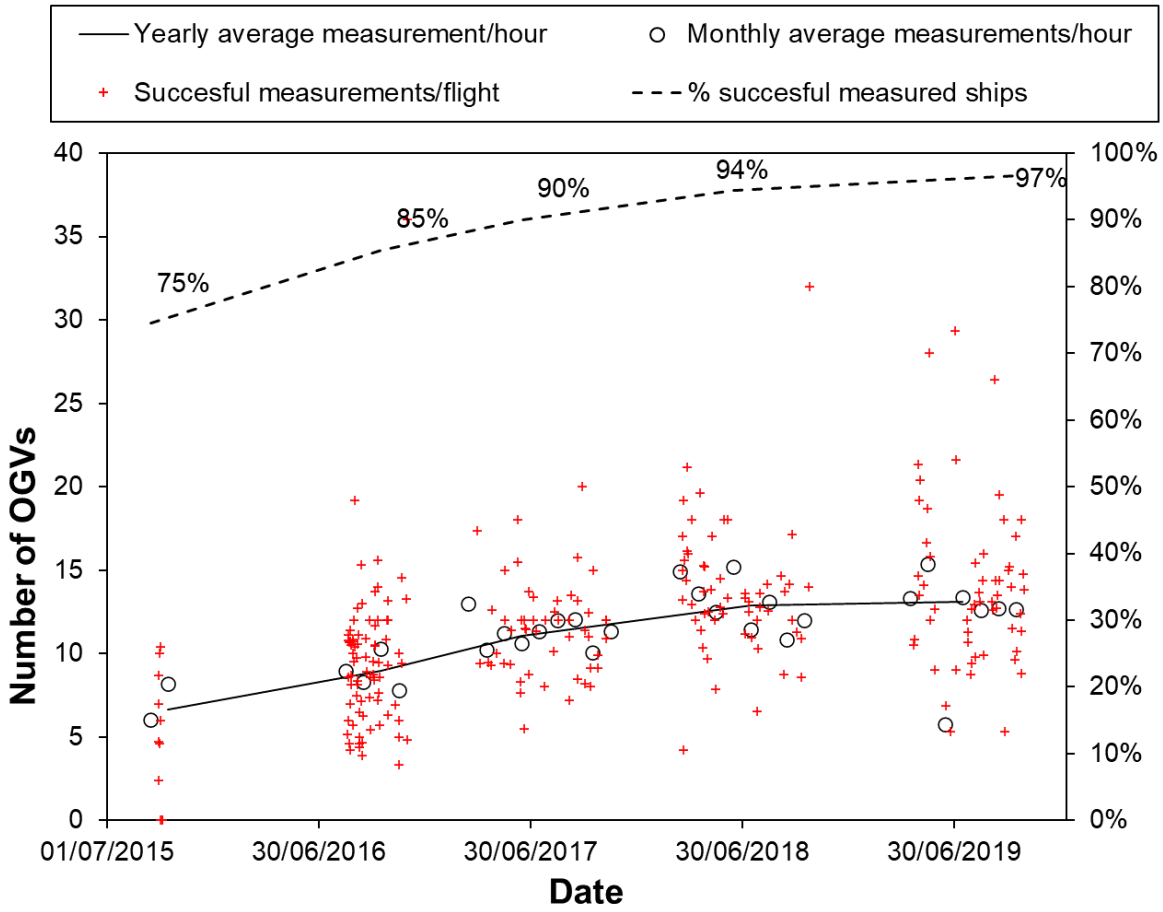


Figure S.2. Evolution of the number of successfully measured OGVs from 2015 until 2019, with the yearly average measurements per flight hour; the monthly average measurements per flight hour; the number.

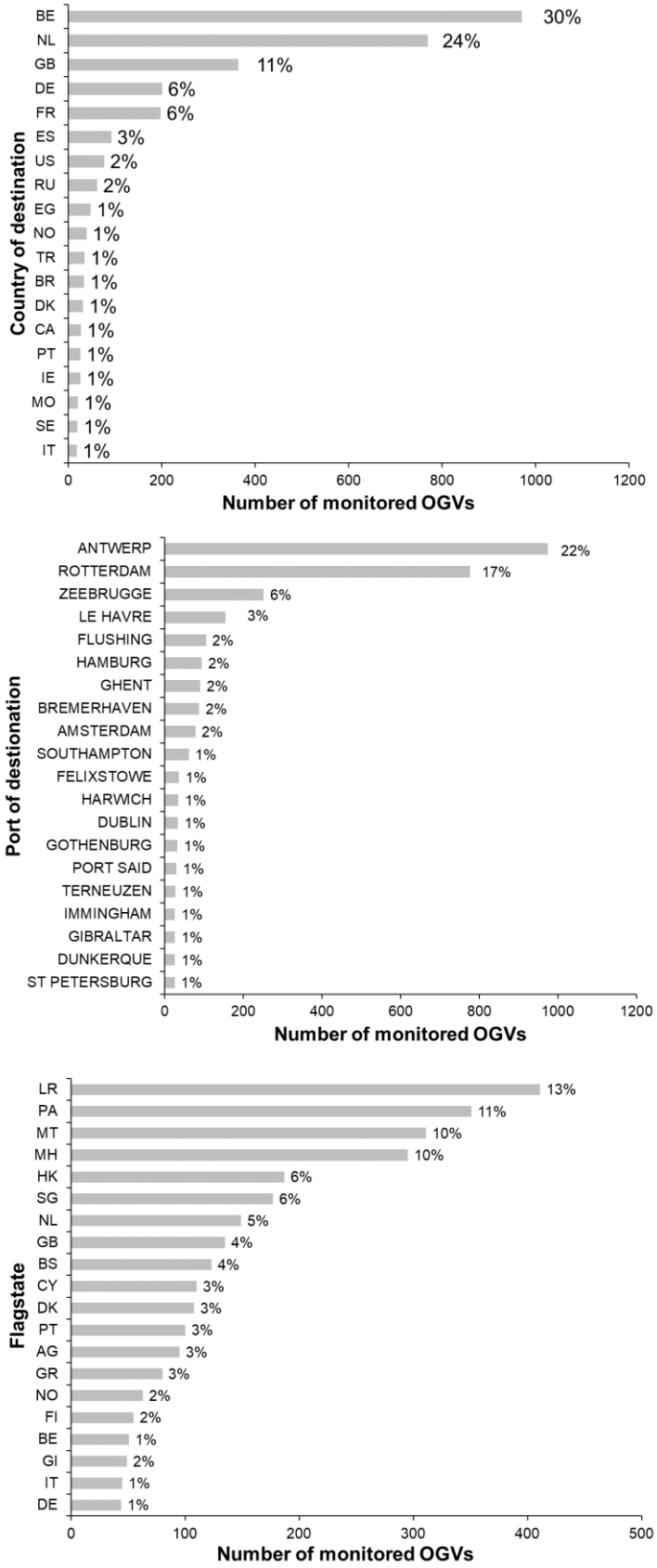


Figure S.3. Histograms of the 20 most observed destination countries (upper); destination ports (middle) and observed flag states (lower).

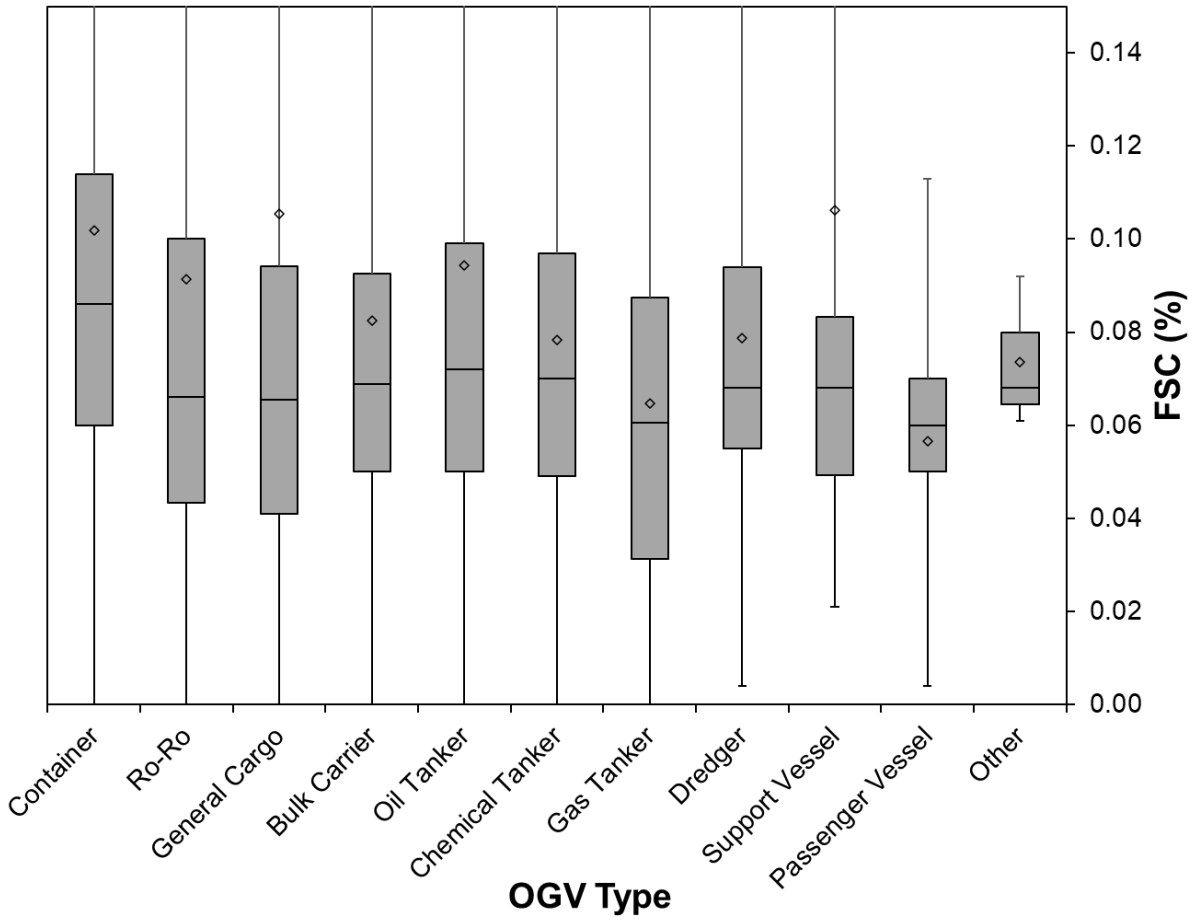


Figure S.4. Box plot with 25%, 75% percentiles medians and annual average (♦) per ship type

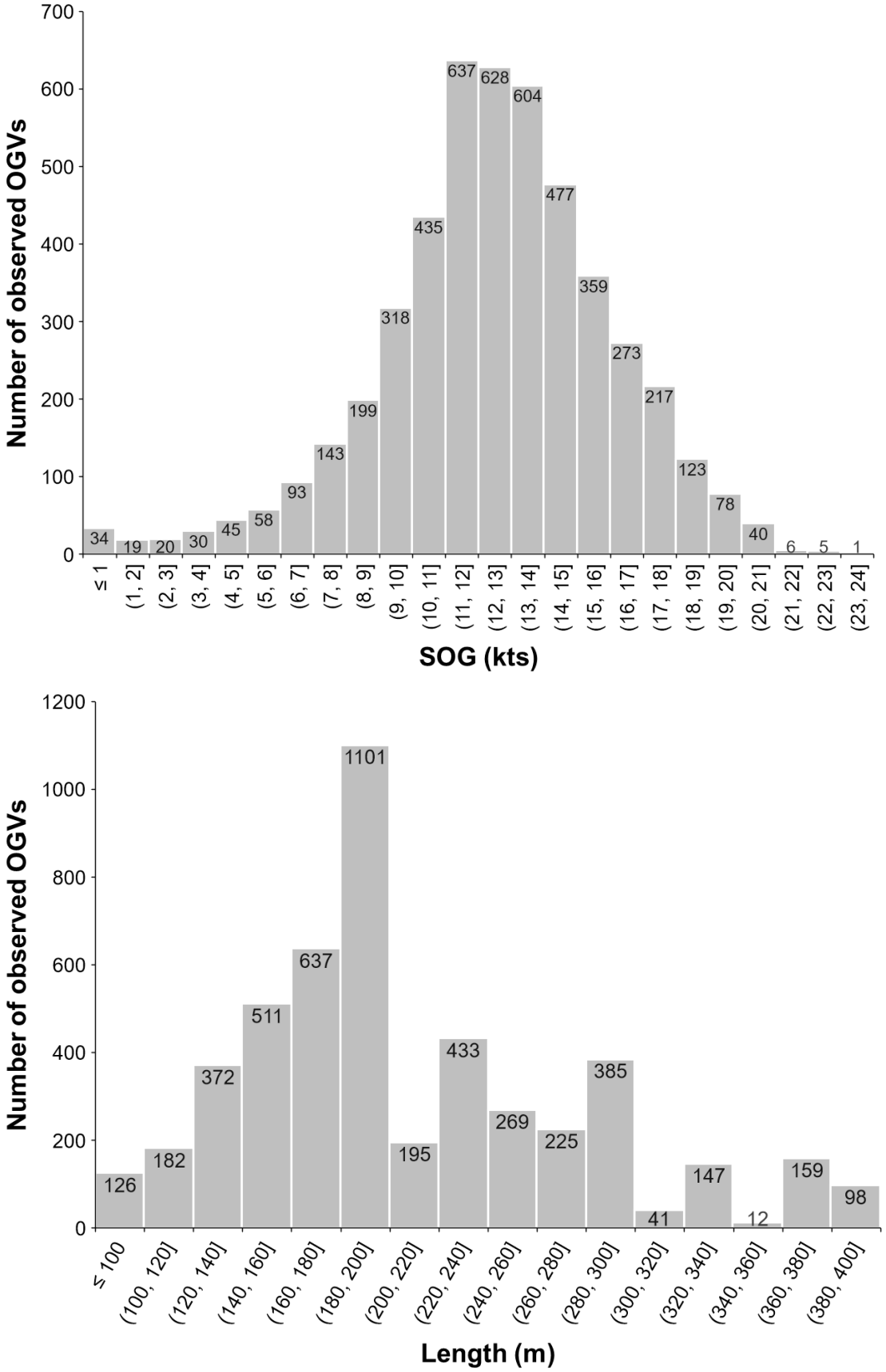


Figure S.5. Histograms of speed on ground (SOG) (upper) and the length (lower) of the observed OGVs.

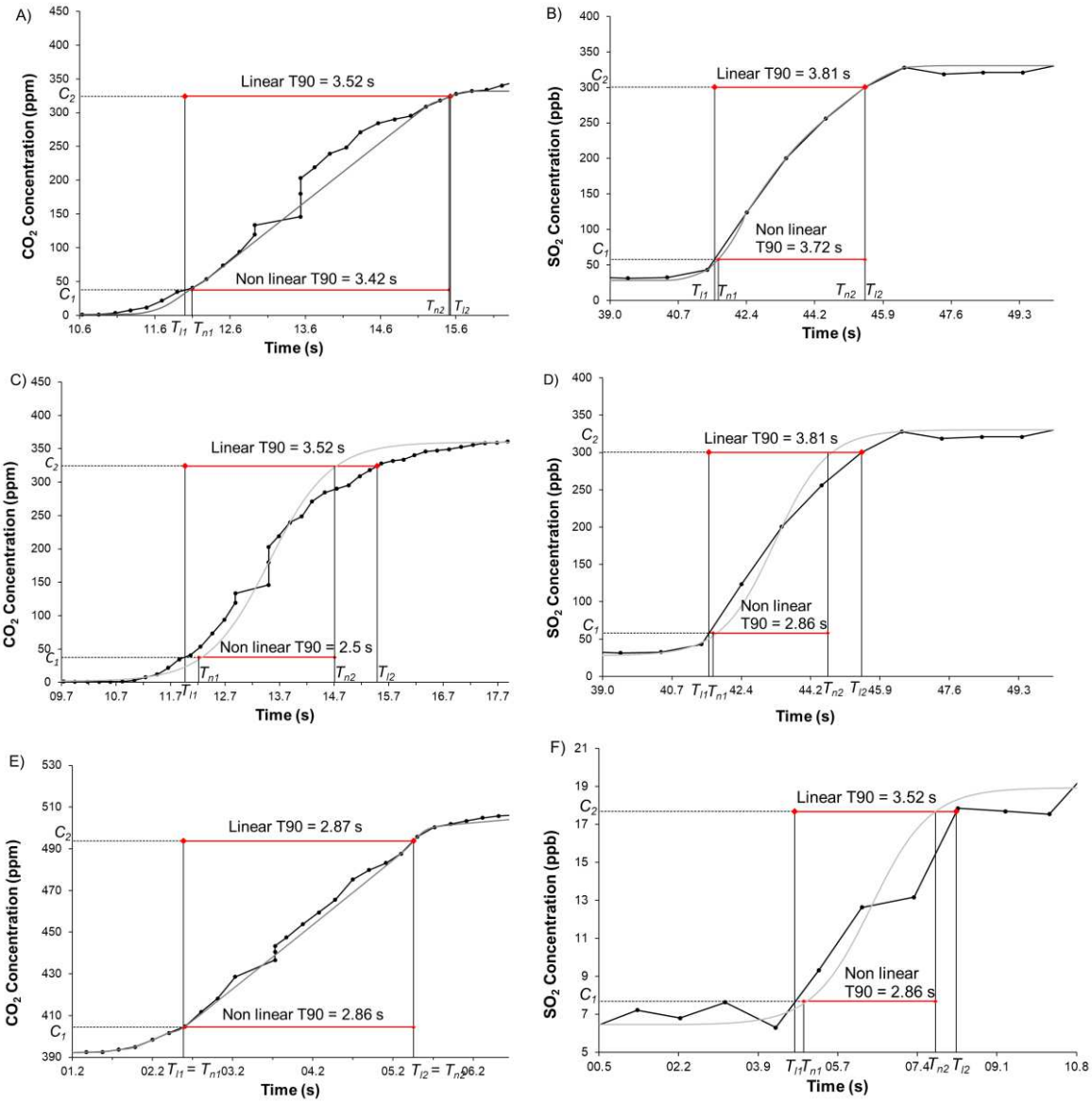


Figure S.6. Response times for large concentration differences based on linear and non-linear interpolation for the Licor 7200RS sensor (CO_2) (A) and for the Thermo 43i TLE sensor (SO_2) (B). Response times for large concentration differences based on linear and plotting on an S-curve for the Licor 7200RS sensor (CO_2) (C) and for the Thermo 43i TLE sensor (SO_2) (D). T90 times for small concentration differences, for the Licor 7200RS using a non-linear interpolation (E) and T90 time, for the Thermo 43i TLE by fitting the data on an S-Curve (F). C_1 and C_2 concentration are defined as the 10% and 90% concentration difference between initial and terminal concentration.

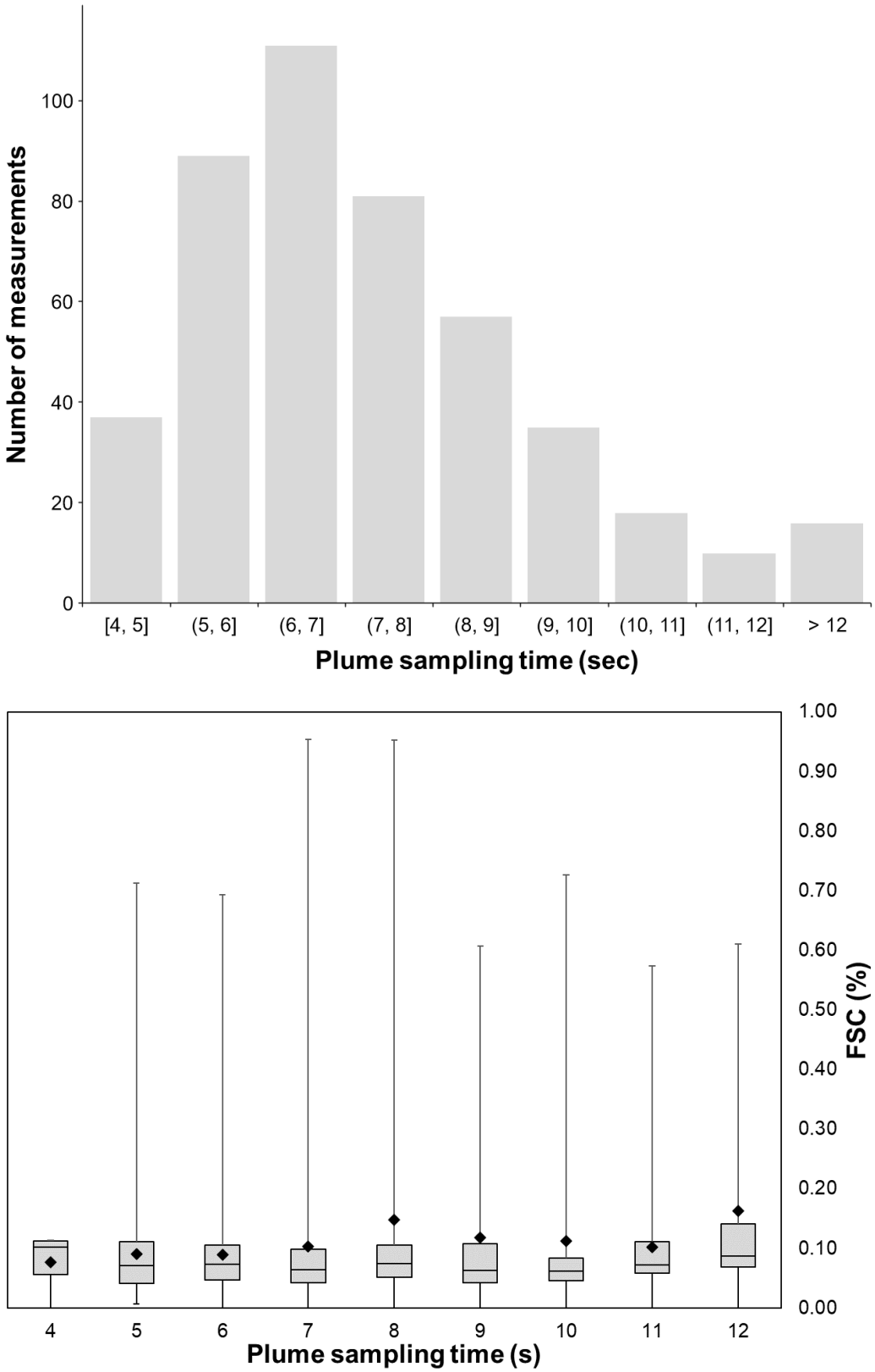


Figure S.7 . Upper: Distribution of sample times. Lower: Box plot with 25%, 75% percentiles medians and annual average (♦) of FSC corresponding to the sampling time.

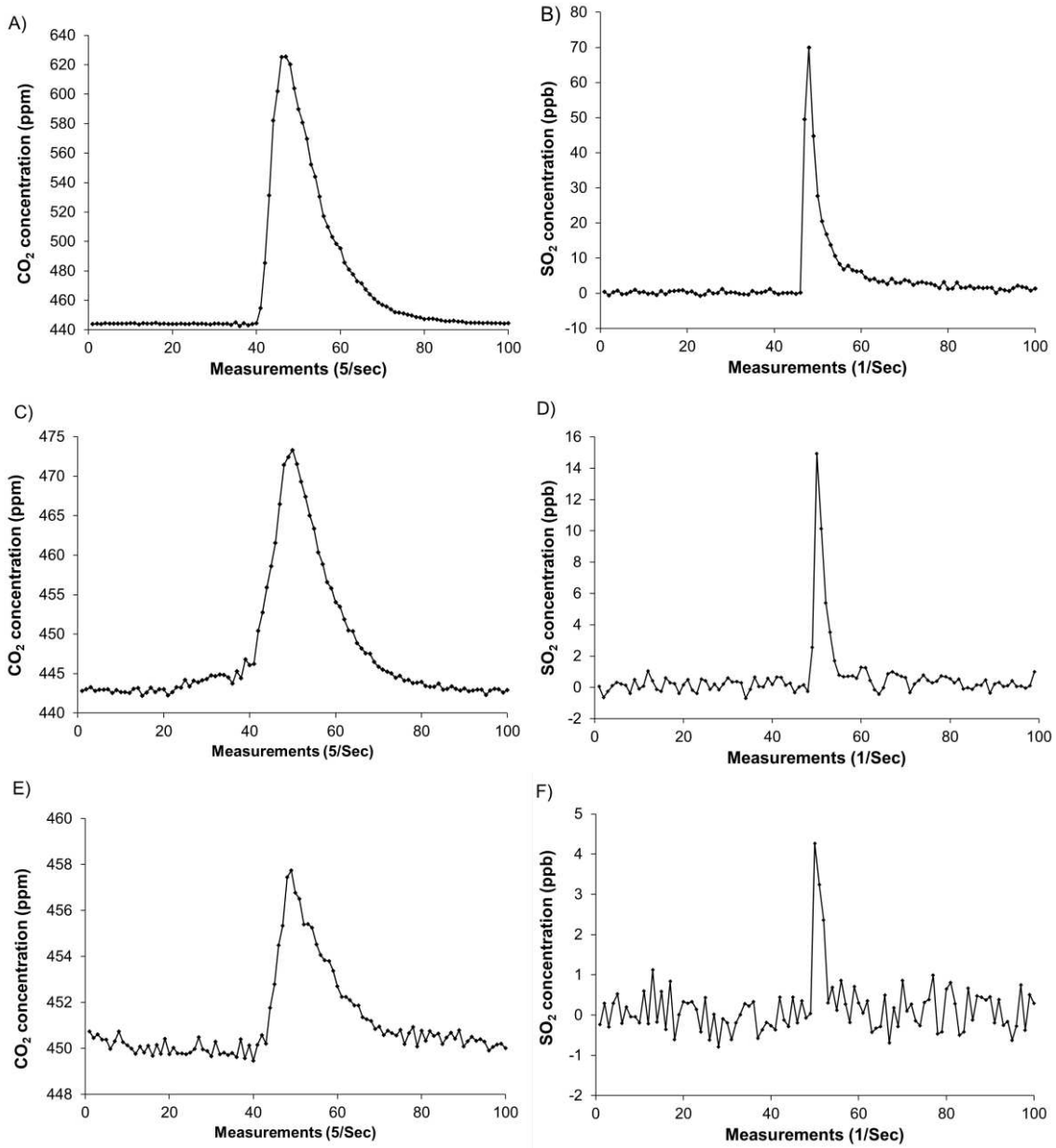


Figure S.8. Figures on eft Side (A, C and E) show CO_2 concentration profiles, figures on the right side (B,D and F) show SO_2 concentration profiles when passing through OGV exhausts plumes. Upper figures show large peaks (A and B) middle figures show medium peaks (C and D) and lower figures show small peaks (E and F).

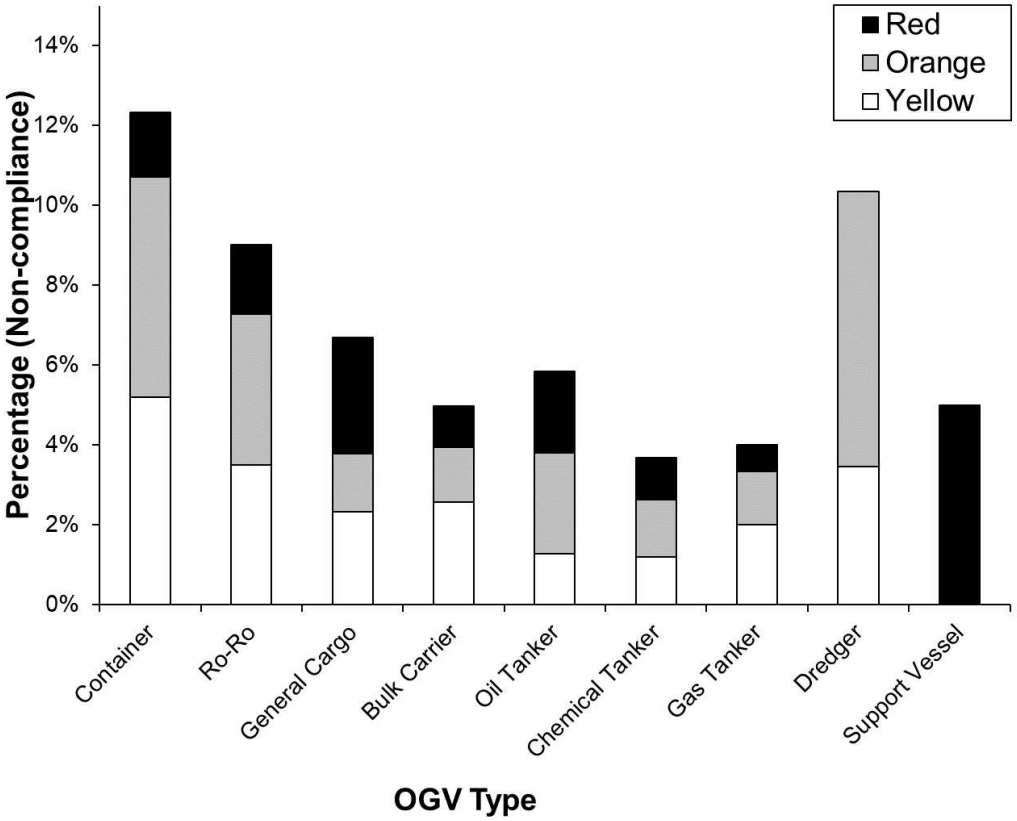


Figure S.9. Comparison of compliance levels between detailed OGV type

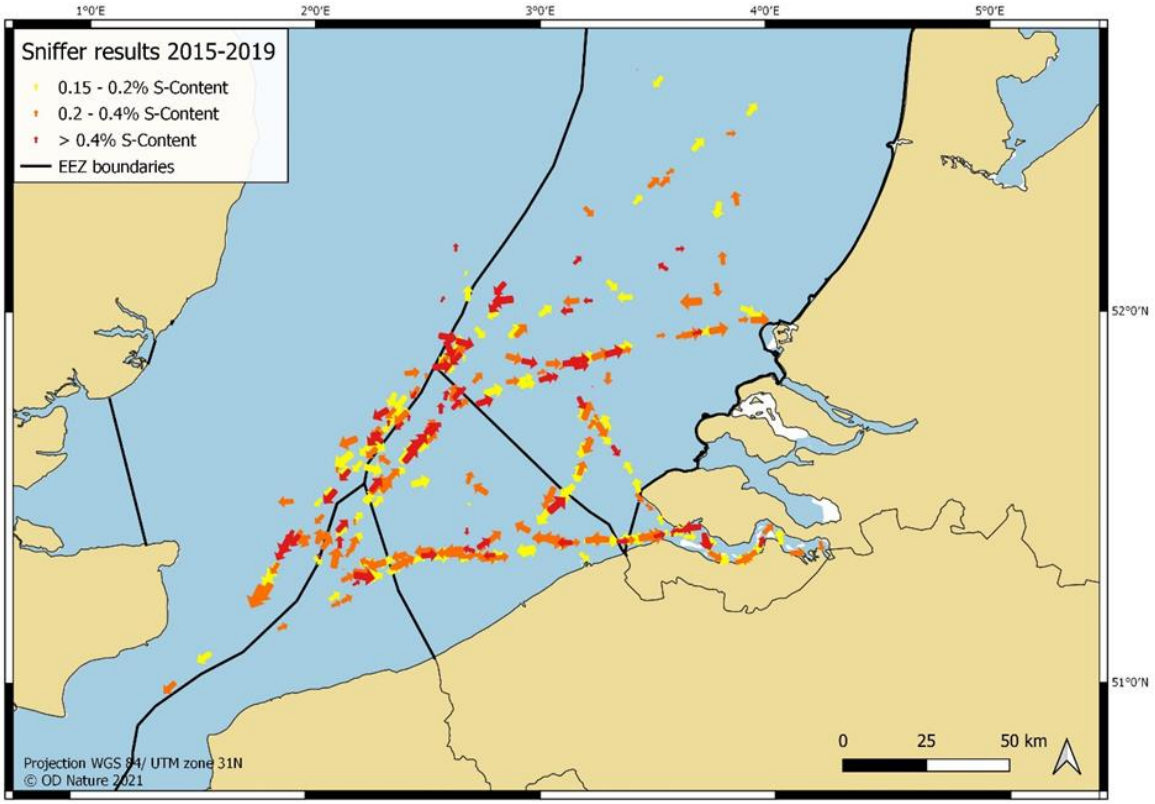


Figure S.10. Geographical visualization of the possible non-compliant OGVs with the indication of the heading, the size of the arrows indicate the speed of the OGVs.

Table S.1. Supplementary uncertainty factors and the combined supplementary standard uncertainty.

Supplementary uncertainties	Max
SO_2 span gas drift (3 months)	4.04%
SO_2 span gas concentration*	3.00%
CO_2 span gas drift (6 months)	1.44%
CO_2 span gas concentration*	2.00%
Measurement accuracy SO_2 sensor	2.00%
Measurement accuracy CO_2 sensor	1.00%
Error on Bias	0.89%
Uncertainty molar mass S	2.49E-06
Uncertainty molar mass O	1.88E-05
Uncertainty molar mass C	0.01%
Uncertainty C content in marine fuel	0.83%
Combined supplementary standard uncertainty	6.15%

** According to gas certificate*

Table S.2. Number of monitored ships categorized per flag for Westerscherscheldt (WS), WHTSS (WH), Rotterdam (Rot), inter-Rotterdam-WHTSS (Rot-WH) and NHTSS (NH) areas.

	WS	WH	Rot	Rot-WH	NH
Total OGVs	534	1,065	485	308	2,193
Green	91.4%	92.1%	91.8%	89.6%	92.5%
Yellow	3.9%	3.5%	2.9%	4.5%	2.5%
Orange	3.0%	3.6%	3.5%	4.2%	2.9%
Red	1.7%	0.8%	1.9%	1.6%	2.1%
FSC-average	0.10	0.09	0.10	0.09	0.09

Table S.3. Comparison of compliance levels for inbound versus outbound traffic for the Westerscheldt (WS), WHTSS and Rotterdam (Rot) area.

	WS				WHTSS				Rot			
	inbound		outbound		inbound		outbound		inbound		outbound	
	#	%	#	%	#	%	#	%	#	%	#	%
Green	259	93%	221	91%	582	92%	373	93%	259	89%	176	96%
Yellow	8	3%	11	5%	22	3%	8	2%	10	3%	3	2%
Orange	9	3%	7	3%	21	3%	16	4%	13	4%	4	2%
Red	3	1%	5	2%	6	1%	3	1%	8	3%	1	1%
S-average	0.09		0.10		0.09		0.09		0.11		0.08	
Compliance		93%		91%		92%		93%		89%		96%

Table S.4. Flight approach scenarios based on the apparent wind.

Nr	Wind direction*	Wind speed*	Apparent wind	Plume ascend	Plume diffusion	Plume location*
1	Opposite	X	Positive	Descend	Very High	Behind
2	Cross	X	Neutral	Chimney level	Medium	Sideways
3	Along	Higher	Negative in front	Chimney level	Medium	In front
4	Along	Equal	Zero	High ascend	Very low	Above
5	Along	Lower	Negative behind	Ascend	Low	Behind

*Relative to the vessel

Chapter 2: Airborne monitoring of compliance to NOx emission regulations from ocean-going vessels in the Belgian North Sea area.



RBINS -MUMM © picture taken during flight 22073 (08/06/22)

Airborne monitoring of compliance to NOx emission regulations from ocean-going vessels in the Belgian North Sea area.

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Abstract

Along the worldwide tightening of standards for sulphur emission from ocean going vessels (OGVs) come actions that are also being taken to reduce nitrogen emission. Particularly, as a milestone in this regard, on January 1st, 2021 the NO_x Emission Control Area (NECA) for the North Sea and Baltic Sea came into effect. In response to the newly established NECA, the sniffer sensor system on the Belgian coastguard aircraft was modified and extended with a NO_x sensor. Moreover, a methodology was developed to evaluate OGV compliance to the NO_x emission limits through in situ measurements of the plume exhaust. The quality and uncertainty of the measurements demonstrate that it is likely to achieve an effective compliance monitoring of the NO_x emission standards on the sea. Those emission standards are further divided into four tiers depending on the keel laying date. As has been proved by the results, NO_x emissions for Tier II OGVs, contrary to what might be expected, are on average higher than those for Tier I OGVs. What is even more problematic, Tier II OGVs have also more often been found to be non-compliant than Tier I OGVs.

1. Introduction

1.1. Impact NO_x emissions

As is known to all, NO_x has a significant impact on human health, the environment and the climate. Health impact from NO_2 involves mainly cardiovascular conditions and respiratory diseases such as (children's) asthma and Chronic Obstructive Pulmonary Disease (COPD). In addition, NO_2 is also a precursor for ozone (O_3) that causes respiratory illness as well. Due to the fact that nitrogen dioxide reacts with water to give a mixture of nitrous acid (HNO_2) and nitric acid (HNO_3), NO_x is one of the major contributors to acid rain [1] which is responsible for the environmental degradation of forests and coral reefs [1,2], for the aggravation of the ocean acidification caused by the emission of CO_2, and even for the damage to structures and artificial surfaces (e.g. historic limestone constructions) [1]. Furthermore, NO_x is also a source of eutrophication with significant environmental and monetary impacts [3–5].

In the EU, air quality standard for NO_2 limit is 40 µg/m^3 annual mean [6]. Nevertheless, as there is in fact no lower threshold for NO_2, the World Health Organization (WHO) applies a substantial lower standard of 10 µg/m^3 [7]. Based on the provisional data for 2020, all of the 33 reporting countries, except Malta, reported values above the WHO standard [8]. In terms of the situation in Belgium, the WHO standard is even largely breached. For example, a recent citizens science project in 2022 indicates that only 1.7% of more than 3000 measurements points in Brussels met the WHO standard [9,10].

1.2. NO_x emissions from maritime transport

Shipping is one of the main contributors of emissions from NO_x on global scale [11]. For the period 2007-2012, the NO_x emission from OGVs contributed to 13% of the global anthropogenic NO_x emission, while

only representing 3.1% of the CO_2 emission [12]. NO_2 data (in molecules/cm^2) from the TROPOMI Sentinel 5 satellite [13] clearly demonstrate that the maritime sector is a substantial source of NO_x emissions, visualizing the maritime transport patterns (Figure 1).

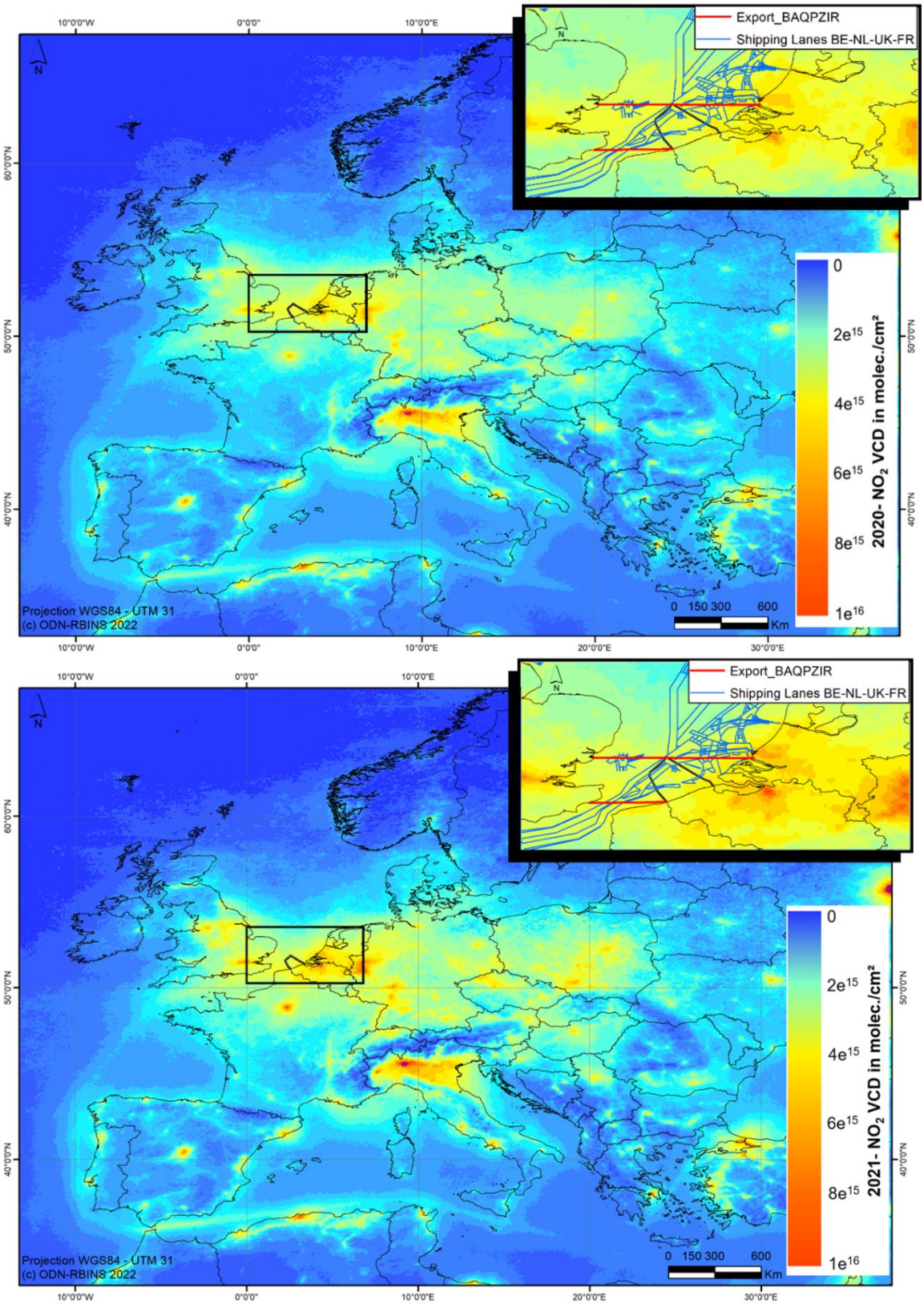


Figure 1. Annual average observed NO_2 molecules/cm^2 VCD (Vertical Column Density) for 2020 (upper) and 2021 (lower) from TROPOMI Sentinel 5 (compiled data provided by BIRA)

1.3. NO_x regulations for OGVs

The international NO_x emission standards for OGVs are laid down by the International Maritime Organization (IMO). As the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes, the 1973 International Convention for the Prevention of Pollution from Ships (MARPOL), alongside its 1978 Protocol (MARPOL 73/78) [14] was amended by the Protocol of 1997 (MARPOL PROT 1997) and further revised in 2008 [15], to include airborne emissions from OGVs in Annex VI. As of 2021, the MARPOL PROT 1997 has been ratified by 101 countries representing 96.75% of the gross tonnage of the worlds merchant fleet [16]. At national level, MARPOL Annex VI was adopted in Belgium in 2007 [17].

Regulation 13 of MARPOL Annex VI envisages a gradual decrease of emissions of NO_x and introduces Emission Control Areas (ECAs) where more stringent emission limits for air pollutants from OGVs should be applied [18]. In 2021, the Sulfur Emission Control Area (SECA) in the Baltic Sea, the North Sea and the English Channel was extended with a NO_x Emission Control Area (NECA) and therefore renamed to Emission Control Area (ECA) [19,20] (Figure 2). Nevertheless, due to the increase in maritime transport, the total NO_x emission from OGVs is still tending to increase [21]

In contrast with the EU sulfur regulations, NO_x emissions from ships are not regulated by an additional EU directive, which means no common European monitoring rules and procedures are in place. As a result, the NO_x inspection data of EU member states are not shared through Thetis EU – the port inspection database managed by the European Maritime Safety Agency (EMSA).

1.4. Marpol Annex VI Regulation 13

Unlike the reduction of Sulphur emissions under the EU Sulphur regulations that suffices to limit the sulphur content in the fuel used, reducing NO_x emissions, in accordance with the MARPOL regulatory approach, needs to be achieved through addressing the combustion processes in the engine. Therefore, engines need to be tested and classified according to the NO_x Technical code, MEPC.1/Circ.679 [22]. Accordingly, in MARPOL Annex VI, the NO_x emission limits in Regulation 13 are also expressed differently from the limits for sulfur emission in Regulation 14. More specifically, the nitrogen content of the fuel is only a small factor in the whole NO_x emission cycle, and therefore the NO_x limits are expressed as the actual weighted amount of NO_x emission (g) per Brake Horse Power (BHP) on the crankshaft (kWh).

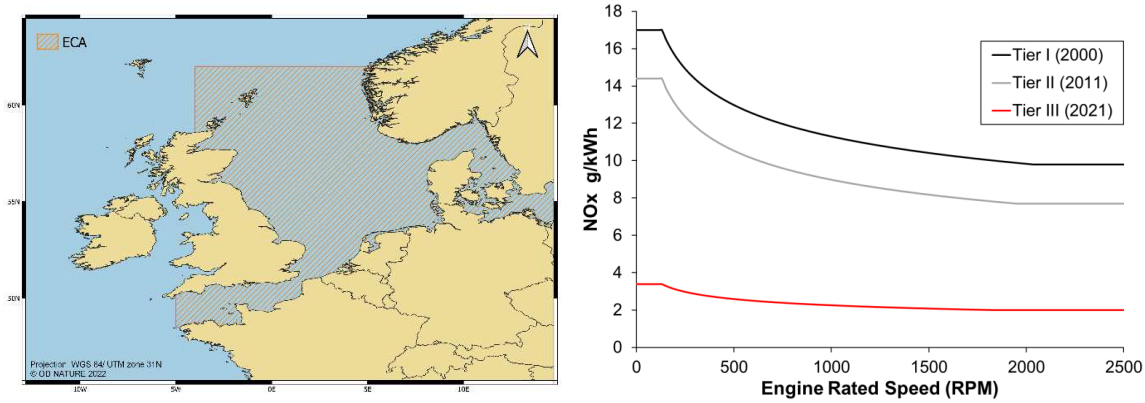


Figure 2. Upper: Emission Control Area (ECA) as defined by MARPOL Annex VI. Lower: NO_x emission limits according to MARPOL Annex VI Regulation 13

1.4.1. Keel laying year

Based on the Keel Laying Year (KLY) of the vessel, as defined as ship constructed (Reg. 2.19), the merchant fleet is divided in 4 tiers in Regulation 13. Tier 0 applies for OGVs with a KLY before 2000

(Reg. 13.7); Tier I concerns ships from 2000 until 2011 (Reg. 13.3); Tier II is for ships from 2011 until 2021 (Reg. 13.4) and Tier III is for ships with a KLY from 2021 onwards (Reg. 13.5). The emission limit per tier is furthermore based on the Engine Rated Speed (ERS or n), which is the point where the engine, expressed in rotations per minute (rpm), produces the maximum power and is defined per engine or engine class. The NO_x emission limits per tier are provided in Figure 2. For OGVs with Tier 0, with a KLY after 1990, the Tier I regulations apply for ships with a rated engine power output of more than 5000 kWh or with a displacement ≥ 90 L per cylinder.

1.4.2. Test cycles

An additional complication in Marpol Annex VI Regulation 13 is manifested as a complexity that 5 different test cycles with 4 to 5 engine loads and corresponding weighting factors have been described in the NO_x Technical code for the verification of the compliance to the emission limits. The described test cycles are used in order to obtain the Engine International Air Pollution Prevention Certificate (EIAPP) and the International Air Pollution Prevention Certificate (IAPP). The EIAPP is issued during the pre-certification of an engine prior to the installation on board of an OGV, while the IAPP is granted during the certification after installation of the engine on board of an OGV, both of which are addressed by a classification society.

Only test cycles for the main engines fall under the scope of this study. The two test cycles for the main engines (E2 and E3) are both based on the same engine load (Power) and weighting factor (WF) (Table 1). To verify compliance, the weighted average emission for the 4 engine loads should not exceed the NO_x limit. The results of the engine emission tests are described in Annex 5 of the NO_x Technical Code, as part of the EIAPP and IAPP should be stored onboard. It is also worth noting that all NO_x sensitive components, which are described in the NO_x technical file, must be stored on board together with the EIAPP and IAPP, and all modifications to these components must be recorded in the NO_x technical file [15,22].

Table 1. Test cycles and weighting factors according to the NO_x Technical code [22]

E2	Speed	100%	100%	100%	100%
	Power	100%	75%	50%	25%
	WF	0.2	0.5	0.15	0.15
E3	Speed	100%	91%	80%	63%
	Power	100%	75%	50%	25%
	WF	0.2	0.5	0.15	0.15

It is important to highlight that only for Tier III a "not to exceed" limit (NTE) is defined, which states that the emission for any engine load should not exceed the NO_x limit with more than 50% at any of the individual engine loads of the E2 or E3 test cycles [22]. To comply with the NO_x regulations in the ECA, engine manufacturers and shipowners may resort to several technical solutions. Among those solutions, the two main abatement techniques employed to lower the emission for regular marine diesel engines are Selective Catalytic Reduction (SCR) and Exhaust Gas Reintroduction (EGR). With SCR, urea is added as a reagent to reduce NO_x to N_2 [23], which works well to meet Tier III standards, although ammonia slips are a potential risk [24]. On the other side, exhaust gasses, in terms of EGR, are injected back in the engine in a controlled manner. This lowers the temperature and oxygen level in the combustion chamber and decreases the NO_x emissions. Although EGR is efficient for NO_x reduction, it is possible to potentially increase the sooth and Black Carbon [25]. In addition to SCR and EGR, other abatement methods include scavenge air moisturizing (SAM) [26], Miller cycle for 4 stroke engines [27] and CSNOx [28]. A shipowner may also decide to opt for new fuels like LNG, but at this moment only about 5% of the OGVs is equipped with an LNG engine [29]. In the future, the increasing use of other fuel sources like ammonia or hydrogen might also contribute to a reduction in NO_x emissions from

OGVs. With abatement technologies like SCR and EGR, there is a remaining risk for NO_x emission violation in case of technical malfunctioning, negligence or intentional misconduct due to economic gain.

1.5. Surveillance area and time frame for the monitoring operations

The Scientific Service of the Management Unit of the Mathematical Models of the North Sea (MUMM) of the Royal Belgian Institute of Natural Sciences is recognized by the Belgian Law as one of the legally competent authorities for the monitoring and enforcement of MARPOL regulations on the sea. Since 1991, MUMM has been responsible for the airborne surveillance of the Belgian North Sea area and neighboring waters, in the so-called Bonn Agreement (BA) Quadripartite Zone of Joint Responsibility (BAQPZJR) (Figure 1) [30]. From 2015 onwards, MUMM has been conducting airborne surveillance operations for the monitoring of MARPOL Annex VI regulation 14, concerning sulphur emissions from OGVs [30]. Although before 2021 the North Sea was not yet recognized as a NECA, the NO_x monitoring operations covered in this study started in July 2020 and lasted until November 2021.

2. Methods and Materials

2.1. Belgian coastguard aircraft

The Belgian coastguard aircraft, a Britten Norman Islander (BN2), was used for this study. Characterized as a Short Take Off and Landing (STOL) aircraft with low stall speed (40 kts), this high wing aircraft has a large wing surface (15 m width for 11 m length), suiting this type of operations. More importantly, the aircraft is equipped with modern avionics, a remote sensing system from Optimare and a sniffer sensor from FluxSense was also purchased in 2015 for the airborne measurement of SO_2 [30].

2.2. NO_x sensor

An Ecotech Serinus 40 NOx sensor, which was purchased from Chalmers University and installed in June 2020, measures its gaseous concentration through using the chemiluminescence characteristics of NO. This sensor can operate in either the "NO_x mode", the "NO mode" or the "All mode" that calculates the NO_2 based on the average NO_x and NO over a chosen time (min 15 sec). Specifically, for the measurement of NO_x, the sample passes through an ozone converter that transforms all the NO_2 in the sample flow to NO. While, for the NO_x monitoring operations, the sensor was set to NO_x mode with a sample time of 1 s.

2.3. Sniffer sensor system modification

The sniffer sensor system on board of the Belgian coastguard aircraft [30] was modified and extended in order to include the NO_x sensor. The same air supply probe was used as for the other gas analyzers in the sniffer sensor, but the NO_x sensor was kept outside of the pressurized loop as the NO_x requires a deeper vacuum and lower airflow (1 l/min). On the one hand, a custom build KNF vacuum pump (modified N022) was installed to provide the airflow. On the other hand, an additional exhaust probe, due to the ozone production, was further installed for the sniffer sensor (Figure S1).

The sniffer software (IGPS presenter and TCP log) was modified by Chalmers University to include the NO_x data. In addition, a yearly updated list all KLYs and MMSI information of 49327 OGVs larger than 70 m was obtained from EMSA. This number of OGVs comes near to the global merchant fleet. This list was linked through the software so that KLY information is available to the operator during flight. Furthermore, on request of MUMM, an entry for the Specific Fuel Consumption (SFC) was added in the SNF menu (Figure 3).

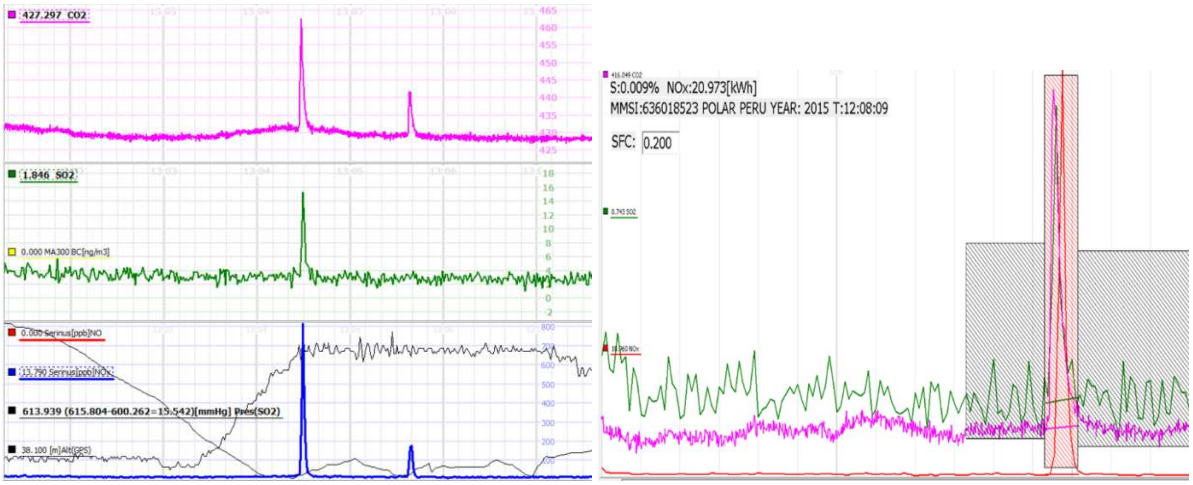


Figure 3. Left: print screen of the "SNF" view with the CO_2 concentration (in ppm) in magenta, SO_2 concentration (in ppb) in green and the NO_x concentration (in ppb) in blue. Right: graph selection view, the start and end of the peak (red striped area) and the background before and after the peak (black striped areas) can bet set by the operator to get a high-quality measurement. The NO_x emission is displayed immediately together with the Fuel Sulphur Content (FSC) (upper left side), the SFC is per default set at 0.2 kg/kWh but can be entered manually (snapshots from the IGPS software, developed by Chalmers University).

2.4. NO_x emission measurements

The NO_x emission factor (EF_{NOx}) in g NO_x/kg fuel can be calculated by using the NO_x and CO_2 concentrations. When crossing the exhaust plume, NO_x and CO_2 concentrations will increase and create peaks compared to the background [value] (bkg) before and after the peak. The surface area of these peaks above the background of the respective concentration plots is used for the calculation of the NO_x emission factor. In terms of the calculation of the amount of kg burned fuel, the amount of carbon (C) is multiplied with the carbon content in the fuel. And with regard to marine fuels, a carbon content of 87% is used [31,32].

$$EF_{NO_x} = \frac{M\,NO_2 \frac{g}{mol}}{\frac{M\,C \frac{g}{mol}}{0.87}} \times 1000 \times \frac{\int [NO_x - NO_{x,bkg}]_{ppb} dt}{\int [CO_2 - CO_{2,bkg}]_{ppm} dt} \left[\frac{g}{kg\ fuel}\right] \quad (1)$$

$$EF_{NO_x} = 3.33 \times \frac{\int [NO_x - NO_{x,bkg}]_{ppb} dt}{\int [CO_2 - CO_{2,bkg}]_{ppm} dt} \left[\frac{g}{kg\ fuel}\right] \quad (2)$$

According to Regulation 13 of MARPOL Annex VI, the molecular weight of NO_2 is used for the calculation of the NO_x emission factor. For the calculation of the NO_x emission in g NOx/kWh, the NO_x emission factor (g NO_x/kg fuel) is multiplied by the Specific Fuel Consumption (SFC).

$$SFC = \frac{kg\ fuel}{kWh\ BHP} \quad (3)$$

$$EF_{P,NO_x} = EF_{NO_x} \times \left(\frac{kg\ fuel}{kWh\ BHP}\right) \quad (4)$$

Based on literature and public engine data, the SFC can generally be found between 0.16 kg/kWh and 0.24 kg/kWh [33–43].

2.5. Sniffer Quality Management System

A Sniffer Quality Management System (SQMS) has been set up with Standard Operational Procedures (SOPs) [30] to guarantee a high reliability of emission measurements on spatial and temporal level and to ensure that the airborne monitoring missions are executed efficiently, safely and in accordance with

standardized measurement procedures. This SQMS system consists of three parts: (i) the operational procedures are described in the OPS manual, (ii) the quality assurance (QA) protocols are described in the QA manual, and (iii) the data management is described in the data manual [30]. The updated three parts, including the NO_x emission monitoring, are described in the sections below.

3. Operational procedures

For the selection and sampling of the exhaust plumes of the OGVs, the same procedures were applied as for the monitoring of SO_2 [30], which means that both the NO_x emission limit from MARPOL Annex VI Regulation 13 and the FSC limit as described in MARPOL Annex VI Regulation 14 were monitored at the same time. As soon as the aircraft sampled the OGV exhausts, gas concentrations of CO_2, SO_2 and NO_x were immediately plotted on the SNF graphs on the IGPS software. The manual calculation of the NO_x emission by aerial operators was done together with the calculation of the FSC by selecting the area before/after the peak (background) and the area of the peak itself.

For the initial NO_x emission calculation, an SFC of 0.2 kg/kWh was used. The KLY was displayed together with the NO_x emission. When this first measurement with the default SFC showed a value exceeding a predefined threshold, marine VHF radio contact was made with the vessel to request the actual fuel consumption of the main engine (in metric tons/hour) and the current main engine power (in kW), to be calculated and provided by the chief engineer. A special radio communication checklist was therefore created for this purpose. For simplification, it was chosen to ask the total main engine power output as the provision of the crankshaft power output may not always be possible, reliable or as fast as the main engine total power output. The total power output will always be slightly higher than the break power at the crankshaft due to friction losses and losses for additional auxiliary systems connected to the main engine. The obtained NO_x emission factor was therefore always an underestimation of the actual NO_x emission factor. Based on the information obtained through radio communication, the SFC was calculated and entered in the IGPS software. Moreover, a second exhaust plume sampling was executed and the NO_x emission factor was determined with the actual SFC. It is also worth noting that NO_x emission factor measurements taken with the default SFC could also be recalculated in case the SFC was only obtained after both measurements occurred.

$$Corrected\ EF_{P,NO_x} = \frac{Initial\ EF_{P,NO_x}}{Default\ SFC} \times Actual\ SFC \tag{5}$$

Whenever it was not possible to contact the OGV due to, for instance, other operations on board of the OGV (e.g. piloting or maneuvering) or when the chief engineer was not available, a lower end SFC of 0.16 kg/kWh was applied as it was preferred to avoid false positives over false negatives. In case the recalculated NO_x emission factor was still higher than the Tier threshold, the OGV was considered as non-compliant and reported to PSC. In case the recalculated NO_x emission fell below the threshold, the OGV was not reported. In the database the calculation of the NO_x emission factors for OGVs without a confirmed SFC however were all based on an SFC of 0.2 kg /kWh for standardization purpose. In case the second measurement confirmed a NO_x emission factor exceeding the Tier threshold, a flight report was drafted and sent to the port inspection authorities of the country of destination (in case this was an ECA port), who could decide whether or not to board for an inspection in the next port of call.

Based on a dataset from IHS Markit, it was demonstrated that the majority of OGVs equipped with two stroke slow speed engines have engine rates below 130 rpm [44]. This is especially the case for tankers (60%), container OGVs (74%), vehicle carriers (75%) and bulk carriers (81%). On the other hand, Roll On Roll Off OGVs (RORO) (17%), cruise OGVs (2%) and ferry's (1%) are not often equipped with slow speed engines but rather with medium speed engines (with engine rates of 500-750 rpm) and

high speed engines (with engine rates > 1000 rpm) [44]. Four stroke high speed engines are often to be found for auxiliary applications on all vessel types. Furthermore, the IMO greenhouse Study 2020 demonstrated that the majority of the OGVs with a Dead Weight Tonnage (DWT) larger than 20 kt have an engine rate under 130 rpm, which was partly based on the IHS Markit dataset and a regression algorithm from the University Maritime Advisory Services (UMAS) for the missing datapoints (Figure S2, upper) [42]. Based on a cross referencing of the airborne dataset from 2015-2020 with a dataset of 1500 OGVs calling Belgian ports in 2019 (data provided by SPF Mobility), this DWT of 20 kt corresponded to an OGV length of minimum 172.9 m (Figure S2, middle).

Ignoring the engine rate, it was decided to focus on operational efficiency due to two reasons: firstly, the focus of the airborne monitoring was the larger segment of the merchant fleet (>100m); secondly, auxiliary systems fall outside the scope of the monitoring. This meant that a fixed limit was applied per Tier level, being the (highest) NO_x limit for engine rates ≤ 130 rpm, not taking into account the lower NO_x emission limit for OGVs with engine rates > 130 rpm. The Tier I limit was therefore set to 17 g NO_x/kWh and the limit for Tier II ships was fixed at 14.4 g NO_x/kWh.

For Tier 0 OGVs, that were built after 1990 with a power output ≥ 5000 kWh, the same rules apply as for Tier I OGVs. Based on the IMO GISIS online database [45], 173 m was found to be the absolute maximum length for ships with a power output as low as 5000 kWh (Figure S2, lower). Thus, all Tier 0 OGVs with a KLY after 1990 and a length > 175 m were considered to be subject to Tier I emission limitations. As a result, limiting the workload for the operators that otherwise needed to look up engine parameters during flight for all Tier 0 OGVs built after 1990. For Tier 0 OGVs built after 1990 with a power output > 5000 kWh but with a size smaller than 175 m, a manual check of the engine power output (on Thetis–EU) was still required, but those ships were only observed occasionally (2.7% of the observed OGVs).

OGVs sailing at an engine load lower than 25% were considered "off cycle", which means that they fall outside the regulated emission "spectrum". Due to the fact that it was not possible to request the engine load information for every individual measurement, a cut off speed of 10 kts was applied. Below this speed a higher threshold level was applied for the initial evaluation. The speed of 10 kts was chosen based on operational criteria. This was a very rough selection criteria, owing to the large variation in loads for different ship types and ship loads. For example, the average speed of bulk carriers and tankers for 2018 was 8-13 kts, for bulk carriers 9-12 kts, while for containers this was 13-17 kts [42]. As such it is likely that several OGVs were included with engine loads < 25%, but a speed higher than 10 kts (type I). In addition, it is not possible to guarantee that all observed OGVs with a speed lower than 10 kts had engine loads lower than 25% (type II) and may therefore be wrongly excluded. For type I errors (false positives), the engine power output derived from the radio communication was used to calculate the actual load, thus assessing if the load was below 25%. Accordingly, type I errors could be completely excluded. Aiming to avoid important type II errors (false negatives), a higher threshold was applied for OGVs with a speed < 10 kts, which meant that high polluting OGVs would still have been noted and reported to the port authorities.

4. Maintenance and calibration procedures

The Quality Assurance Manual consists of all detailed maintenance and calibration procedures. This part was updated with maintenance and calibration procedures for the NO_x sensor that was calibrated using a zero (synthetic air) and span gas of 300 ppb NO in N_2. The respective calibration gases were connected to the NO_x sensor directly to reset the sensor background (offset) and to set the calibration factor (slope). The span gas and zero gas mixtures were tested on regular intervals by the ISO certified air quality laboratory of the Brussels Environmental Agency (BIM). The NO concentration was very

stable over time with an average variation of 2.3%. The calibration interval was therefore set at 3 months (together with the SO_2 span gas).

5. Data management

All NO_x measurement data, together with the collected data on the fuel consumption, engine loads, SFC and NO calibration factors, were included in the sniffer database. The sniffer data management procedures were updated to include the NO_x data. A similar presentation was achieved to present the NO_x emission measurement data and relevant engine data, besides the FSC data. The data management was also adopted with the procedures for the annual collection of the KLY from EMSA and its application on the IGPS software.

5.1. Statistical Analysis

A Kolmogorov Smirnov test was used to assess the normality of the NO_x emission measurement data, showing that the NO_x data did not follow a Normal distribution ($P < 0.05$), which was the reason why non-parametrical tests were used. As the NO_x emission data is continuous, the Kolmogorov Smirnov test was chosen over the Mann-Whitney U test to compare the emission distribution of different groups (Years, Tiers, OGV type, region) [30]. Distributions were found to be significantly different when $P < 0.05$ [46]. To determine a difference in compliance levels between groups (Tier level, OGV Type, Year), a two-sided Chi Square test was used. Statistical significance was defined when $P < 0.05$ [47,48].

6. Results and discussion

6.1. Description of the sampled OGVs

During a total of 78 flights and 127.2 operational flight hours performed in the period 2020-2021, NO_x emissions of 1407 OGVs were successfully measured together with the measurement of the FSC. This comes down to an average number of successful emission measurements of 11.2 OGVs per flight hour. This is roughly the same amount of measurements per flight hour as the overall 10.4 inspected OGVs per hour for FSC monitoring for the period 2015-2019, but notably lower than the 12.9 average number of monitored OGVs for FSC monitoring for the year 2019 [30]. Some improvement might be possible for the following years due to experience gained. Nevertheless, it can be concluded that by including NO_x emission in the airborne OGV emission monitoring program, the absolute number of monitored ships decreased by almost 15%.

6.2. Efficiency of flight operations

On the one hand, when assessing the monitored compliance to different MARPOL Annex VI regulations, there is a vast improvement. Up until 2020 only FSC was monitored, hence the number of monitored MARPOL Annex VI regulations equaled the number of monitored OGVs. From 2020 onwards, by including NO_x monitoring, this was increased to a total average amount of 22.4 monitored MARPOL Annex VI regulations per flight hour (Figure S3).

When assessing the ratio of the successfully measured OGVs, after a small decrease in 2020, due to additional flight time that was spent to setup the NO_x measurement methodology, the success rate did increase back to 97%. This means that adding the NO_x emission monitoring did not significantly affect the number of failed attempts.

6.3. Emission measurements

6.3.1. Temporal analysis

NO_x, emission levels were measured for 1407 OGVs, of which 403 in 2020 and 1004 in 2021. The lower number of OGVs for 2020 was a consequence of the impact of the Covid19 pandemic on the number of flight hours. Of these OGVs, 11% belonged to Tier 0, 53% was Tier I and 36% was Tier II. So far,

neither Tier III OGVs nor significant difference in the distribution of Tier 0, Tier I and Tier II OGVs between 2020 and 2021 ($P = 0.683$) have been observed. Although the KLY dataset for 2022 only contains 445 Tier III OGVs (<1%), this does not mean that no new OGVs have been constructed in 2021. In fact, the KLY database contains 1426 OGVs that have a built year from 2021 but a KLY before 2021, corresponding to 76% of the ships built ≥ 2021, as well as 8 OGVs that have even a KLY < 2011. When looking at the 1055 OGVs built in 2021 that have length larger than 70 m and are larger than 5000 Gross Tonnage (GT), only 138 had a KLY in 2021 (13%). Ship builders have prepared numerous keels in the years before 2021, which are used for the construction of new OGVs and to avoid the much stricter Tier III emission limits. Also, in the following years a large section of the newly built OGVs will still have a KLY < 2021, hence delaying the impact of the emission regulations. Zhang et al. have estimated that the implementation of the Tier III limits would prevent up to 33300 (30100-36400) premature deaths as from 2021 [49]. By evading the implementation of the Tier III standards by 87% of the OGVs built in 2021, 29000 (26200-31700) premature deaths were therefore not avoided. As for the following years still a large section of the newly built OGVs will have a KLY < 2021, the overall impact of the delay of the effective implementation of the Tier III standards on the non-avoided premature deaths is expected to be a multiple of this figure.

For all Tier 0 OGVs with a KLY ≥ 1990 the engine power was looked up in the Thetis–EU database (Figure S4). Based on a linear regression, on average, OGVs with a length from 117.9 m have an engine power above 5000 kWh ($R^2 = 0.74$). The maximum OGV length corresponding to an engine power lower or equal to 5000 kWh was 160 m, and it was therefore chosen to adjust the limit of 170 m to 160 m. In total 81% of the Tier 0 OGVs was subject to the Tier I emission limits, these OGVs are referred as Tier 0(I). The other 19% Tier 0 OGVs had either a KLY before 1990 or a total engine power < 5000 kWh, and are referred as Tier 0 OGVs.

The average measured NO_x was 13.0 g/kWh, which was lower than the NO_x emission limit for Tier I and Tier II ships with engine rates below 130 rpm. In comparing the average NO_x emission between 2020 and 2021, it can be noted that the average NO_x emissions were not significantly different but were remarkably higher for 2021 (13.1) compared to 2020 (12.6) ($P < 0.1$). This is counterintuitive, since the ECA was not yet in place in 2020. The average speed of the observed OGVs was marginally lower in 2020 (12.6 kts), compared to 2021 (12.7 kts) with no significant difference ($P > 0.1$), while the median speed was slightly higher for 2020 (12.6) compared to 2021 (12.5).

6.3.2. Analysis per tier

When comparing the average NO_x emission per tier, it was assumed that Tier II OGVs would have a lower NO_x emission than Tier I OGVs, as the NO_x emission limit for Tier II OGVs is lower than for Tier I. However, it was witnessed that the average NO_x emission for Tier II OGVs (13.5 g/kWh) was higher than the average NO_x emissions for Tier I (12.6 g/kWh) and even comparable to the overall NO_x emission of Tier 0(I) (13.5 g/kWh) (Figure 4).

The emission distributions per Tier were compared statistically. There were no significant differences observed in NO_x emission distributions between Tier 0(I) and Tier I for the year 2020 ($P > 0.1$) and the year 2021 ($P > 0.1$). In contrast, during the overall period 2020-2021, a significant difference was observed ($P < 0.025$). When comparing the NO_x emission distributions between Tier I and Tier II, the distributions were found to be significantly different for the year 2020 ($P < 0.005$), the year 2021 ($P < 0.001$) and for the overall period 2020-2021 ($P < 0.001$). This finding confirms the observed higher average NO_x emission for Tier II OGVs for all time periods. For NO_x emission distributions between Tier 0(I) and Tier II, there was no significant difference observed for the period 2020, 2021 or the overall period ($P > 0.1$). This phenomenon can be interpreted as a finding that the Tier II OGVs did not

significantly emit lower NO_x emissions compared to Tier 0(I) OGVs. The average higher NO_x emission levels for Tier II OGVs were also observed by the Danish EPA, although those measurements were performed by reanalyzing historic data from before the ECA came into force [50].

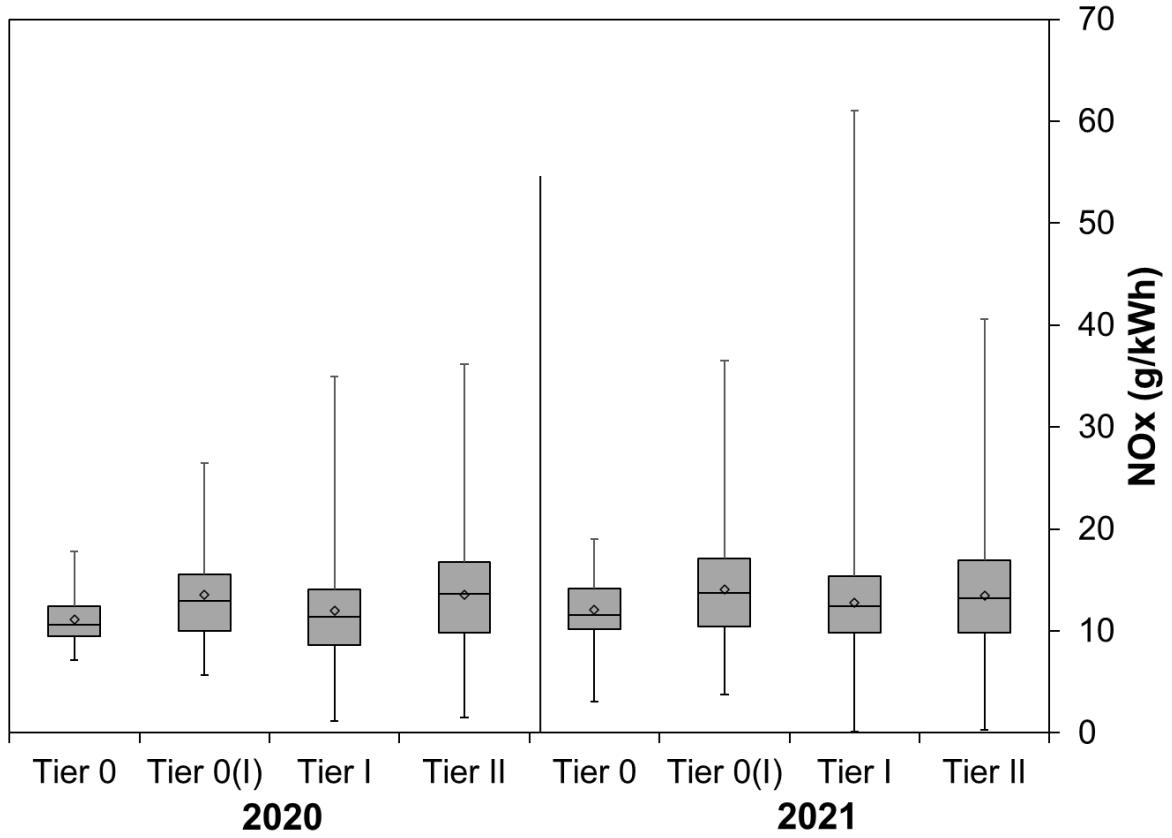


Figure 4. Box plot of NO_x emissions (g/kWh) per Tier level for the period 2020-2021, with 25% and 75% percentiles, median, and average (♦).

These findings are in clear contrast with the assumption that the average NO_x emission for Tier II OGVs would be lower than for Tier I and Tier 0 OGVs. Based on the emission limits, an emission reduction of 15.3 % by Tier II OGVs would be expected compared to Tier I. However, on average the observed Tier II OGVs emit in fact 7.4% more than the observed Tier I OGVs. A possible explanation for the higher observed actual NO_x emissions in the Belgian and neighboring waters lies in the fact that the average speed of the OGVs passing in the North Sea is low compared to the average OGV cruising speed, the overall average observed speed was 12.7 kts. As the cruising speed strongly depends on the OGV type and the operational mode, a closer look was taken on the speed of container OGVs. The average speed for all container OGVs that were en-route in the northern shipping lanes was 13.7 kts (Figure S5, upper), whereas the most optimal speed, the slow steaming speed for container OGVs is 18-20 kts, the minimum cost speed for container ships is 12-15 kts, these speeds are commercially not efficient at the high seas [51], however it seems that these speeds are used by OGVs passing in the North Sea.

Lower sailing speed lead subsequently to lower engine loads corresponding to lower weighting factors. Whereas for Tier 0(I) and Tier I OGVs the NO_x emissions tend to be more stable over different engine loads, Tier II OGVs have a different NO_x emission profile [34]. Engine manufacturers design their Tier II engine to optimize fuel efficiency. As fuel efficiency conflicts with NO_x emissions reduction, a trade-off needs to be made. By taking advantage of the weighting factors per engine load, engine manufacturers are able to design engines in such way that NO_x emissions in lower loads are higher than for the higher

loads. Nevertheless, the overall weighted average NO_x emission approaches the limit and thus optimizes fuel consumption. As a result, Tier II OGVs may consume less fuel, but emit more NO_x, which is especially the case for engine loads of 25% and 50% that occur during coastal operations, which can be illustrated by an example of a test result for a Tier II engine (1945 kW and ERS of 1000 rpm). The weighted average is just below the limit while the unweighted average is above the limit (Figure S5 lower).

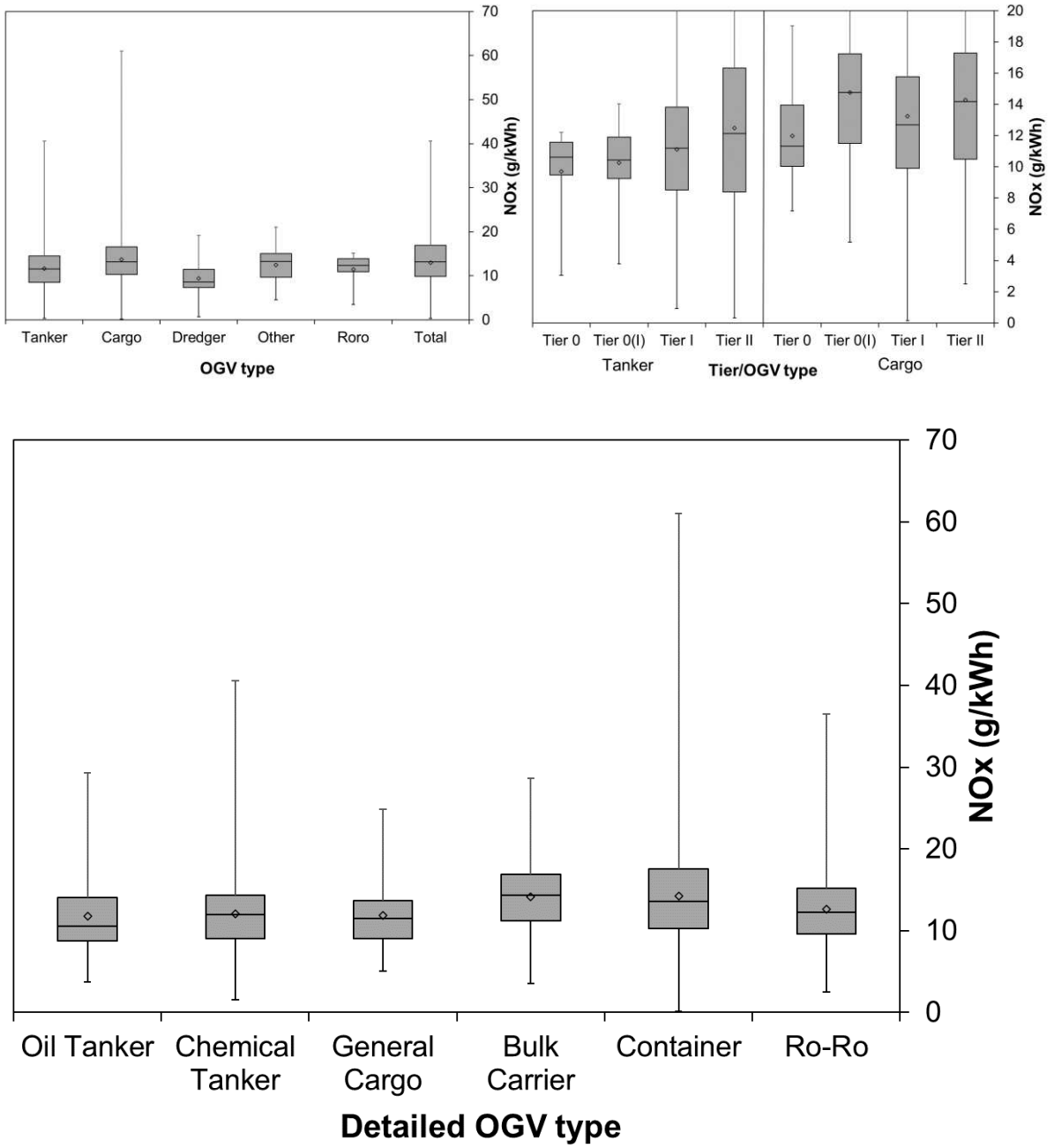


Figure 5. Upper left: Box plot for the NO_x emissions for different OGV types. Upper right: Boxplot of different tiers for cargo and tanker OGVs. Lower: Box plot for detailed vessel type (Ro-Ro and vehicle carriers were combined to Ro-Ro). With 25% and 75% percentiles, median, and average (♦).

6.3.3. Results per OGV type

The OGV type was first derived from the MMSI number obtained through AIS. Of the observed OGVs, the majority were cargo OGVs (66.3%) followed by tankers (29.9%). The rest were other vessel types (1.5%); ROROs and passenger OGVs (1.4%), dredgers (0.6%), military OGVs (0.1%), fishery OGVs (0.1%). For 0.2% of the OGVs, no vessel type could be assigned due to missing or incomplete AIS data. As a result of the limited categories in the MMSI data protocol, based on AIS information, it is not possible to differentiate between various types of cargo OGVs. Accordingly, container OGVs, bulk carriers, general cargo OGVs and vehicle carriers are considered as cargo OGVs. When comparing the NO_x emission distributions per vessel type, a higher average value was found for cargo OGVs (13.7 g NO_x/kWh) compared to tankers (11.7 g NO_x/kWh) (Figure 5, upper left). This difference was found to be significant ($P < 0.001$). The other vessel types were not compared due to the low number of observations per vessel type. When comparing the different NO_x distributions per Tier level for tankers and cargo OGVs, a higher average NO_x emission was observed for Tier II. Based on statistical analysis, it was showed that Tier 0(I) and Tier I were not significantly different for cargo OGVs and tankers. However, Tier II was significantly different from Tier I for both cargo OGVs and tankers ($P < 0.005$). When comparing Tier II with Tier 0(I), no significant difference was observed for neither cargo OGVs nor tankers ($P < 0.01$) (Figure 5, upper right). The ratio of the amount of tanker OGVs and container OGVs did not differ from each other significantly between 2020 and 2021 ($P = 0.062$).

In addition to this first analysis, for the large majority of the observed OGVs, the detailed vessel type could also be obtained by cross referencing with the GISIS database (99%). The higher average NO_x emission for cargo OGVs is apparently due to the significant higher NO_x emissions for container OGVs and bulk carriers ($P < 0.001$) (Figure 5, lower). Moreover, a significant difference was also observed between oil tankers and chemical tankers ($P < 0.05$).

6.4. Specific Fuel Consumption

Fuel consumption was collected for 42 OGVs. Analysis showed that SFC values were observed from 100 g/kWh up to 350 g/kWh, with an average of 201/kWh (standard deviation SD = 46 g/kWh), confirming that the SFC of 200 g/kWh used per default was representative. To avoid under- or overestimations of the NO_x emissions due to unreliable information received by marine VHF, it was decided to define an acceptance limit for the SFC. All values falling outside the 95% confidence interval (average +/- 1.96xSD), which means that values below 100 and above 300 will not be accepted. In those cases, the 200 g/kWh standard was used. No correlation could be made between the SFC versus the OGV length nor OGV type (Figure S6). When comparing the SFC between OGV types or Tier level, no clear patterns were observed ($P < 0.1$), although this dataset was largely insufficient for an in-depth analysis.

6.5. Engine loads

Based on the obtained information and the engine characteristics from the EMSA Thetis–EU database [52], engine loads were derived for all OGVs that were contacted. According to this analysis, the average load of the observed OGVs was 34%, ranging from 6% up to 77% (Figure S7, upper). The loads were all rounded to 5% and divided in 4 categories (0-25%, 25-50%, 50-75% and 75-100%). The category that was most observed was the 25-50% load (60% of the measured OGVs), but on the second place was the 0-25% category (23% of measured OGVs). As no limits are defined for the 0-25% category, it probably means that compliance of these OGVs could not be technically determined. When comparing the difference in engine load per Tier, it was observed that Tier II OGVs sail generally at lower engine loads compared to Tier I (24% versus 14%), although this effect, due to the low amount of data, could not be proven statistically ($P = 0.643$). When comparing the 2 lower categories (0-50%) with the two higher categories (50-100%), the relative difference becomes less profound, with 84% of Tier II OGVs

and 71% of the Tier I OGVs in the 0-50% engine load category. Again, this was not found to be statistically significant ($P = 0.451$).

Based on the comparison of the engine load with the OGV speed (Figure S8, upper), it could be demonstrated that both were strongly correlated (R^2=0.83). In accordance with the propeller law, the engine load can also be derived from the maximum speed and the actual speed [42,50,53–55].

$$Modelled\ load = \left(\frac{actual\ speed}{Maximum\ speed}\right)^3 \times CF \quad (6)$$

A modelled load was calculated and compared to the actual load (Figure S8, lower), which indicated a good correlation ($R^2 = 0.778$). Through employing the least square method, the correction factor (CF) was determined for the Belgian North Sea area ($CF = 1.28$). Nevertheless, due to some potential large differences, instead of relying solely on the modelled load by default, it was decided to continue with the marine radio communication procedure to obtain the actual engine load. In case no radio communication could be established, the modelled load was used to determine the engine load.

When examining the distribution of a sub dataset for which the modelled load was calculated (Figure S7, lower), roughly the same distribution was observed as for the actual load, with a majority (46%) of the modelled engine loads in the 25-50% category and 26% in the 0-25% category. However, the amount of Tier II OGVs in the 0-25% category (24%) is lower than the amount of Tier I OGVs (28%). The same is observed in the 0-50% category where Tier II represent 68% compared to 76% for Tier I. As is manifested in the result, based on this dataset, it cannot be argued that Tier II OGVs sail at lower engine loads and therefore are not more off cycle compared to Tier I OGVs.

When the NO_x emission is expressed in function of the engine load only, a weak correlation is observed. Remarkably, when comparing this relation per Tier level a stronger decrease (slope -5.06) of the NO_x emission is observed in function of the engine loads for Tier II compared to Tier 0(I) and Tier I OGVs (slope -0.5) (Figure S9). This confirms the assumption that the higher observed NO_x emissions for Tier II are most likely related to the higher emissions of Tier II engines on lower engine loads. As a result of the lower weighting factors for the 25% and 50% load, emission load profiles for Tier II OGVs indicate that this is indeed the case [34].

6.6. Measurement quality

Similar as for the FSC measurements [30], it was chosen not to calculate a quantitative quality indicator. Instead, it was decided to assess if a NO_x met the quality standards, based on a set of qualitative requirements. For high quality NO_x measurements, firstly, the NO_x and CO_2 gas sensors should have comparable response times; secondly, the NO_x measurements should have a good signal to noise ratio (SNR). These restrictive conditions are in addition to the common requirements that also count for the FSC measurements: (i) plume could be successfully linked to an OGV; and (ii) no interference from land pollution or other sources.

6.6.1. Response time

As the flow is split before the pressure and flow regulators, the NO_x sensor has with 1 l/min a substantial lower flow than the CO2 sensor. Thanks to a change from single-headed to a two-headed pump, the flow in the CO_2 sensor was increased from 6 l/min to 8 l/min. The responding time of both the CO_2 and NO_X sensors were determined by using the calibration gas mixtures. For the NO_x sensor, the NO gas calibration with a concentration of 273 ppb NO was used, which corresponds to a concentration-difference (ΔC). A span gas with a concentration of 479 ppm was used for the CO_2 sensor. These differences with the respective CO_2 and NO_x concentration in the environment correspond from small

to medium peaks. The responding time was found by determining the time difference (ΔT) between 10% of the beginning (C_b) and end concentration (C_e).

$$\Delta T = T_{90} - T_{10} \tag{7}$$

Where

$$\Delta C = C_2 - C_1 \tag{8}$$

$$C_1 = C_b + 0.1 \times \Delta C \tag{9}$$

$$C_2 = C_e - 0.1 \times \Delta C \tag{10}$$

For the determination of the T_{10} and T_{90}, a linear interpolation was employed based on the concentrations before and after the C_1 and C_2 concentrations.

$$C_i = C_{i-1} + \frac{C_{i+1} - C_{i-1}}{2} \tag{11}$$

$$T_i = T_{i-1} + (T_{i+1} - T_{i-1}) \times \frac{C_{i+1} - C_i}{C_{i+1} - C_{i-1}} \tag{12}$$

The curve between the start and end concentration was however not linear but followed a sigmoid curve. For CO_2, the time resolution was 0.2 Hz, whereas the time resolution for the NO_x sensor was only 1 Hz (similar to the SO_2 sensor), which means that the curve, for the CO_2 signal, between T_{i-1} and T_{i+1} follows approximately a linear shape. The difference between the T90 based on linear interpolation is therefore very similar to the T90 for nonlinear interpolation. For the NO_x signal, the time between two measurements was *ca.* 1.0 s and the error from the linear interpolation could be significant. Accordingly, a nonlinear interpolation was used for the determination of T_i. The nonlinear interpolation between T_{i-1} and T_{i+1} showed a very desirable fit, which can be drawn as a conclusion that no additional S-curve fitting was required. Based on a nonlinear interpolation, the T90 time of the NO_x sensor was 2.3 s (Figure S10, upper). For the CO_2 sensor, the T90 was 2.7 s, although slightly higher than NO_x sensor. Yet, it is worth noting that both sensors provide a very comparable response time (Figure S10, lower).

6.6.2. Signal to noise ratio

The signal to noise ratio is a quality measure for a signal, by comparing the power of the signal, or the peak amplitude (A_{plm}) to the background noise (A_{bkg}) [56].

$$SNR = \frac{A_{plm}}{A_{bkg}} \tag{13}$$

The amplitude of the noise (A_{bkg}) of the CO_2 sensor depended on the sensor measurement resolution and the background conditions, which was calculated by looking at the standard deviation of the background concentration over 60 measurements. The background conditions over sea were more stable, resulting in lower CO_2 noise (standard deviation SD = 0.25 ppm) as over land (SD = 1.6 ppm). For CO_2, the minimum peak height to provide high quality exhaust plumes was established at 5 ppm [30], which corresponds to a SNR of 20, whereas 15 is considered as the minimum SNR for high quality peaks. The amplitude of the background was determined by the standard deviation of the background concentration over sea (before and after exhaust plumes were sampled). For NO_x the amplitude of the background is relatively low (0.58 ppb) when a SNR of 20 is applied. This demonstrates that the minimum peak height for a high-quality measurement is 11.6 ppb, which is much lower than the average observed peak height of 198.7 ppb, thus corresponding to an SNR of 341. A minimum peak height for NO_x was set at 15 ppb, although this minimum peak height, for the vast majority of the measurements, was easily met when

the peak height for CO_2 was more than 5 ppm. Only for three measurements, the CO_2 peak height was higher than 5 ppm while the NOx peak was below 15 ppb, and these concerned all three gas tankers.

6.7. Measuring uncertainty and compliance thresholds

Similarly as for FSC [30], the total NOx uncertainty measurement (U) can be described as a combination of the measurement bias (b) and the standard deviation (u_{tot}):

$$U = |b| + \sigma . u_{tot} \tag{14}$$

In contrast to the FSC, where fuel samples from port inspections were used to calculate the bias [30], no reference data is available for NO_x. Nevertheless, it can be assumed that there is a negative systematic error for several reasons. The first is the difference between indicated power of the main engine, which is requested through radio communication and the brake power which is used in the NO_x technical code. The brake power is measured at the crankshaft using a brake dynamometer. For conformity and simplification, the indicated power is requested when contacting an OGV. As the indicated power is always higher due to friction losses of the shaft and auxiliary systems connected with the main engine. The ratio between indicated power and brake power is expressed as mechanical efficiency (N_m) that is in the order of magnitude of 95% at full power but can be as low as 75% at rated speed (Heywood, 2018; Hyvönen et al., 2006; Lewander et al., 2009; Stanton, 2013; WINGD, 2016, 2017). The use of the indicated power instead of the brake power means an overrating of the power output in the SFC formula, which will result in an underestimation of the SFC and NO_x emissions by *ca.* 15%.

The next factors are the temperature and a humidity correction. The NO_x Technical Code describes that a correction should be applied for the air intake temperature and humidity.

$$k_{hd} = \frac{1}{1 - 0.0182 \times (H_a - 10.71) + 0.0045 \times (T_a - 298)} \tag{15}$$

In the Belgian part of the North Sea, the annual average temperature is 11.9°C (maximum 14.5°C) with an average humidity of 5.6 g/kg dry air. The corresponding combined average negative correction is 3.4% with a range between 2-4% (Figure S11).

The last factor is the impact from auxiliary engines and generators. These are generally four stroke engines with a higher ERS and have therefore lower emission limits. As only OGVs that are en route are measured, the impact of the exhausts of these engines on the emission measurements of the main engine is limited. Nevertheless, due to a dilution effect, main engine exhaust with higher NO_x/CO_2 ratios might be mixed with lower auxiliary engine exhaust with lower NO_x/CO_2 ratios, creating a negative bias. The part of the auxiliary exhausts in the total OGV exhaust is impossible to determine in flight, nevertheless auxiliary engine(s) can take up to 10-15% of the used fuel on the total journey. This amount can be even higher when the ship is sailing at very low speeds [60,61] Auxiliary engine emission limit corresponds to circa 58-64% of the limit of main engines (ERS $\geq$ 1000 rpm), the negative bias is therefore estimated to be in the order of magnitude of 4-6%. As a result, the combined negative systematic error is estimated to be 15-25%. The NO_x Technical Code provides a margin of 10% to account for the simplified measurement methods as described in Chapter 6 and an additional 10% allowance for the use of non-residual marine (non-RM) graded fuel (ISO8217:2005) such as distillates like Marine Gas Oil (MGO) [22], although the combined allowance should not exceed 15%. For this reason, the negative systematic error was not used to correct the measurement data for reporting to PSC, which was mostly eliminated by the 15% allowance.

The second part of the uncertainty is described by the standard deviation of the measurements. When comparing the results of repeated measurements, it was observed that in most cases the measurement

data correlated strongly ($R^2 = 0.84$) (Figure S12, upper). Furthermore, no strong relative effect is observed on the difference between both values, although the difference between two measurements is clearly smaller for lower NO_x values than for higher measurement values (Figure S12, lower).

The standard deviation u_{tot} can be calculated based on the intra reproducibility coefficient CV_{RW} and the sum of all additional supplementary uncertainty factors (u_{sup}) [62].

$$u_{tot} = \sqrt{(CV_{RW})^2 + \sum \left(u_{sup,i}\right)^2} \tag{16}$$

$$CV_{RW} = \frac{1}{\sqrt{2}} \sqrt{\frac{\sum_{i=1}^{n} \left(\frac{x_{i1} - x_{i2}}{0.5(x_{i1} + x_{i2})}\right)^2}{n}} \times 100(\%) \tag{17}$$

To calculate the standard deviation, three intra reproducibility coefficients have been calculated for three different ranges of NO_x emission values: 0-10 g NO_x/kWh, 10-20 g NO_x/kWh and ≥ 20 g NO_x/kWh. The CV_{RW} values are displayed in Table S.1.

The supplementary uncertainty factors are listed in Table S.2. For the reported indicated power, an uncertainty of 6.8% was used [63]; while for the provided fuel consumption, 10% was used [64], although this does not include an uncertainty due to human errors during reporting. Of the 43 contacted OGVs, 16% provided unreliable data, for which the standard SFC of 200 g/kWh was used. With the bias and total uncertainty values, the combined uncertainty was calculated for the three NO_x emission levels.

6.8. Compliance thresholds

As for FSC, a color flag system that was composed does not only incorporate the measurement uncertainty, but also reflects on the level of non-compliance [30]. The compliance threshold (T) was defined as the NO_x emission measurement value from which the OGV is considered to be non-compliant and would therefore be alerted to PSC authorities. The Threshold is reached as soon as the NO_x emission minus the measurement uncertainty is higher than the Tier limit (L) plus the NTE.

$$L_{Tier_i} + NTE = T - U_T \tag{18}$$

$$T = \frac{L_{Tier_i} + NTE}{1 - \sigma \times u_{to}} \times (1 + b) \tag{19}$$

6.8.1. Tier I and Tier II

The lowest alert level (the yellow flag color) uses a 68% confidence interval (CI), which is not to exceed the limit (NTE) of 15%, corresponding to the 15% margin of the NO_x Technical Code. The medium alert level (the orange flag color) uses a 95% CI with a NTE limit of 20% for Tier I. The red flag is used for high non-compliance alerts, with a CI of 99% and a NTE limit of 50%. The NTE levels for the orange and red flags are higher to take into account a tolerance level for the weighting factors.

6.8.2. Tier III

As no data yet exists for Tier III, the uncertainty for this measurement range could not yet be calculated. Nevertheless, it can be assumed that this would be comparable to the uncertainty of Tier I and Tier II. For the Yellow flag, a 50% NTE limit was used corresponding to the NTE limit of the NO_x Technical Code. For the Orange and Red flag, a NTE of 60% and respectively 65% was used to incorporate an additional tolerance due to the low emission limit and unknown uncertainty.

6.8.3. Operational thresholds

For operational use, the thresholds were further rounded up to 5 g NO_x/kWh for Tier I and Tier II and to 1 g NO_x /kWh for Tier III. Thus, it is convenient for the operators to create operational thresholds (T_{ops}) (Table 2) that are memorized and applied in flight. The determination of the initial $T_{ops\text{-}21}$ was based on test measurements from 2020. Although the initial uncertainties differed only slightly from the updated uncertainties, several T values decreased with the uncertainty calculation from the complete 2020-2021 data. Therefore, the $T_{ops\text{-}22}$ were lowered for the compliance monitoring operations from 2022 onwards.

Table 2. NO_x Color flag thresholds per Tier level.

Tier	L_{Tier}	Color flag	*NTE*	σ	T	$T_{ops\text{-}21}$	$T_{ops\text{-}22}$
Tier I*	17	Yellow	15%	1	21.2	25	25
		Orange	20%	1.96	31.8	35	35
		Red	50%	2.576	53.2	60	55
Tier II	14.4	Yellow	15%	1	17.9	20	20
		Orange	20%	1.96	26.9	30	30
		Red	50%	2.576	45.0	50	45
Tier III	3.4	Yellow	50%	1	5.4	7	6
		Orange	60%	1.96	7.5	9	8
		Red	65%	2.576	8.9	12	9

6.9. Compliance rate comparison

6.9.1. Temporal compliance comparison

The measurements were evaluated in flight according to the $T_{ops\text{-}21}$ thresholds. There are several different situations discussed below. In case a possible non-compliant OGV was observed, radio contact was established to retrieve the engine parameters to calculate the SFC and a second measurement was conducted. If no radio contact could be established due to pilot operations on board of the OGV, an SFC of 160 g/kWh was applied. In case, the data was unreliable (in 15% of the cases), an SFC of 200 g/kWh was applied. On the condition that the second measurement did not confirm the initial value, the lowest of the two values was used and the OGV was therefore not reported as non-compliant. In case the second measurement confirmed the first measurement, both values were reported. In the last situation that the two measurements were assigned with two different color flags, the lower of the two was used to avoid reporting false positive alerts.

In 2020, 16 OGVs were observed with NO_x emissions exceeding the operational thresholds ($T_{ops\text{-}22}$). But as the NECA was not active yet in 2020, the OGVs were not reported. In 2021, there were 43 possible non-compliant OGVs observed – among which, 23 were reported, while the other 20 concerned OGVs without Tier information at the moment of the measurement were not reported. The overall compliance rate was 95.9 % in 2020 (according $T_{ops\text{-}22}$) and 95.6% in 2021, with an overall compliance of 95.7 (Figure 6). No difference in compliance was observed between 2020 and 2021 ($P = 0.814$).

7. Compliance per Tier

When comparing the compliance rate between Tier levels, no difference in compliance was observed between Tier 0(I) and Tier I for 2020 ($P = 0.833$) and 2021 ($P = 0.702$). However, Tier II had a significantly higher non-compliance rate than Tier I for 2020 ($P = 0.000$) and 2021 ($P = 0.000$). Tier II was even found to have a significantly higher non-compliance rate than Tier 0(I) for 2021 ($P = 0.0102$), although this was not the case for 2020 ($P = 0.2035$). This finding confirms the significantly higher observed average NO_x emission for Tier II OGVs, which is in contradiction to the objectives of MARPOL Annex VI Regulation 13.

This does not necessarily mean that all Tier II OGVs on a global scale have a lower compliance rate compared to Tier I OGVs. But for the fleet composition and navigation parameters of the maritime traffic in the southern North Sea area, this seems to be the case. It is clear that the lower compliance rate for Tier II OGVs in the southern North Sea must be tackled to ensure the effective implementation of the emission reduction regulations and to reduce the impact of air pollution from the maritime sector for the North Sea coastal communities.

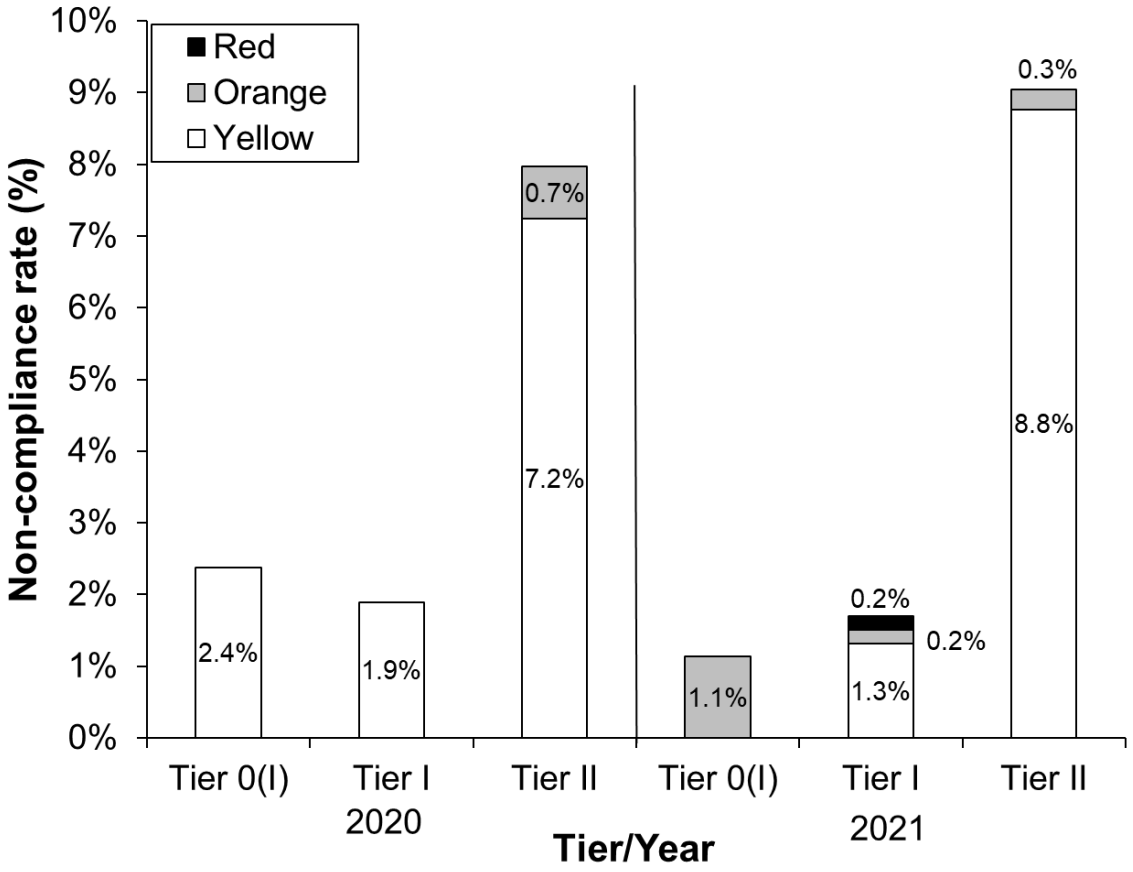


Figure 6. Compliance levels according to $T_{ops\text{-}22}$ per Tier per year.

It must be noted that the use of rounded thresholds (T_{ops}) for operational reasons inevitably results in false negatives. In total, 103 OGVs had a NO_x emission between T and T_{ops} (7%). As no confirmation measurements were made for these OGVs, the exact number of false negatives could not be established. To estimate the number of potential false negatives, the NO_x emission values were recalculated with an SFC of 160 g NO_x/kWh. Based on this SFC, the number of potential false positives was only 7 OGVs (or 0.5%). Hence the number of potential non-compliant OGVs that were not reported to PSC was fairly limited. In addition, this number is largely insignificant compared to the operational advantage of using rounded T_{ops} values. Furthermore, this shows the importance of obtaining the actual SFC value for the NO_x compliance monitoring. By using the higher-end SFC value of 200 g/kWh for the initial measurement, more false positives can be avoided than by using the unrounded T values.

7.1.1. Compliance per OGV type

Based on the AIS OGV type category, the only OGV types that were observed to be non-compliant were tankers and cargo OGVs. Figure S.13 illustrates that overall a higher non-compliance rate was observed for cargo OGVs (10.1%) compared to tankers (3.5%) and this difference was found to be significant ($P = 0.0155$). By comparing compliance rate per detailed vessel type, it was observed that

container OGVs had a significantly higher non-compliance compared to all other types ($P < 0.05$), while no significant difference was observed in compliance between the other types of cargo vessels ($P > 0.05$).

When comparing the compliance rate between cargo vessels and tankers per tier, only a significant difference was observed for Tier II ($P = 0.0187$). For Tier 0(I) and Tier I OGVs, the difference in compliance is not significant ($P = 0.06$). However, when comparing the compliance rate between Tiers per vessel type, Tier II OGVs for both cargo and tanker OGVs have a significant higher non-compliance rate ($P < 0.001$ for cargo and $P = 0.0092$ for tanker), indicating that the higher Tier II emissions are not restricted to one OGV type.

7.1.2. Engine rated speed

As compliance levels were based on an evaluation according to the NO_x emission limits for OGVs with an ERS < 130 rpm, some OGVs with higher rpms were possibly wrongfully considered to be compliant (false negative). Therefore, a set of thresholds was defined for OGVs with an ERS of 500 rpm (Table S3).

To evaluate the number of possible false negatives, the OGVs were identified as exceeding the 500 rpm thresholds ($T_{ops\text{-}5}$) but were classified as compliant. This concerned 201 OGVs and for those, the actual ERS was looked up. The OGVs with an ERS between 130 and 500 rpm were very close to 130 rpm (146,160 and 167 rpm). For these OGVs, the NO_x limit is not much different, and applying the exact NO_x limit would not have resulted in a different evaluation. For the OGVs with and ERS ≥ 500 rpm, it was assessed if these could be potential false negatives. According to the procedures for alerts without radio contact, an SFC of 160 g/kWh was applied and the NO_x emission values were recalculated. After this correction, only one of the OGVs with an ERS ≥ 500 rpm was found to exceed the $T_{ops\text{-}5}$, a Tier II (dredger) OGV with a NO_x emission of 17.1 g NO_x / kWh.

In addition, for the OGVs with an ERS of 600 and 700 rpm, an ERS specific threshold rounded up to 5 g NO_x/kWh ($T_{OPS\text{-}ERS}$) was calculated. Based on these thresholds, the OGV with an ERS of 750 rpm (a Tier I chemical tanker) would have exceeded its specific threshold (19.1 g NO_x/kWh). This means that in total 2 potential OGVs (or 0.15%) were wrongfully assigned as negative due to not incorporating the lower emission limits for higher ERS and applying a rounded threshold level (Table S4). In addition to the 201 OGVs searched for the determination of the potential false negatives, ERS data was acquired for 157 additional OGVs. Of this total of 358 OGVs, 16% had an ERS > 130 rpm and 11% had an ERS > 500 rpm. It was observed that higher ERS values were mainly observed for OGVs with a length < 200 m, 25% of the OGVs with a length < 200 m had a ERS > 130 (Table S3). When looking only at OGVs with a length > 200 m, the amount of OGVs with an ERS > 130 rpm was reduced to 4%. It was observed that the OGV type played the most important role as indicator for higher ERS values, with ROROs, dredgers, cruise liners and gas tankers having a higher likelihood to have an ERS > 130 rpm (on average 54%) compared to general cargo (29%), tankers (15%), containers (5%) and bulk carriers (4%) ($P < 0.001$).

When assessing the Tier level, it was observed that the amount of OGVs with an ERS > 130 was significantly higher for Tier0(I) (30%) and Tier I (25%), compared to Tier II OGVs (10%) ($P = 0.001$). The same effect was observed for ERS > 500 rpm ($P = 0.001$). When the data are restricted to OGVs > 200m, the number of Tier II OGVs with an ERS > 130 rpm (2%) are no longer significantly lower than for Tier I OGVs (4%) ($P = 0.0518$). As the OGV type appeared to be a decisive factor, the fleet compositions of the Tier I and Tier II subsets were further examined, which showed a very comparable amount of OGV types. On average, the amount of OGVs with an ERS < 130 RPM was rather comparable between Tier I and Tier II, with 85% for Tier I and with 87% slightly higher for Tier II.

However, when looking only at container and tanker OGVs, Tier II OGVs were found to have a significantly higher amount of OGVs with an ERS < 130 rpm ($P = 0.001$). Hereafter, based on this dataset, it can be concluded that container and tanker Tier II OGVs have a significantly higher amount of OGVs with an ERS < 130, which further indicates that the intentional downrating of the main engine may be used as strategy to increase the emission limits for Tier II OGVs.

Consequently, it can be concluded that the inclusion of specific thresholds according to the ERS in the SOPs would not result in a significant higher number of observed non-compliant OGVs. Nevertheless, due to the higher ERS that were mainly found with passenger OGVs and RORO OGVs, it was decided to use the $T_{Ops\text{-}5}$ for all ROROs, ferries, passenger OGVs < 200 m as the threshold for the initial measurement. In addition, the ERS will be requested during the radio communication, together with the correct SFC, which can reduce the potential number of false negatives, without too much additional workload for the operators in flight.

7.1.3. Off cycle engine load

As no limits are available for engine load below 25%, it is important to avoid reporting OGVs with engine loads under 25% as these OGVs are considered to be "off cycle". Based on the reported engine power and the available total indicated power, it was observed that relatively more OGVs were classified as non-compliant with low engine loads. The amount of compliant OGVs increased with the engine loads, for the engine loads $> 75\%$ almost all OGVs were classified as compliant (97%). When comparing the compliance rate for OGVs with engine loads $< 50\%$ with OGVs with engine loads $> 50\%$, a significant lower compliance rate was observed for OGVs sailing at low engine loads ($P = 0.0241$).

For the engine load $< 25\%$, technically there are no limits in place. Nevertheless 3 OGVs with an engine load $< 25\%$ were observed to be over the lowest reporting threshold. As their speed was just over 10 kts, these OGVs were not withheld and reported to the PSC, which can therefore be considered as possible false positives. To avoid reporting false positives as of 2022, the engine load will be requested during the radio communication. If no communication is established, a calculated load will be used based on the propeller law (see sect. 3.4). In addition, as of 2022, a threshold speed of 8 kts, on the one hand, will be used for RORO and passenger OGVs; on the other hand, a threshold speed of 12 kts will be used for cargo and tanker OGVs. It is also worth noting that only red and orange flag color alerts will be reported for OGVs sailing at lower speeds.

7.2. Geospatial analysis

7.2.1. NO_x emissions in North Sea between 2020 and 2021

When looking at the difference in NO_2 between 2020 and 2021 based on the TROPOMI Sentinel 5 data, it was found that the NO_2 emissions over land were substantially lower in 2020 compared to 2021. The difference was most profound in densely populated areas like Belgium, the northern part of France, the eastern side of Germany the southern part of the Netherlands and the central and southern part of the United Kingdom (Figure 7). The lower levels of NO_2 over land in 2020 compared to 2021 can largely be attributed to the public measures to control the Covid19 pandemic in 2020. These lower emission levels for NO_2 in 2020 were also observed for other areas [65]. However when looking at the shipping lanes in the North Sea, the Mediterranean Sea and the Atlantic Ocean, these lower NO_2 emission for 2020 were much less profound. In fact for the northern part of the North Sea the emissions actually decreased noticeably between 2020 and 2021. It remains unclear if this reduction in NO_2 between 2020 and 2021 is significant and can be attributed to the implementation of the NECA in 2021 or if other factors play a role as well.

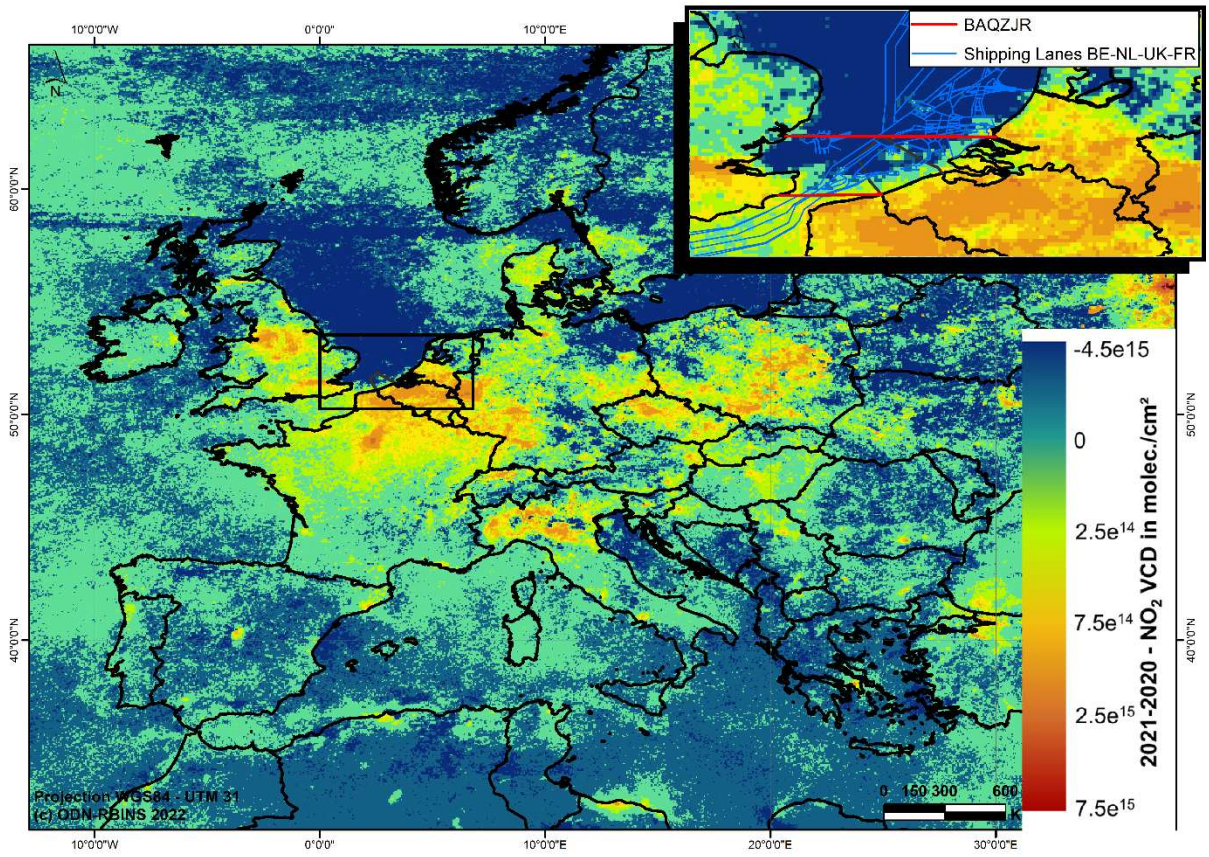


Figure 7. Difference between the annual average observed NO_2 in 2021 and the annual average observed NO_2 in 2020 (in molecules/cm^2 VCD) from TROPOMI Sentinel 5 (based on data provided by BIRA).

7.2.2. Spatial distribution compliance

The map in Figure 8 visualizes all monitored ships according to the flag color. When assessing the non-compliant OGVs on a geospatial basis, no clear patterns can be observed at first sight, although more red flags were observed in the inland Westerschelde estuary and the Westhinder Traffic Separation Scheme (WHTSS) in and nearby coastal waters. In the North Hinder Traffic Separation Scheme (NHTSS) further offshore, no red flags were observed. This could possibly be explained by the fact that on average OGVs have a higher speed in the NHTSS and consequently also have a higher engine load with a resulting lower NO_x emission, further confirming the impact of the higher NO_x emissions for the lower engine loads for Tier II.

The surveillance area was divided in 5 sub areas: NHTSS, WHTSS, Rotterdam area, Inter Rotterdam-WHTSS and Westerschelde. The average NO_x emission was compared between these areas but were not found to be significantly different ($P = 0.6498$). When comparing the NO_x emission distributions per Tier level for the different sub-areas, Tier II was found to be significantly different from Tier I for the WHTSS ($P < 0.005$) and the NHTSS ($P < 0.001$). However, for the other areas, no significant difference was observed, although for these other zones, only a limited number of observations per Tier were available. (Figure S14)

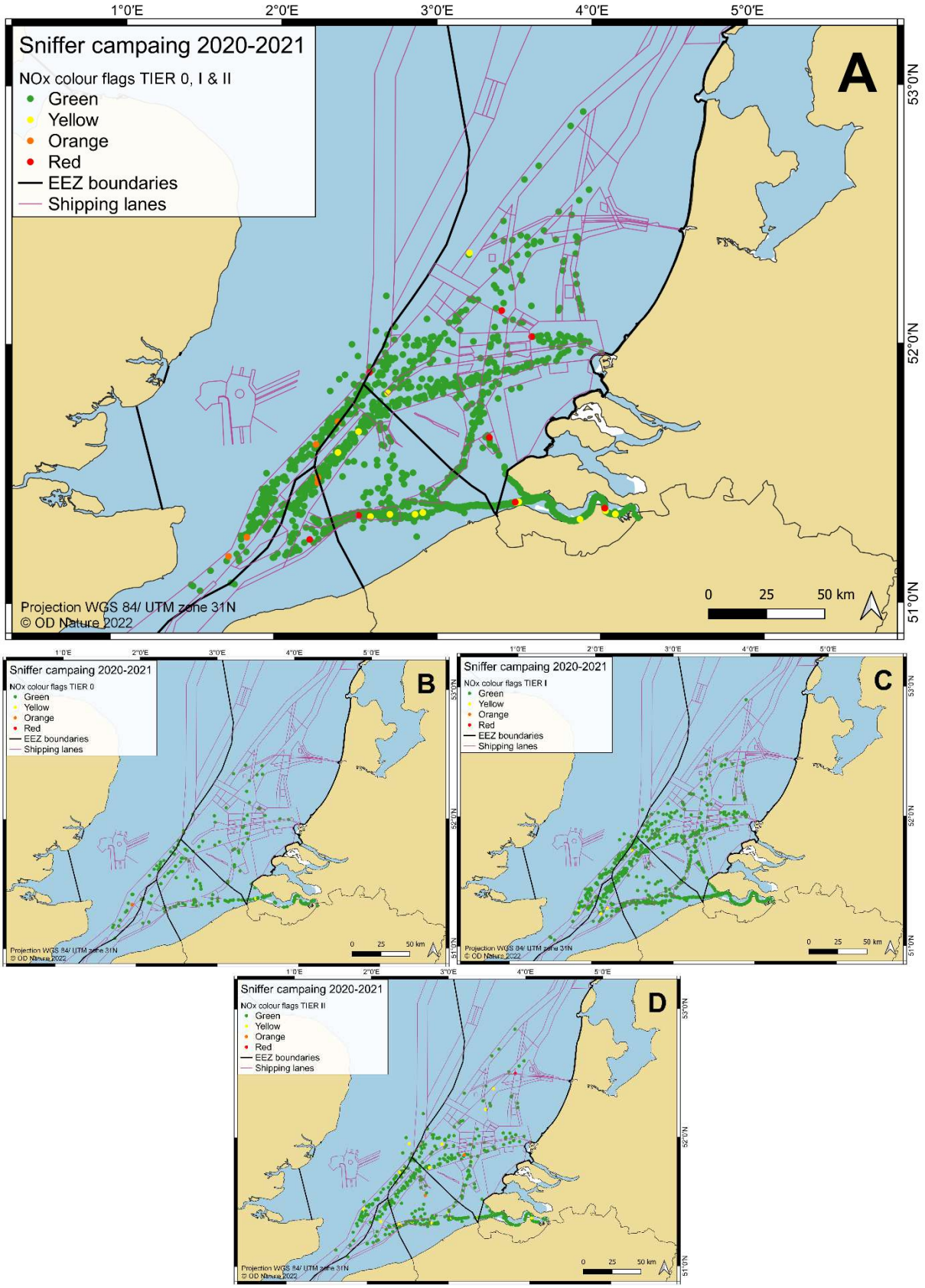


Figure 8. Geographical visualization of the monitored OGVs with the NO_x color flags, for all Tiers (A), Tier 0(I) OGVs (B), Tier I OGVs (C) and Tier II OGVs (D).

For the inland Westerschelde area the NO_x emissions from OGVs have the most drastic impact on human health. The average observed NO_x emission in this zone is higher (13.34 g/kWh) than the other areas (12.9 g/kWh), although not statistically significant ($P > 0.1$).

When comparing the compliance rate per zone, a higher non-compliance rate was observed for the WHTSS, but this was not found to be significant. When examining the Tier level of the non-compliant vessels, the higher non-compliance level for Tier II is again clear and present for all areas. For the WHTSS and NHTSS, this was even found to be significant ($P = 0.005$ and $P = 0.001$); while for the other areas, the number of Tier II observations was too low to compare the frequencies (Figure S15).

8. Conclusion

The enforcement of NO_x emission regulations in seaports is limited to documentary inspections. In this paper, it is demonstrated that the airborne sniffer monitoring methodology based on compliance thresholds for NO_x emission measurements in an operational setup is scientifically proven and reliable. The methodology thus provides opportunities for the enforcement of real-life NO_x emissions from OGVs on the sea. The sniffer sensor system on board of the Belgian coastguard aircraft was modified and extended to include the NO_x sensor. The measurement quality on spatial and temporal level is assured based on the Sniffer Quality Management System that has been set up with Standard Operational Procedures. For every Tier level, specific thresholds have been defined taking into account (i) the measurement uncertainty; (iii) the confidence interval, and (ii) a tolerance for the effect of the weighted average.

Analysis of TROPOMI Satellite data showed a notable reduction of NO_2 levels in the northern part of the North Sea in 2021 compared to 2020. Although this reduction coincides with the introduction of the NECA, It is however still unclear if this reduction is directly related to the NECA implementation as laid down by MARPOL Annex VI Regulation 13.

During the timeframe of the operations (2020-2021), NO_x emissions of 1407 OGVs were successfully measured with an average NO_x emission of 13 g/kWh. The average NO_x emission factors are not significantly different between 2020 and 2021, thus demonstrating that shipowners did not notably change their behavior since the entry into force of the North Sea NECA in 2021. In 2020, although 16 OGVs were observed with NO_x emissions exceeding the operational thresholds, those OGVs were not reported, due to the fact that the NECA was not active yet in 2020. In 2021, 43 possible non-compliant OGVs were observed, of which 23 OGVs were reported, with the overall compliance rate: 95.7%.

NO_x pollution from OGVs is considered as an import factor for human health in Belgium and neighboring countries, due to the high shipping density in the North Sea, the close proximity of the shipping lanes and the already high anthropogenic NO_x pollution. Unfortunately, the monitoring operations demonstrate that the standards for Tier II OGVs, as described in MARPOL Annex VI Regulation 13, miss their target in reducing the NO_x emissions from OGVs. The predetermined emission reductions from OGVs are, at least for the Southern North Sea, not realized.

When comparing the average NO_x emission per Tier, it was assumed that Tier II OGVs would have a lower NO_x emission than Tier I OGVs as the NO_x emission limit for Tier II OGVs is lower than for Tier I. However, it was noted that the average NO_x emissions for Tier II OGVs was significantly higher than the average NO_x emissions for Tier I. Furthermore, Tier II OGVs were not only observed to have a higher average NO_x emission, but were also often found to be non-compliant significantly.

Engine manufacturers design their Tier II engine to optimize fuel efficiency. As fuel efficiency conflicts with NO_x emissions reduction, a trade-off needs to be made. The use of weighting factors per engine

load creates an opportunity to reduce fuel consumption and still be on average compliant to the NO_x emissions limits. Engine manufacturers are able to design engines in such way that NO_x emissions in lower loads are higher than the higher loads, nevertheless the overall weighted average NO_x emission approaches the limit for optimizing fuel consumption. For engine loads below 25%, no limits are even defined by MARPOL Annex VI Regulation 13. As a result, although consuming less fuel, Tier II OGVs may emit more NO_x, which is especially the case for engine loads of 25 and 50% that occur in the maritime traffic in the Southern North Sea. An improvement of the NO_x emission reduction impact of the standards could be achieved by defining NTE limits for Tier I and Tier II, applicable for the whole engine load spectrum like for Tier III.

The definition of emission limits according to the age of the OGV is the backbone of MARPOL Annex VI Regulation 13. Unfortunately, by applying the KLY instead of the year built in the regulations, a gap in the regulations is exploited, as many OGVs have been built since 2021, but yet have a KLY before 2021. Therefore, the effective favorable impact of Tier III standards in the field, and thus on the environment and public health, will be delayed by several years. This is demonstrated by the fact that only 13% of the OGVs with a length >70 m and a Gross Tonnage >5000 GT with a built year in 2021 had a KLY in 2021. The use of this regulatory gap, resulted in an estimated 29000 premature deaths in 2021, these premature deaths could have been avoided if Tier III standards would have been applied for all OGVs built in 2021, a figure which is expected to rise substantially in the following years.

Last but not least, the ERS plays an import aspect in MARPOL Annex VI Regulation 13. For the vast majority of the observed OGVs, the ERS is lower than 130 rpm, which allows the use of (higher) linear values resulting in higher NO_x emissions. Tier II OGVs have been found to be significantly more often rated at an ERS <130 rpm, which take advantage of the highest NO_x emission limit. Nevertheless, for ROROs, passenger OGVs and OGVs <200 m, there is a higher probability for ERS above 130 rpm. The compilation of an additional ERS dataset could further improve the monitoring methodology and lower the number of false negatives.

The airborne monitoring dataset is available on: https://doi.org/10.24417/bmdc.be:dataset:2687

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10. Supplementary figures and tables

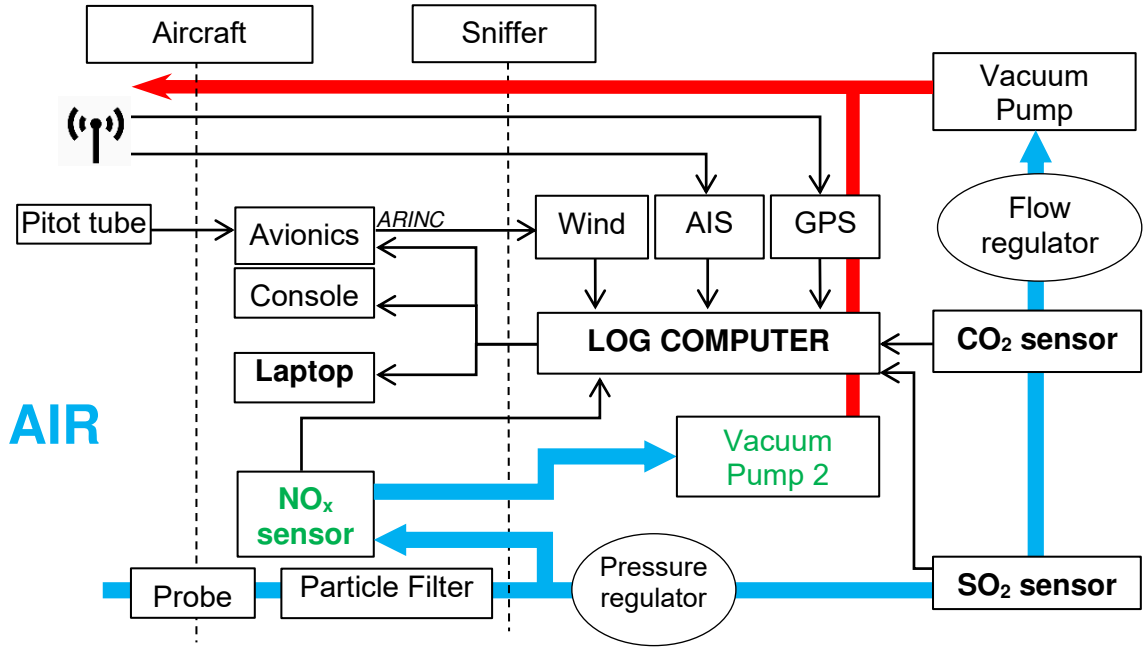


Figure S. 1. Schematic presentation of the sniffer sensor system with the NOx sensor

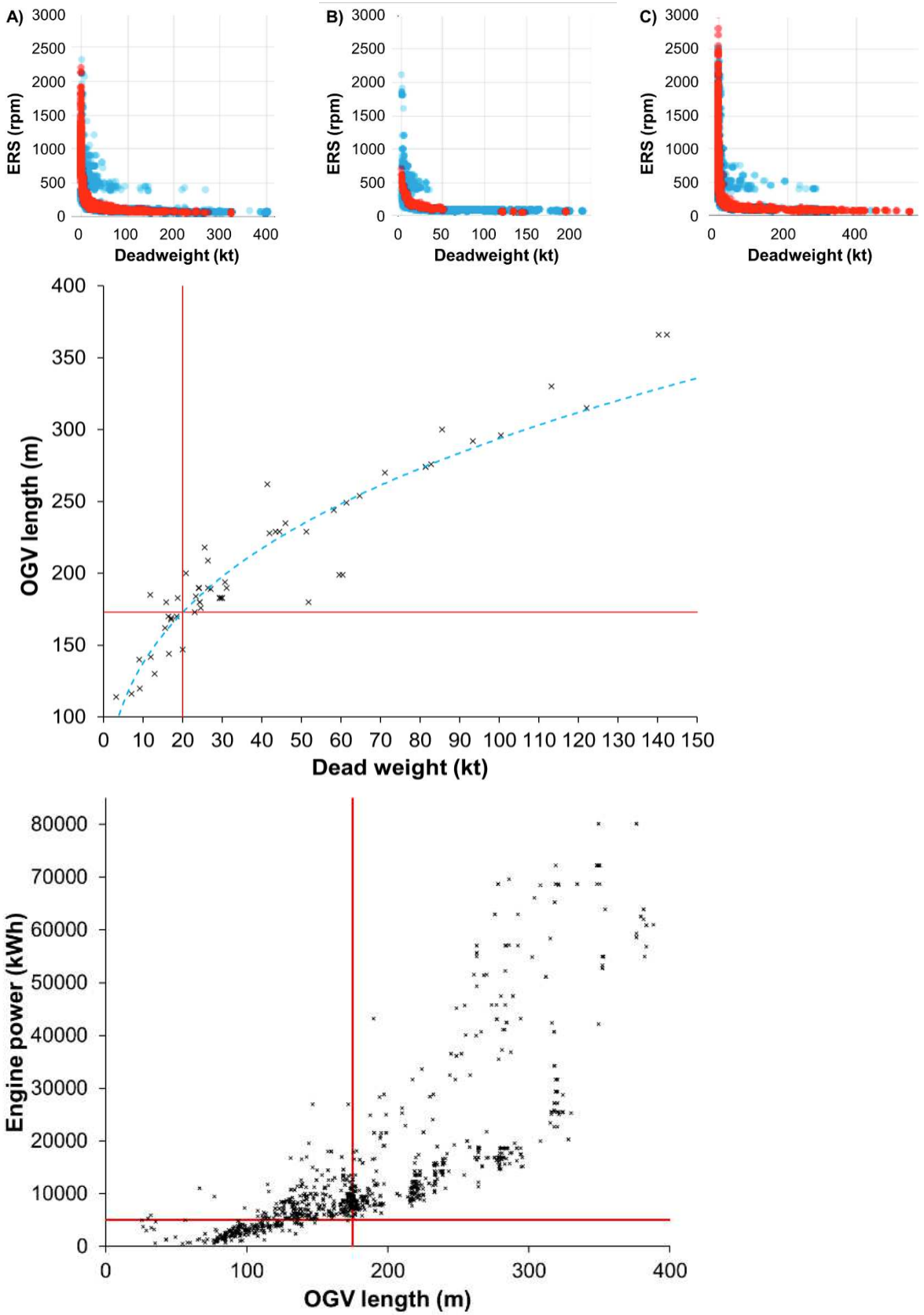


Figure S.2. Upper: ERS (rpm) related to Dead Weight for bulk carriers (A), containers (B) and oil tankers (C) [42]. Middle: Dead Weight (kt) versus OGV length, based on cross linking the airborne monitoring dataset with the Belgian and Netherlands PSC dataset. Lower: Length versus power output based on data from GISIS online dataset (IMO, 2020b)

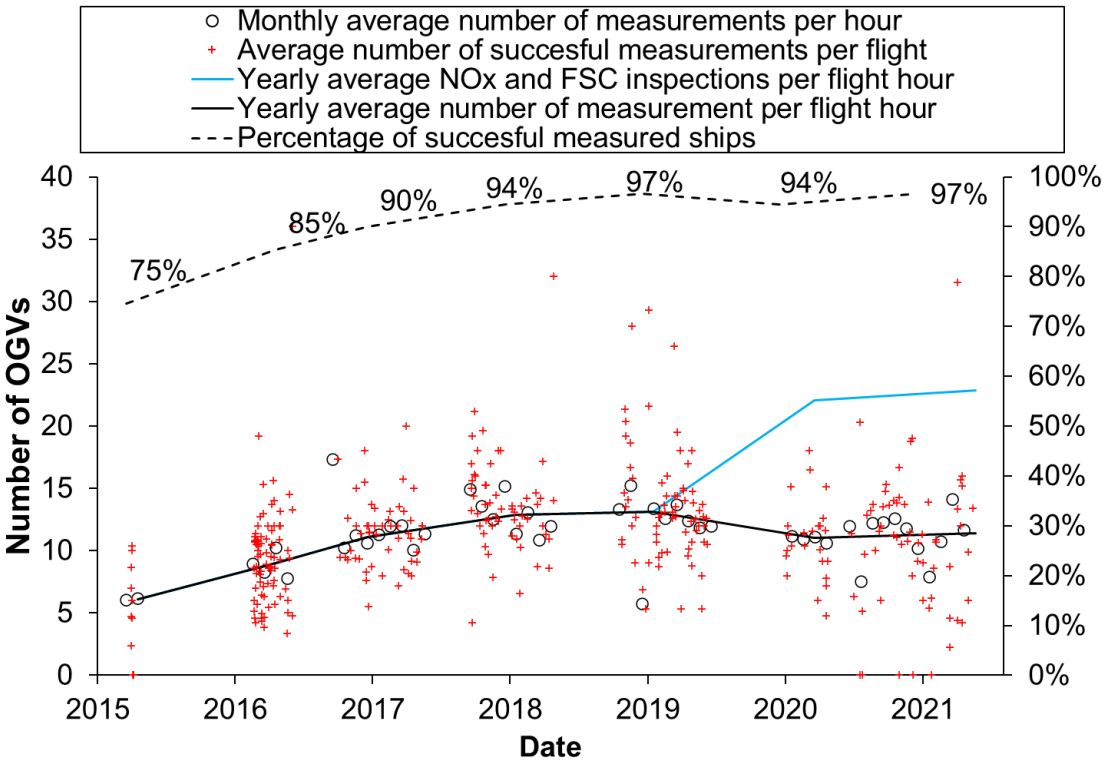


Figure S.3. Evolution of the number of successfully measured OGVs from 2015 until 2021.

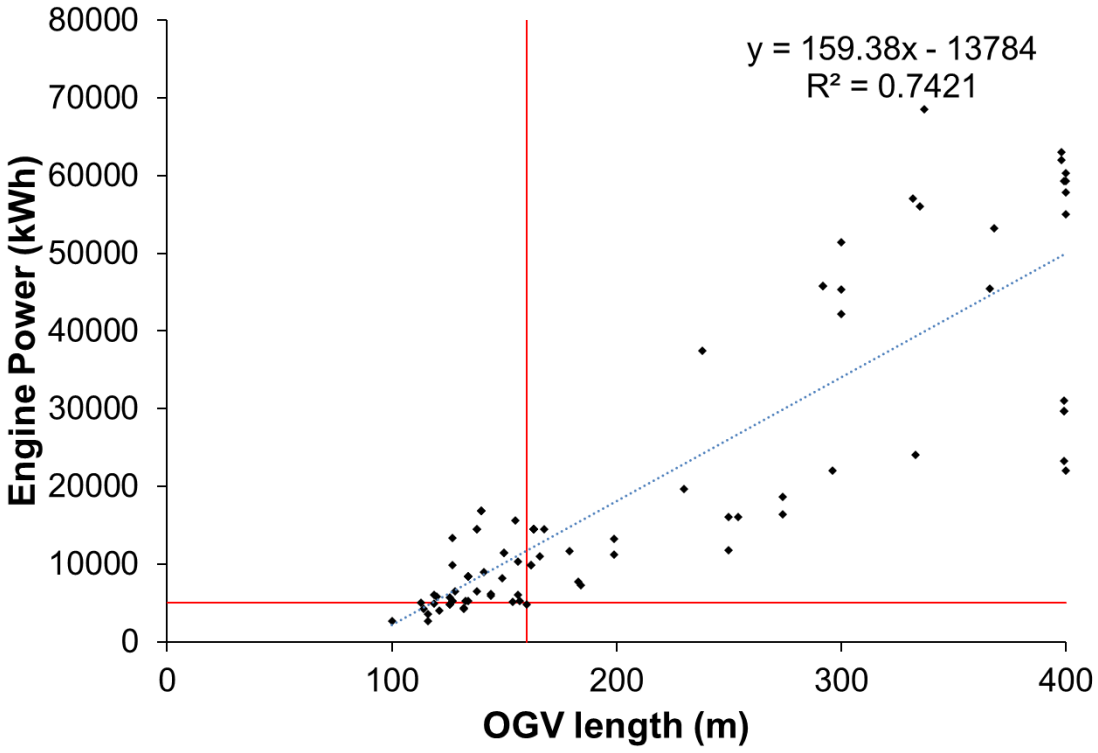


Figure S.4. OGV length (m) versus total engine power (kWh).

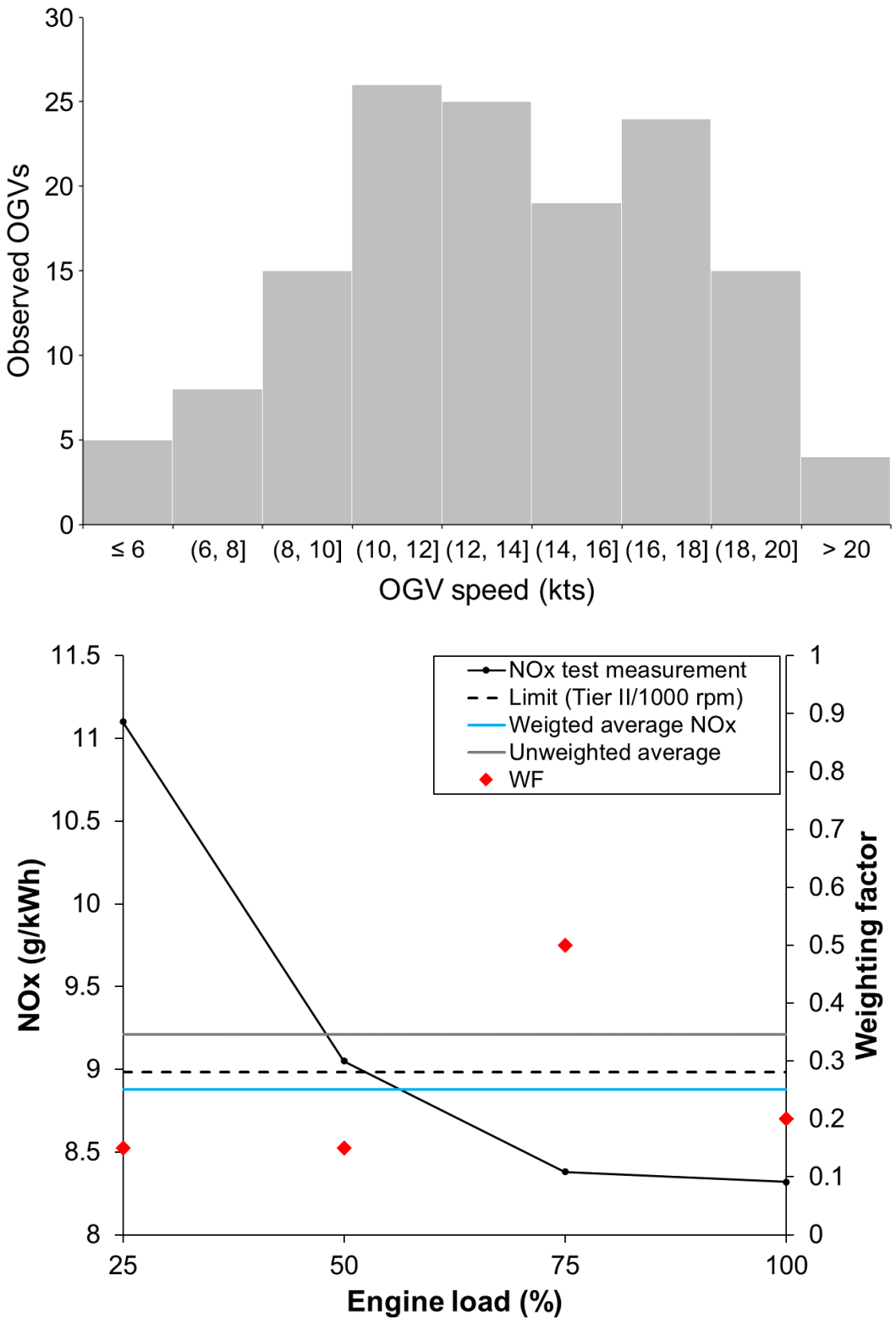


Figure S.5. Upper: Overage observed sailing speed for container OGVs in the North Hinder Traffic Separation Scheme (NHTSS) for the period 2020-2021. Lower: Results from a measurement test cycle (E2) for a Tier II engine of 1945 kW with an ERS of 1000 rpm. The emission limit is 8.98 g NO_x/kWh (black dotted line). The weighted average (blue line) with weighting factors (WF) gives an emission of 8.87 g NOx/kWh, whereas the unweighted average is 9.21 g NO_x/kWh.

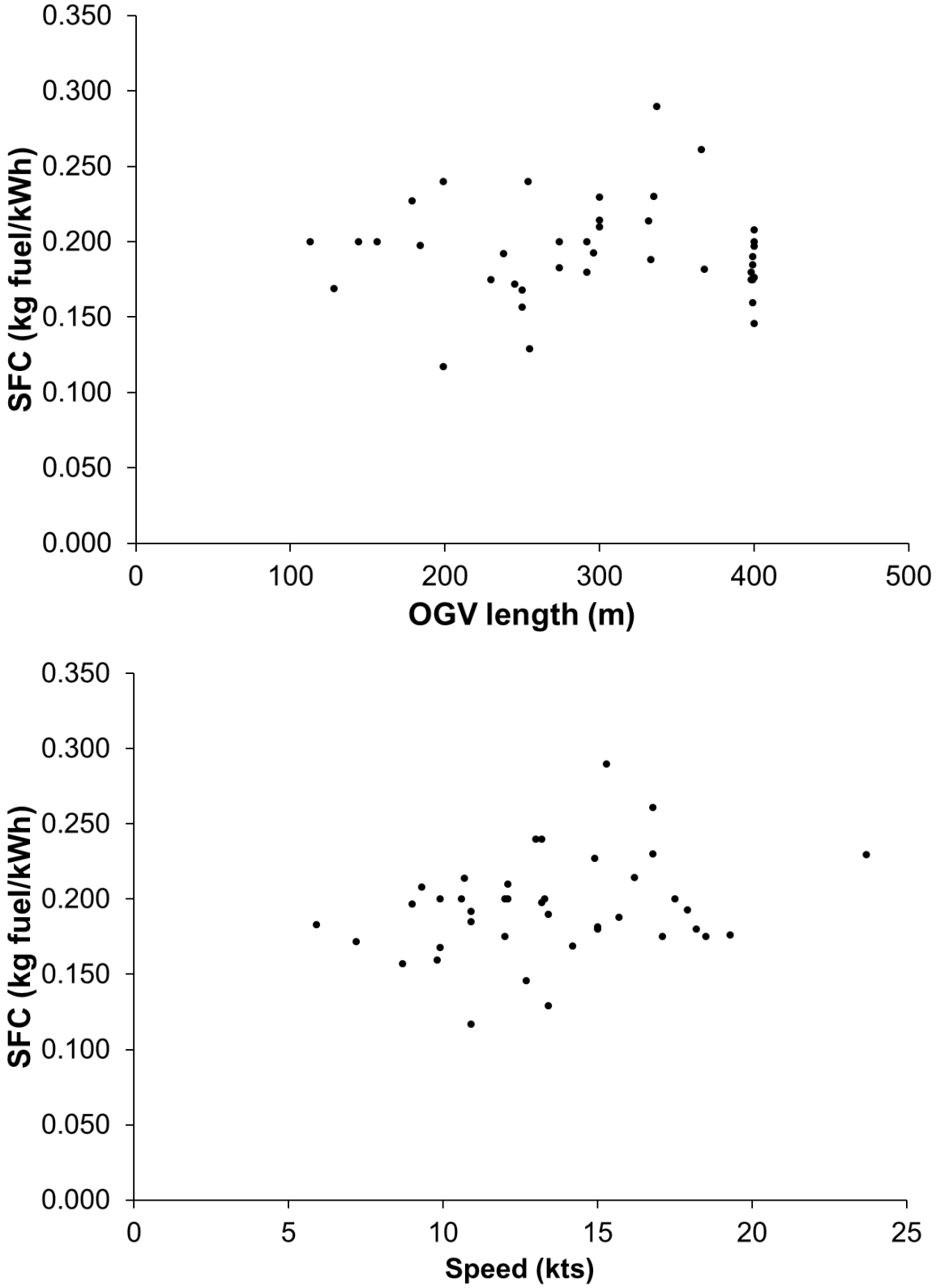


Figure S.6. Upper: SFC obtained through marine VHF radio communication compared to the OGV length (m). Lower: SFC obtained through marine VHF radio communication compared to the OGV speed on ground (kts).

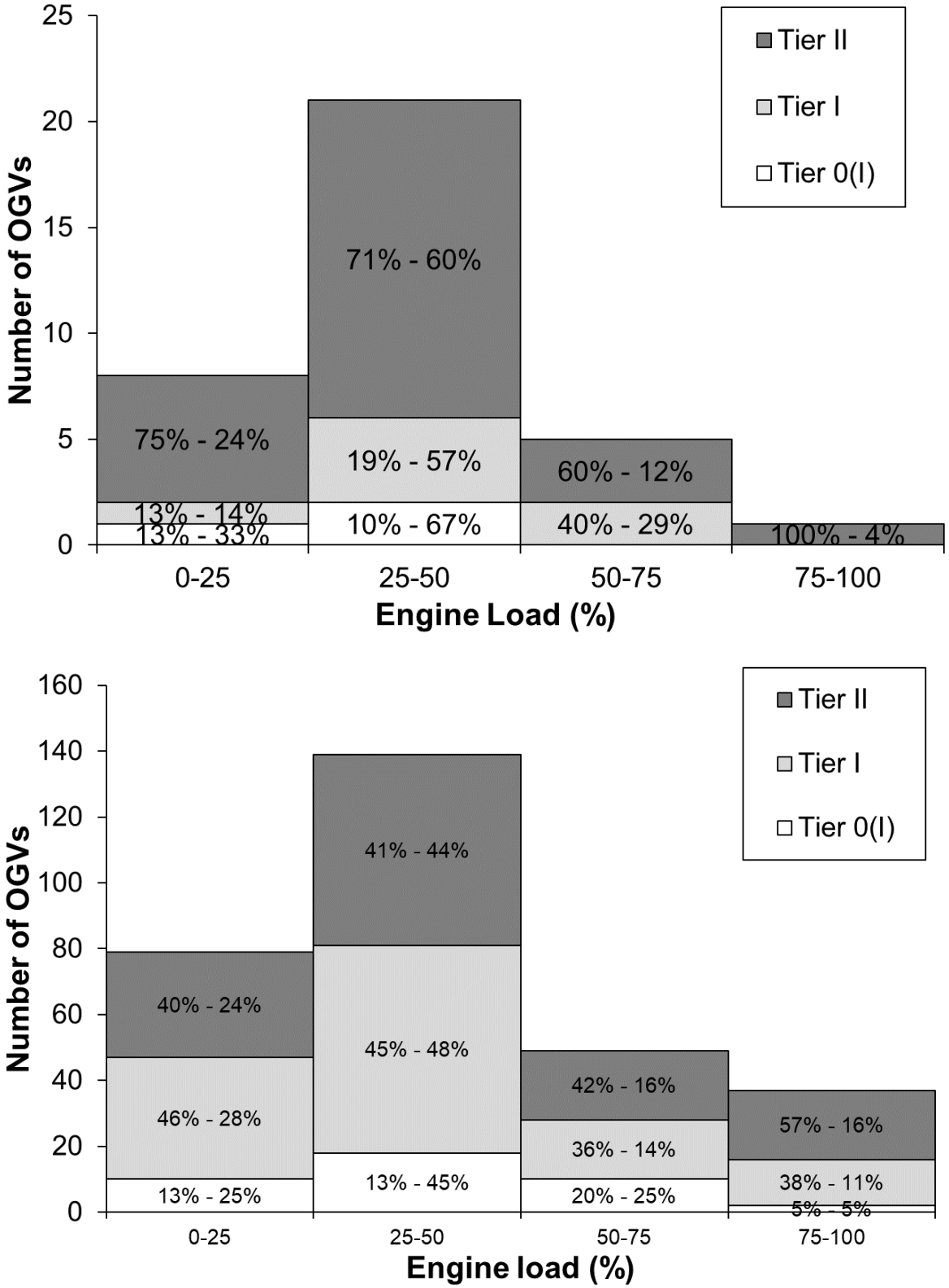


Figure S.7. Upper: Engine load histogram based on the actual engine loads. Lower: Histogram based on calculated engine loads. The first percentage is the relative amount of a Tier level per engine load, the second percentage provides the relative amount of each engine load per Tier.

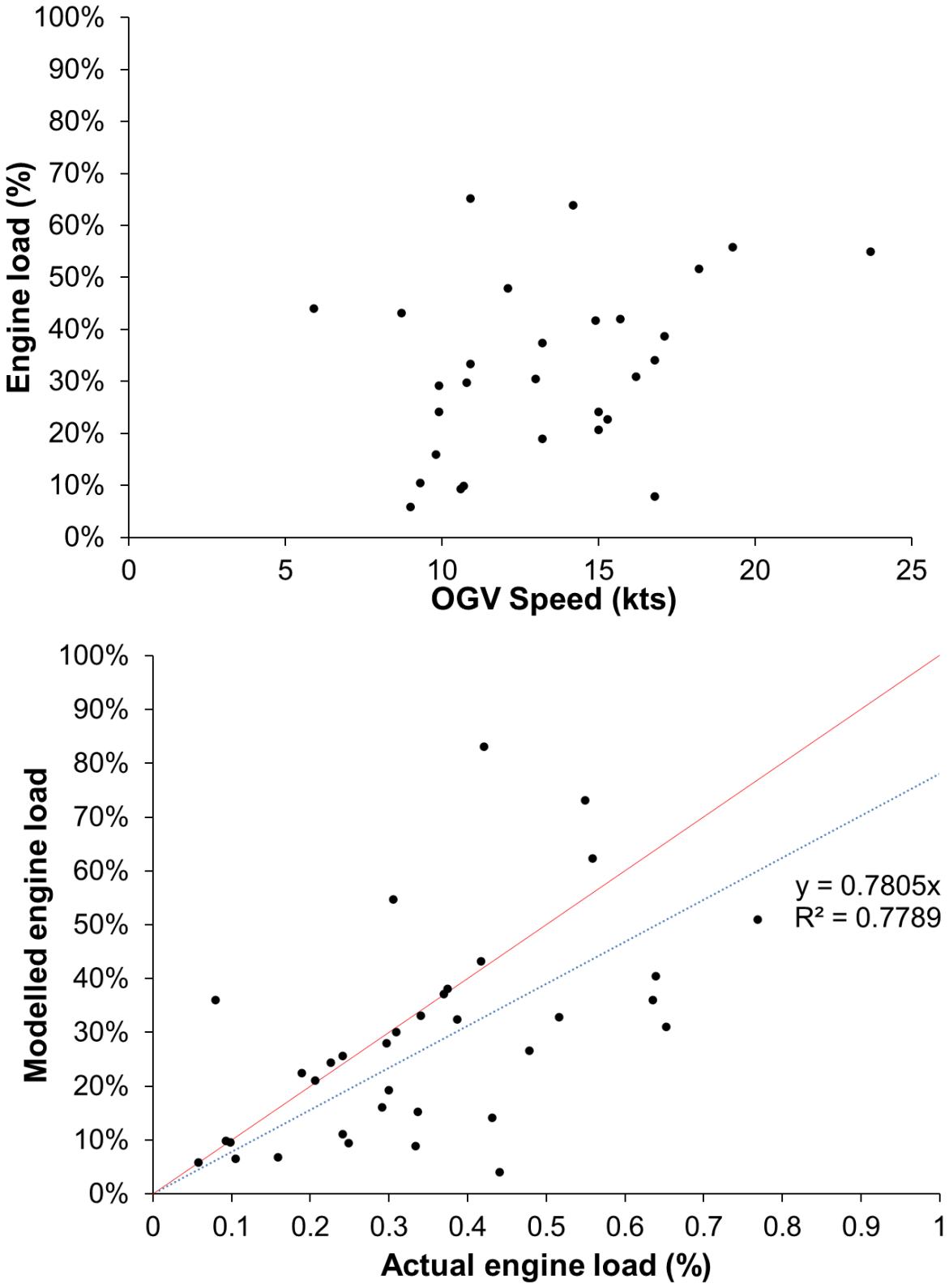


Figure S.8. Upper: Engine load compared to the OGV speed. Lower: Modelled load versus the actual load shows can be used to calculate the CF.

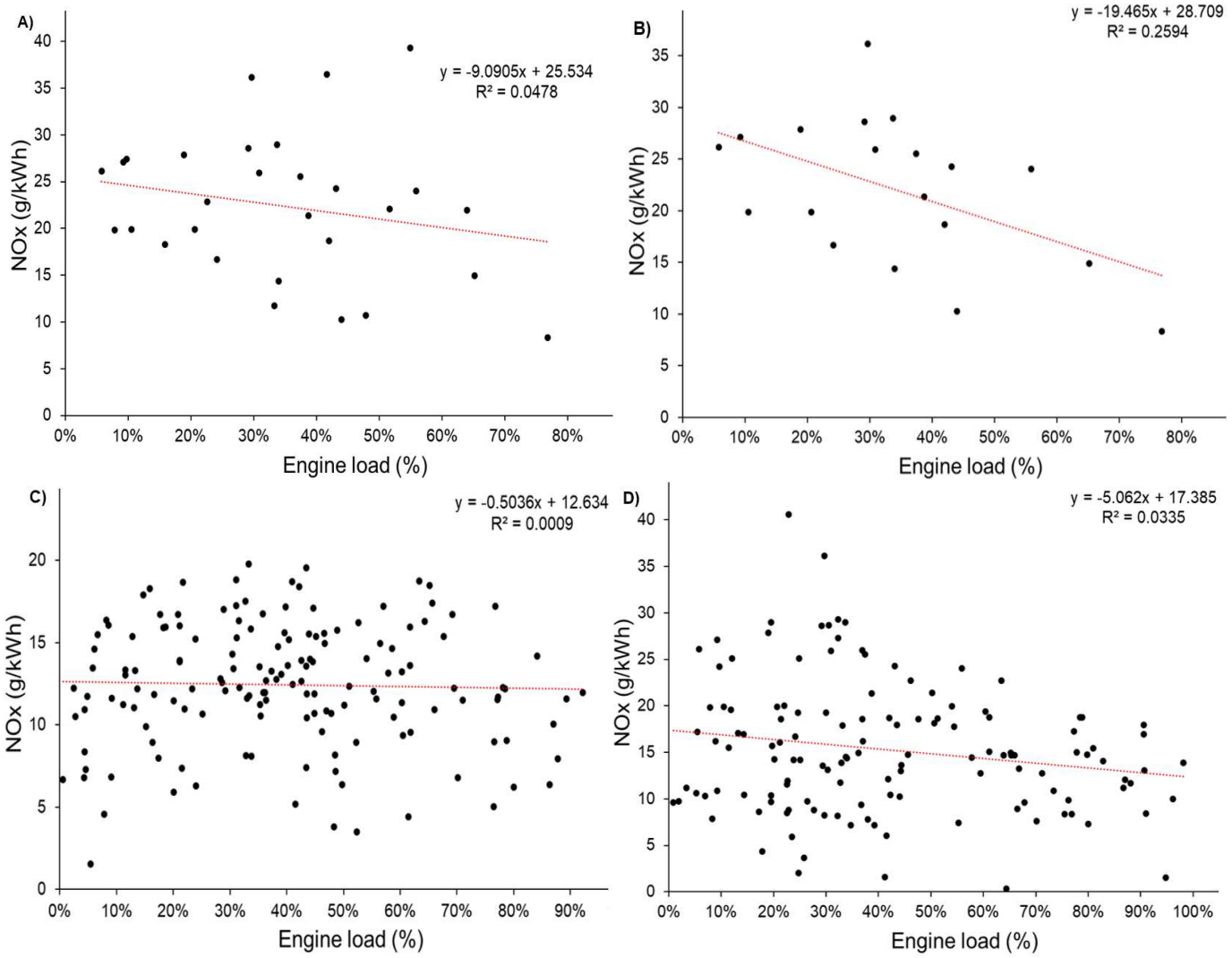


Figure S.9. Engine loads in function of NO_x emissions for A) all Tiers based on actual engine loads; B) for Tier II based on actual engine loads; C) for Tier 0, Tier 0(I) and Tier I, based on modelled engine loads; D) for Tier II based on modelled engine loads.

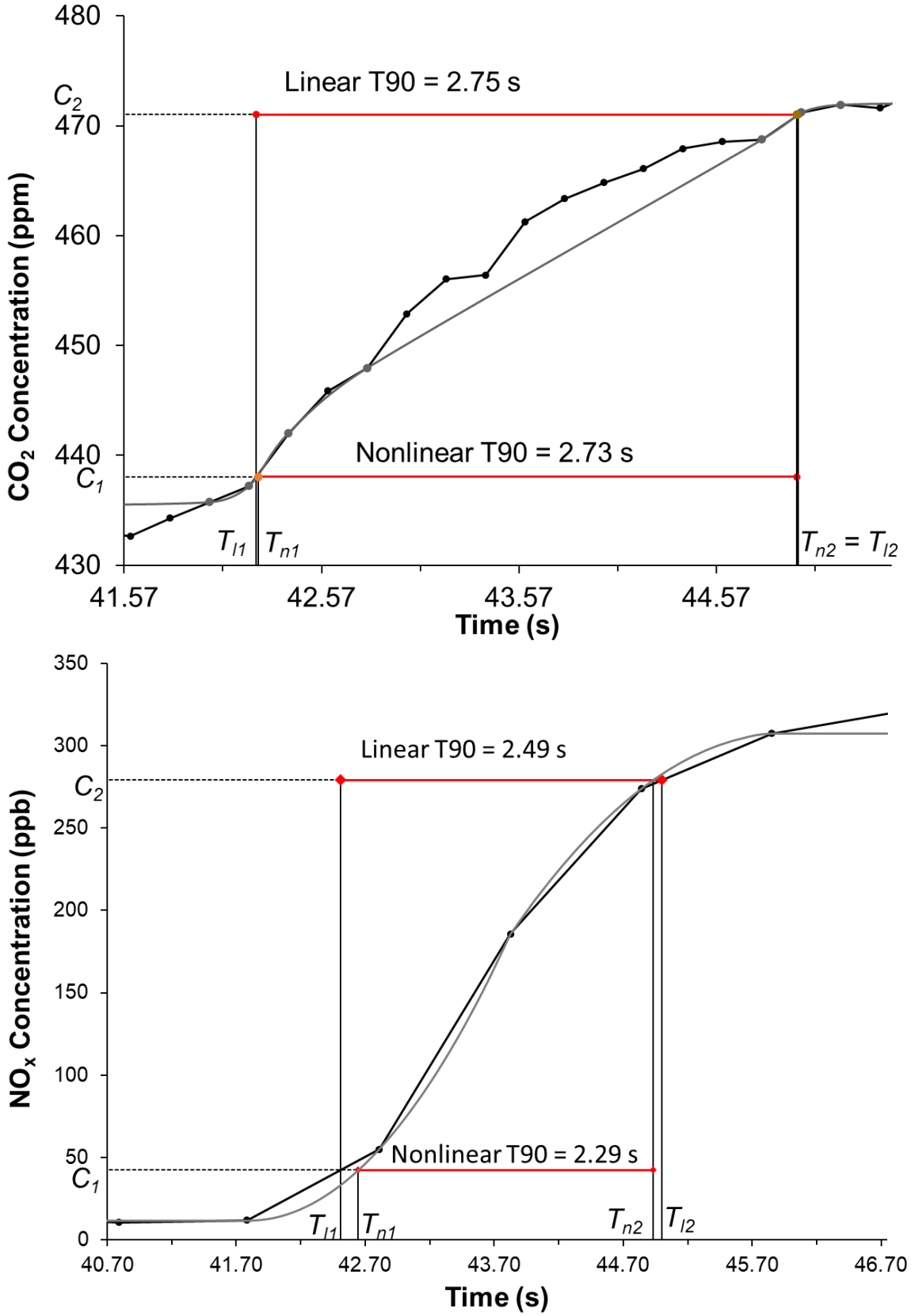


Figure S.10. Upper: T90 response time for medium concentration differences for the Licor 7200RS sensor (CO_2) Lower: T90 response time for medium concentration differences for the Ecotech Serinus (NO_x). C_1 and C_2 concentration are defined as the 10% and 90% concentration, corresponding times were calculated, using linear (T_{li}) and nonlinear interpolation (T_{nli}) on the points before and after of the C_i points.

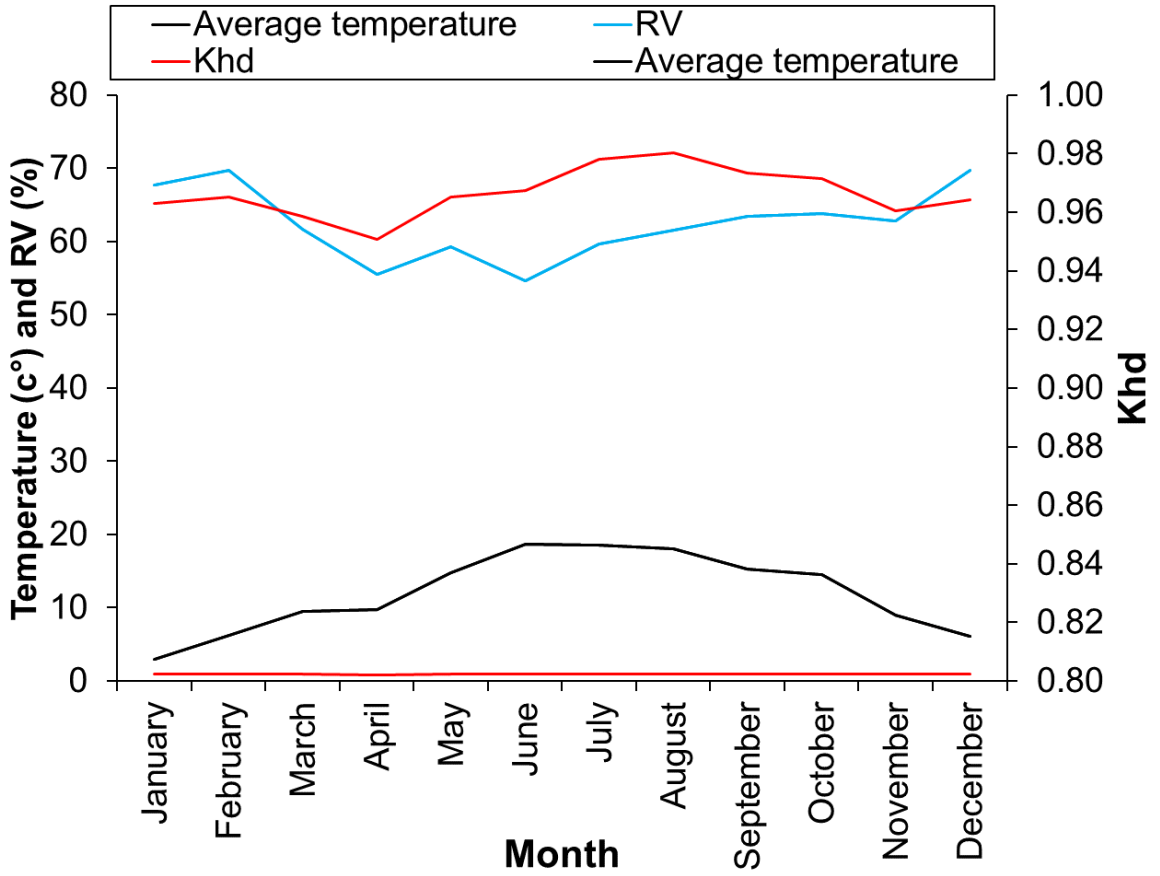


Figure S.11. Monthly temperature and humidity correction (khd) for the Belgian North Sea [66].

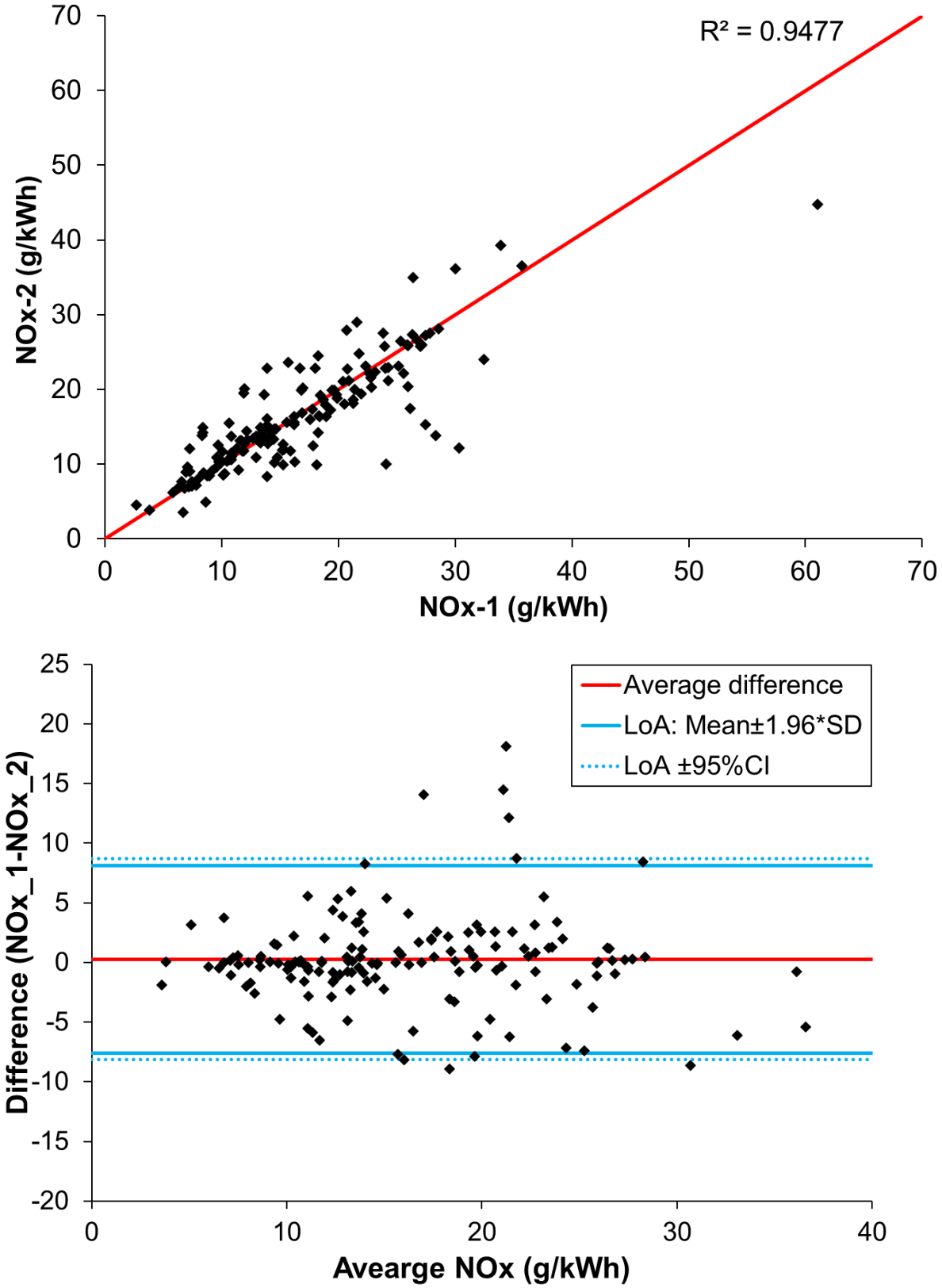


Figure S.12. Upper: regression between two repeated measurements showing a very high correlation. Lower: Limits of Agreement (LoA) graph, shows that the large majority of the measurements falls within the LoA, although for some repeated measurements large differences have been observed that fall outside the LoA.

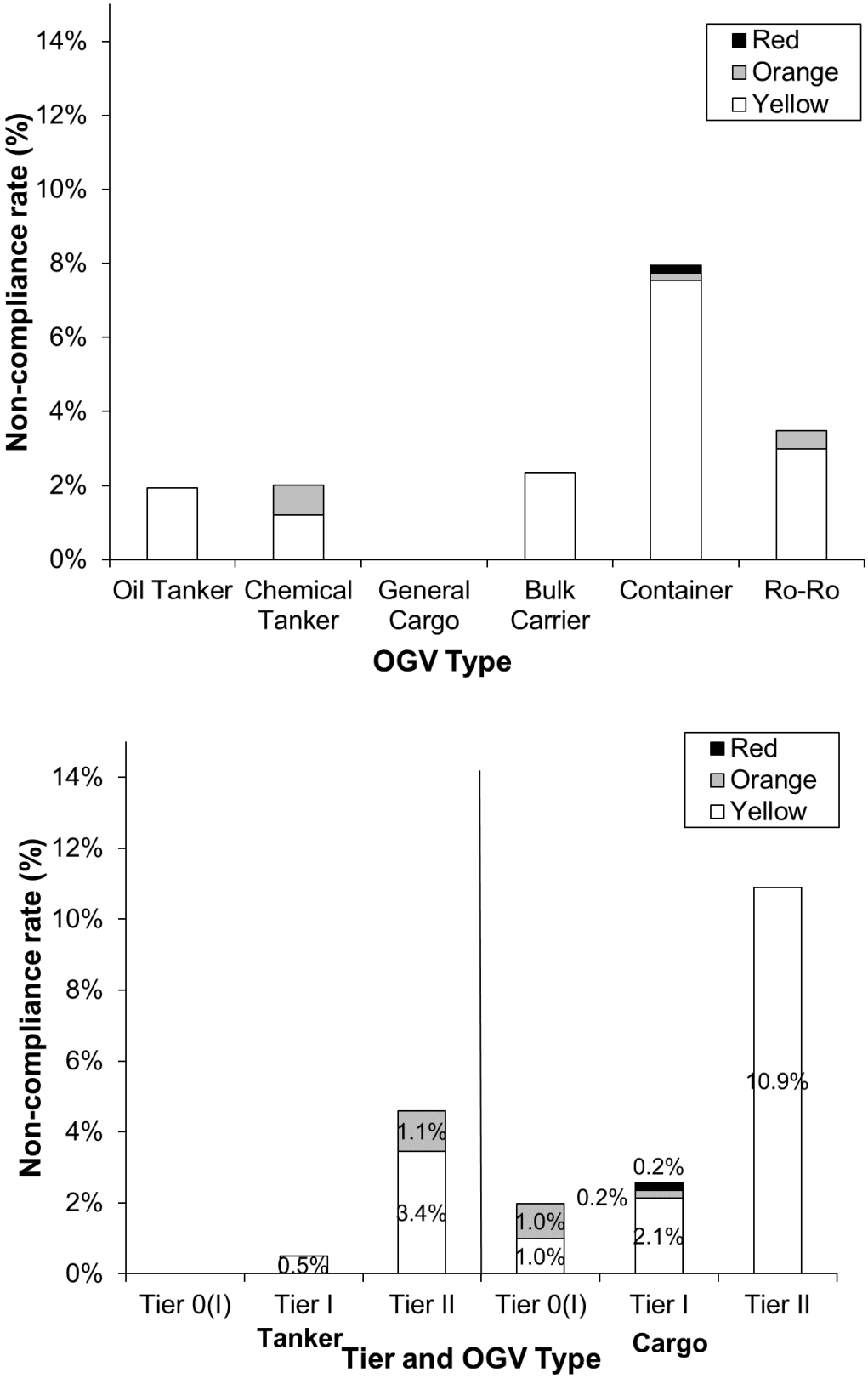


Figure S.13. Upper: Non-compliance rate per detailed vessel type. Lower: Non-compliance rate per tier for tanker and cargo OGVs

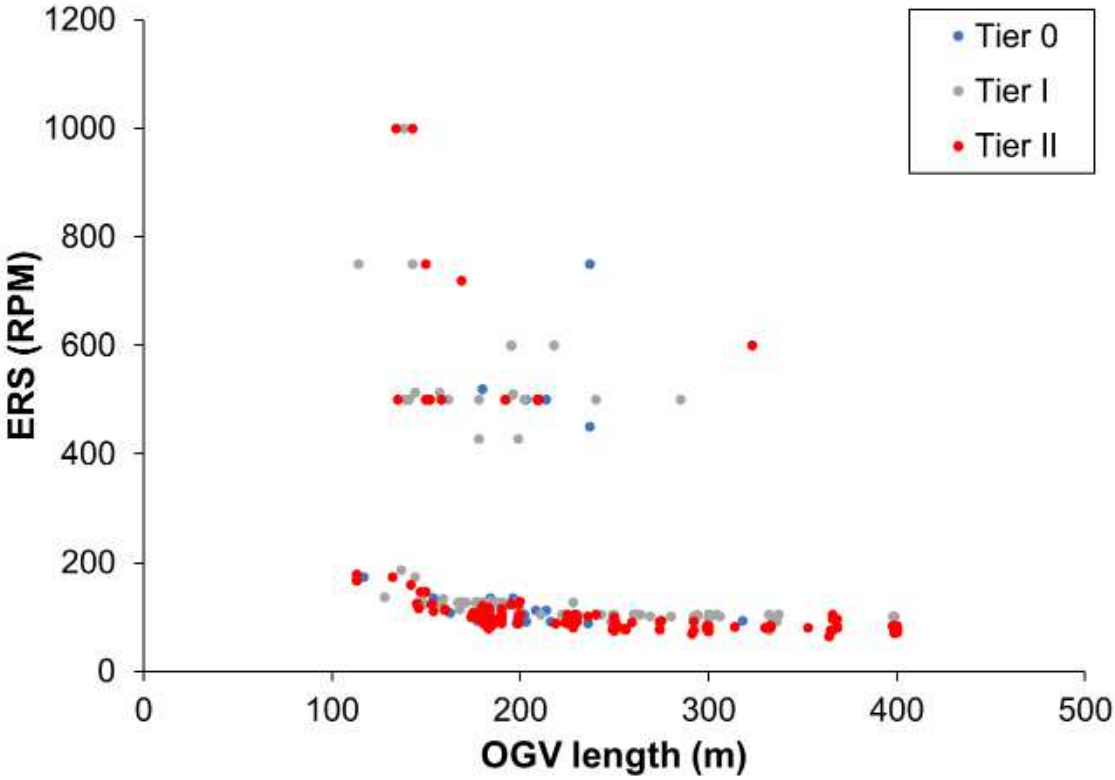


Figure S.14. ERS (rpm) compared to OGV length (m) based on a subset of 360 OGVs.

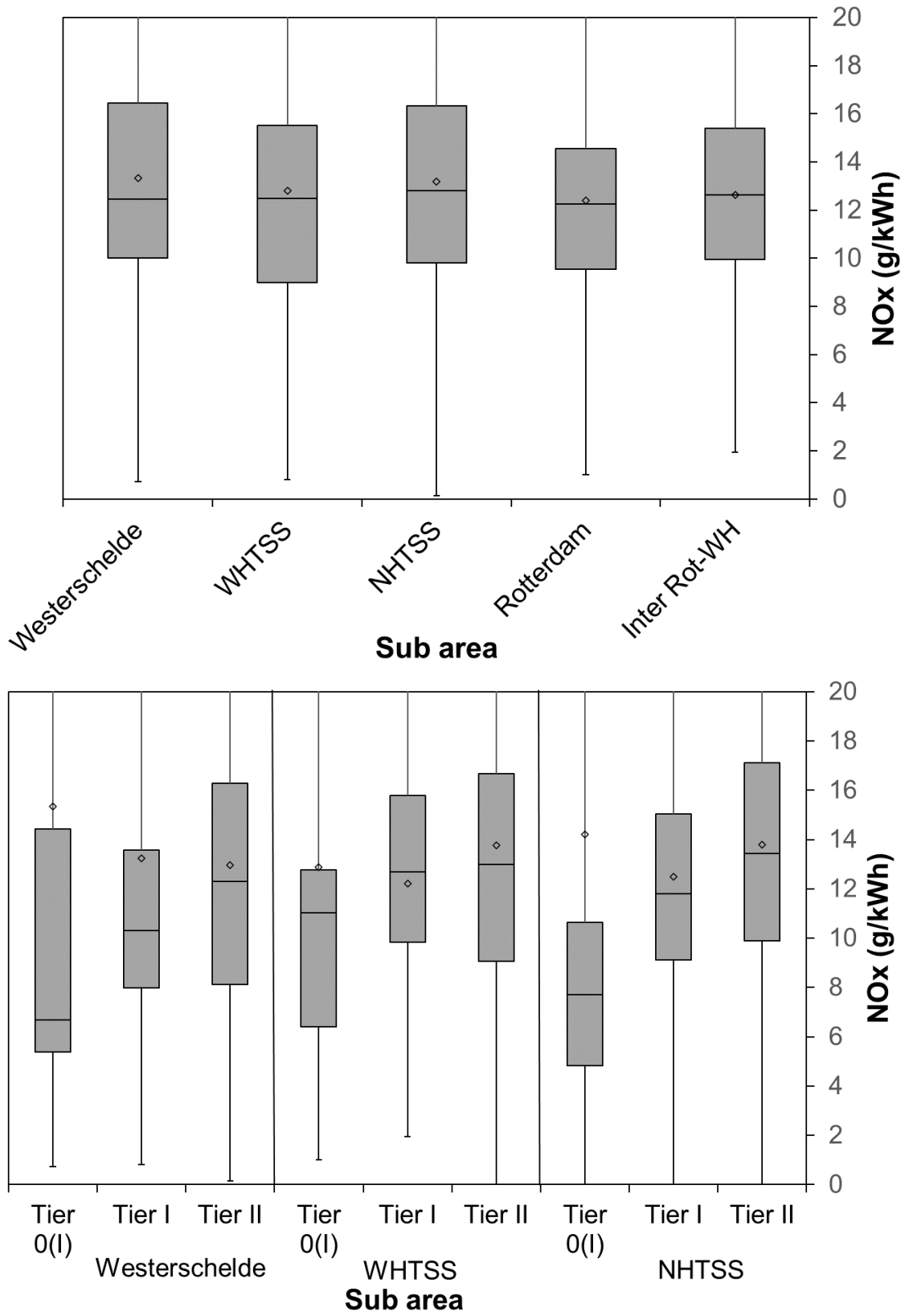


Figure S.15. Upper: Box plot of the NO_x distribution per subarea. Lower: Box plot of the NO_x distribution per Tier for the Westerschelde, WHTSS and NHTSS.

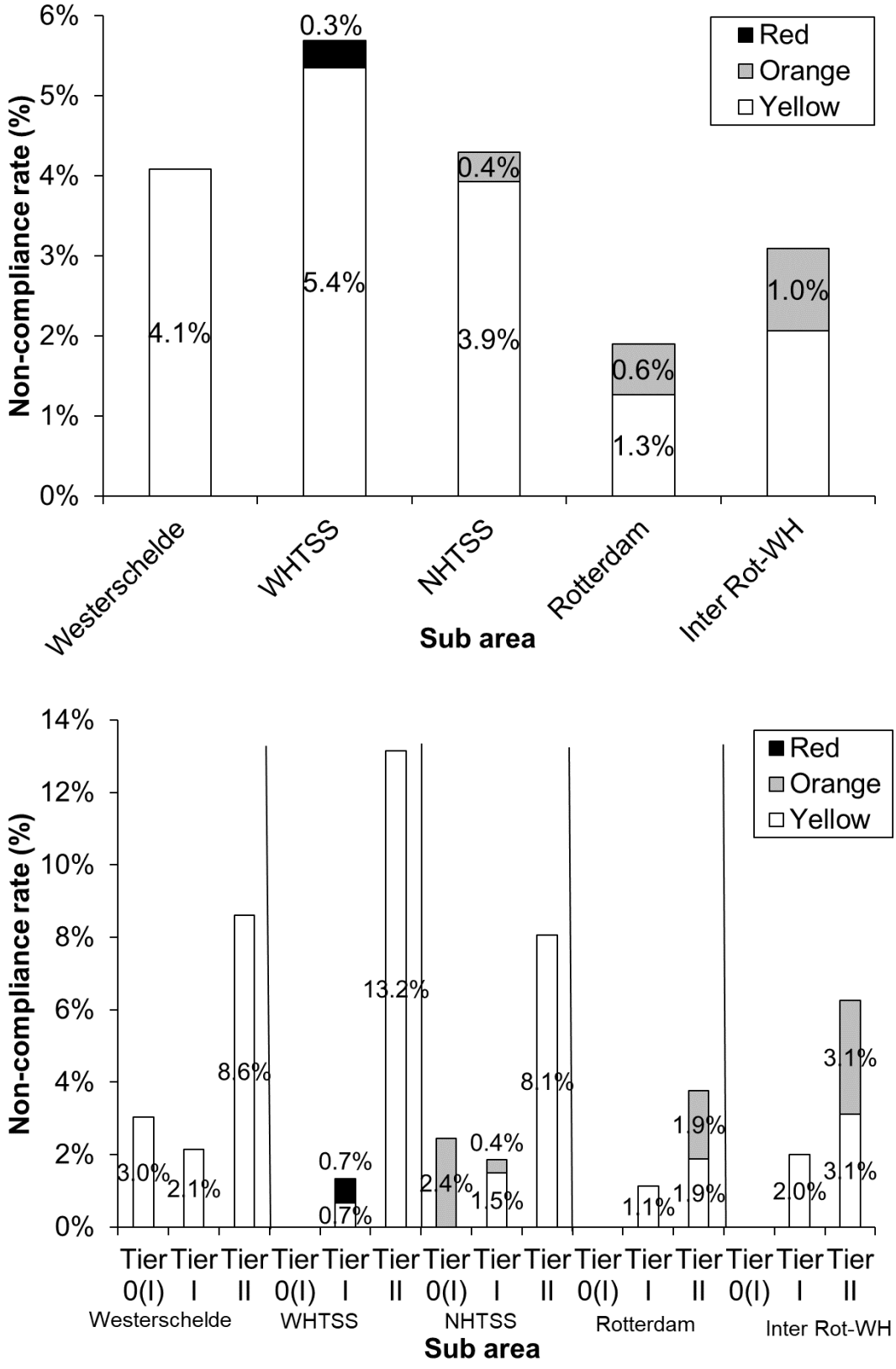


Figure S.16. Upper: Non-Compliance level per sub area. Lower: Non-compliance level per sub area per Tier.

Table S.1. Intra-Assay Coefficients of Variability, freedom of degrees and total uncertainty.

NO_x range	0-10	10-20	>20
CV_{RW}	16.1%	14.9%	18.6%
n	24	79	45
u_{tot}	21.9%	21.1%	23.9%
$\|b\|$	13.4%	13.4%	13.4%
U (σ=1.96)	29.6%	28.0%	33.4%

Table S.2. Supplementary uncertainty factors and the combined supplementary standard uncertainty.

Supplementary uncertainties	Max
NO_x span gas drift (3 months)	1.97%
NO_x span gas concentration*	3.00%
CO_2 span gas drift (6 months)	1.44%
CO_2 span gas concentration*	2.00%
Measurement accuracy NO_x sensor	0.50%
Measurement accuracy CO_2 sensor	1.00%
Uncertainty molar mass N	6.07E-05
Uncertainty molar mass O	1.88E-05
Uncertainty molar mass C	0.02%
Uncertainty C content in marine fuel	1.34%
Uncertainty Indicated power	6.8%
Uncertainty fuel consumption	10.00%
Combined supplementary standard uncertainty	12.97%

** According to gas analysis certificate*

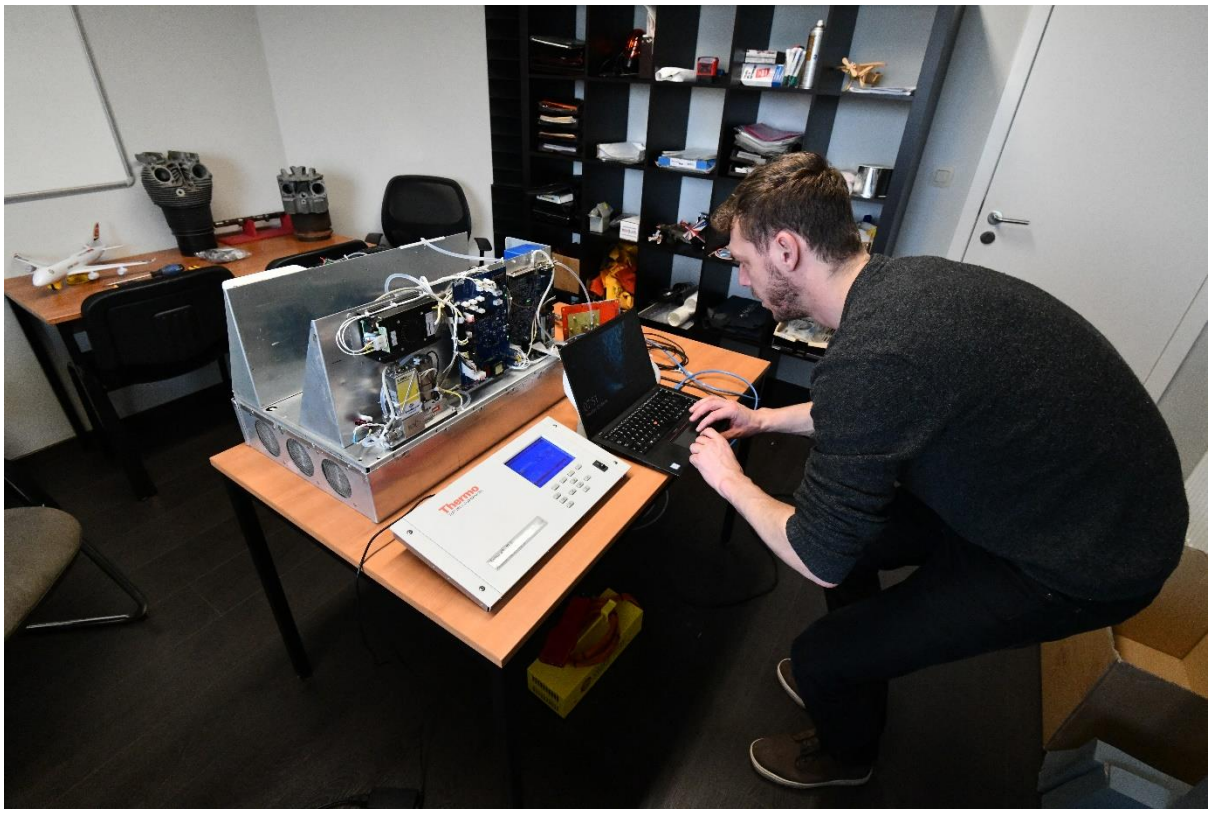
Table S.3. Thresholds for OGVs with ERS of 500 rpm.

Tier	L_{Tier}	Color flag	NTE	σ	T	$T_{ops\text{-}5}$
Tier I	13	Yellow	15%	1	16.1	20
		Orange	20%	1.96	24.3	25
		Red	50%	2.576	40.6	45
Tier II	10.5	Yellow	15%	1	13.0	15
		Orange	20%	1.96	19.7	20
		Red	50%	2.576	32.8	35
Tier III	2.6	Yellow	50%	1	4.1	5
		Orange	60%	1.96	5.7	6
		Red	65%	2.576	6.9	7

Table S.4. Potential false negatives (β) for OGVs with an ERS > 130 rpm.

Tier	OGVs	ERS >130	ERS >500	β $T_{ops\text{-}5}$	β $T_{ops\text{-}ERS}$
Tier 0(I)	10	0	0	0	0
Tier I	43	4	3	0	1
Tier II	148	7	2	1	1

Chapter 3: Measurement of Sulfur-Dioxide Emissions from Ocean-Going Vessels in Belgium Using Novel Techniques.



Personal picture (12/03/2018)

Measurement of Sulfur-Dioxide Emissions from Ocean-Going Vessels in Belgium Using Novel Techniques

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This article belongs to the Special Issue Air Quality and Human Health

Abstract

Air pollutants emitted by ocean-going vessels (OGVs) cause numerous environmental and human health problems. In 2016, the Belgian Coastguard aircraft was equipped with a sniffer sensor to monitor compliance with MARPOL Annex VI Regulation 14. However, the sensor was susceptible to NO and Volatile Organic Compounds (VOCs), which had a negative impact on the measurement uncertainty. The elimination of measurement errors was achieved by modifying the sensor, including among others the addition of a NO_x sensor and a custom-designed hydrocarbon kicker. This resulted in a substantial improvement in the measurement quality and uncertainty of the derived Fuel Sulfur Content (FSC). As a direct result of this, the reporting thresholds for non-compliance drastically improved. The data analysis of sampled OGVs showed that compliance levels notably improved between 2019 and 2020 (from 95.9% to 97.3%), coinciding with the implementation of the Global Sulfur Cap. Findings in this study have also demonstrated that OGVs equipped with emission abatement technology (scrubbers) are more susceptible to non-compliance with Regulation 14 of MARPOL Annex VI. Given these results, this article provides an answer to the question of how to monitor effective implementation of NO emissions from OGVs.

1. Introduction

1.1. Belgian Sniffer Program

The international emission limits for SO_2 for ocean-going vessels (OGVs) have been described in Regulation 14 of Annex VI, MARPOL Convention [1,2]. The international regulations have been translated in the EU Directive (2016/32) relating to a reduction in the sulfur content of certain liquid fuels [3]. Since 2015, the Management Unit of the Mathematical Model of the North Sea (MUMM), a Scientific Service of the Royal Belgian Institute of Natural Sciences and competent MARPOL legal authority [4], has been carrying out airborne MARPOL Annex VI compliance monitoring operations over the North Sea. A sniffer sensor was purchased in 2016 and added to the surveillance instrumentation of the Belgian Coastguard aircraft [5]. This sniffer sensor is based on the in-situ measurement of the ratio of SO_2 over CO_2 in the smoke plume of an OGV to calculate the SO_2 emission factor and derive the Fuel Sulfur Content (FSC). The sniffer sensor is commercially available from FluxSense (Sweden), but the hardware and the software of the system used in the Belgian Coastguard aircraft have been modified to meet the operational demands of the Belgian Coastguard. Standard Operational Procedures (SOPs) were defined based on best practices and in collaboration with other European monitoring agencies [6]. The monitoring practice implies that the aircraft passes through the OGV exhaust plume at a safe distance from the OGV. During the passage, the sniffer sensor measures the concentration of SO_2 and CO_2 before, during and after the passage through the smoke plume. The increase of the SO_2 and CO_2 concentration relative to the background values is then used for the calculation of the SO_2/CO_2

ratios. A mechanism was put in place to alert Belgian port inspection authorities to target those potential violations. By conducting these "remote" measurements (theoretically these types of measurements are in fact in-situ measurements), the Belgian port inspection authorities may reduce the number of mandatory port inspections by 50% [7].

At the start of the strengthened sulfur regulation in 2015 and 2016, non-compliance rates of more than 10% were observed, generating large numbers of alerts for port inspection authorities [5,8]. However, due to the improved compliance rates in 2018 and 2019, fewer alerts were generated. This increased compliance rate was also observed by other monitoring agencies [5,9–12]. To increase the detection capability for potential non-compliant OGVs, it was considered essential to reduce the measurement uncertainty, as this would allow a reduction of the reporting thresholds.

In order to comply with the sulfur emission regulations, shipowners, in line with MARPOL Annex VI, may choose to equip their OGVs with Exhaust Gas Cleaning Systems (EGCS), which are also known as scrubbers. With these scrubbers, OGVs can still use Heavy Fuel Oil (HFO) with high sulfur content [13–15]. Recent studies have indicated that scrubber OGVs create potential local and regional environmental health hazards. The scrubber systems dispose of high volumes of treatment water or wash water. The SO_2 in the exhaust will react with water with the formation of sulfuric acid. The disposed wash water is categorized by low pH levels and contains high levels of harmful substances such as heavy metals and polycyclic aromatic hydrocarbons (PAHs) [15–20]. Whereas in 2015, the scrubber OGVs were still rather uncommon, by the end of 2021 the amount of OGVs equipped with a scrubber reached 30% of the global tonnage in box ship capacity [21]. Given the increased use of scrubbers on OGVs and the complexity to inspect these systems in port, more understanding of the compliance behavior of scrubber OGVs is imperative as this would allow researchers to assess the environmental and health impact of the maritime sector on a global and regional level.

1.2. Interactions from Other OGV Emissions

OGVs are a source of various gaseous pollutants, mainly sulfur oxides (SO_x), nitrogen oxides (NO_x), particle matter (PM), Volatile Organic Compounds (VOCs), Black Carbon (BC) and Organic Carbon (OC) [22–24]. In addition, OGVs emit vast amounts of greenhouse gasses (mainly CO_2) and therefore contribute substantially to global climate change. The SO_2 sensor, which is used in the sniffer sensor system, is the main sensor for monitoring compliance with sulfur emission regulations by OGVs. Previous studies, however, have demonstrated that SO_2 showed a cross-sensitivity to NO. This measurement error was estimated at 0.8–1.5% depending on the used SO_2 sensor. This means that up to 1.5% of the NO concentration measured in the exhaust of an OGV would be wrongfully assigned as SO_2 [25,26]. Nevertheless, the exact cross-sensitivity for the SO_2 sensor (Thermo Scientific 43i TLE) with the specifications of the sensor setup (i.e., airflow, pressure, ...) used on board the Belgian Coastguard aircraft was not yet determined. To reduce the measurement uncertainty, it was considered essential to correctly assess this NO cross-sensitivity for the SO_2 sensor. In 2020, the sniffer sensor system was further expanded to include an additional NO_x sensor for the monitoring of compliance with MARPOL Annex VI Regulation 13 [27], which provided a potential way forward to reduce the measurement uncertainty. However, more research was required to properly incorporate the NO_x sensor in the measurement methodology and SOPs of the OGV emission monitoring program of the Belgian Coastguard aircraft.

Furthermore, VOCs have also been found to influence the measurements of SO_2. VOCs are mainly a result of the use of maritime lubrication oils and the combustion of marine fuels [24]. The VOCs have a tendency to stick to the internal sensor parts and disturb the measurement of SO_2. After passing through an OGV exhaust plume with high amounts of VOCs, a delay of up to several minutes could be observed

on the SO_2 concentration plots, before the SO_2 concentration slowly returns to the background concentration. During previous measurement campaigns, this was visually identified as "SO_2- tails" (Figure 1) [5]. When this occurred, the concerned measurement was either rejected as low quality, or the tail was not included in the FSC calculation. In the latter case, only the section of the peak was used that corresponded to the CO_2 peak. Whenever a measurement with a tail was observed that indicated a possible non-compliance, the measurement was categorized as "low quality" when reporting to the maritime inspection authorities. Although this operational approach worked well temporarily, it was decided to develop a more permanent, rigorous solution to remove this VOC effect, in order to eliminate this interference permanently and further reduce the measurement uncertainty.

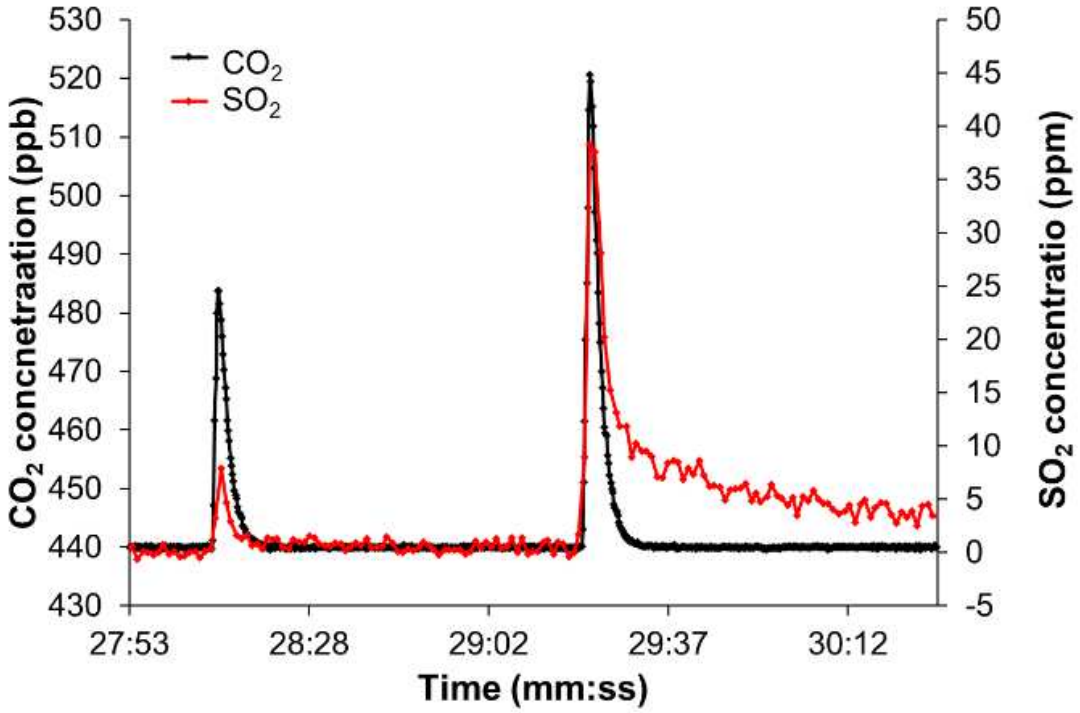


Figure 1. Graphs of CO_2 and SO_2. The left peak is not impacted by VOCs, since SO_2 and CO_2 returned to background concentrations at the same time. The right peak of SO_2 was impacted by VOCs, visible by a tail behind the peak in which the SO_2 signal is returning very slowly to the background concentration.

1.3. Research Area and Time Frame

The measurements used for this research were taken in the period from 2020–2021. Within this timeframe, the global maritime shipping industry was substantially impacted by the global Covid-19 pandemic and highly reduced fuel prices, which is taken into account when examining the results of the airborne measurements. The current research was executed in the same surveillance area as the sniffer campaigns from the 2015–2019 research, covering the Belgian part of the North Sea [5]. The Belgian waters include its territorial waters and its Exclusive Economic Zone (EEZ) are ca. 65 × 87 km, resulting in a total surface of 3454 km^2 [28,29].

2. Methods and Materials

2.1. Airborne Platform and Sniffer Sensor

The Belgian coastguard aircraft is a fixed-wing Britten Norman Islander (BN2). This high-wing aircraft is well suited for low-level operations at low speed due to the large wing surface (width of 14 m for a length of 11 m) and low stall speed (32 kts). The sniffer sensor modified for this study was originally

developed by Chalmers University (Gothenburg, Sweden) [30]. The sensor integrates (i) a SO_2 sensor (Thermo 43i TLE); (ii) a CO_2 sensor (Bioscience Licor 7200RS); (iii) a powerful vacuum pump (KNF 838); (iv) pressure and flow regulators (Bronkhorst); (v) a log computer (Zatoc ID64); (vi) a combined Automatic Identification System (AIS) and Global Positioning System (GPS) receiver (Comar SLR200NG); and (vii) an Aeronautical Radio INC (ARINC) module. In addition, a 50 mm particle filter with a pore size of 1µm avoids contamination of the gas analyzers and the pressure and flow regulators. A 3/8" stainless-steel probe is installed on the bottom of the aircraft to sample the outside air.

2.2. NO_x Sensor

A NO_x sensor (model: Serinus 40, manufacturer: Ecotech, Gothenburg, Sweden) was added to the instrumentation on board the coastguard aircraft in June 2020. The sensor uses the chemiluminescence characteristics of nitrogen oxide (NO) to measure its gaseous concentration. During standard operations the sensor was set to the "NO_x" mode. In this mode, the airflow passes through a "NO_2 to NO converter" which transforms all NO_2 into NO using a catalytic heated process. For the measurement of NO the sensor was set to the "NO mode". In this mode, the NO_2 to NO converter was bypassed, meaning that only the NO concentration was measured with a response time of 1 s. In the "all gasses" mode, the sensor provides both gas concentrations, although with a time resolution of 10 s. as the sensor switches continuously between "NO_x mode" and "NO mode". To obtain the NO_2 concentration, both NO and NO_x concentrations are first measured separately, and afterward the NO is subtracted from the NO_x to obtain the NO_2 concentration. An air delay loop is installed to allow the simultaneous measurement of NO and NO_x on the same air sample. Due to the required longer time resolution, this "all gasses "mode is not useful for airborne monitoring operations and the air delay loop was bypassed.

As the NO_x sensor is installed in the rear compartment of the aircraft, this would result in a time shift between the measurement of SO_2 together with CO_2 and NO_x due to the length of the tubing. To limit the time shift, tubing of 1/8" was used, although the time shift remained at 4 s. The software, therefore, was adjusted in order to be able to correct this time shift.

2.3. Hydrocarbon Kicker

Off the shelf, the Thermo 43i TLE instrument is equipped with a hydrocarbon (HC) kicker to remove VOCs from the airflow. This HC kicker consists of (i) an inner compartment, i.e., a very narrow (1/8") semipermeable tube that is guided inside (ii); an outer compartment, which consists of a standard Teflon tube of 1/4". The airflow outlet of the outer compartment is connected to (iii); a very thin capillary. The airflow inside the inner compartment is opposite of the airflow in the outer compartment. The inner compartment is connected to the airflow inlet of the SO_2 sensor measurement chamber. The outlet of the sensor measurement chamber is connected to the outer compartment. When leaving the other side of the outer compartment, the airflow first goes through a capillary and afterward the vacuum pump. The vacuum pump and capillary create a negative pressure in the outer compartment, thus forcing the VOCs through the semipermeable wall before entering the measurement chamber. The VOCs are disposed of through the air outlet.

However, the standard HC kicker is designed for an airflow of 0.5–1 L/min. The small size of its inner compartment does not allow for a higher airflow with the same VOC removal capacity. The maximum airflow in the sniffer sensor system of 8 L/min was substantially higher than the maximum airflow for a standard HC kicker. The standard HC kicker therefore could not effectively remove the VOCs from the airflow, because of which the HC kicker was removed from the SO_2 sensor in the original sniffer sensor design. To solve the VOC error on the SO_2 measurements, a novel custom-designed high-volume HC kicker was developed. This high-volume HC kicker is based on ten parallel connected standard (low-volume) HC kickers (Figure 2, upper).

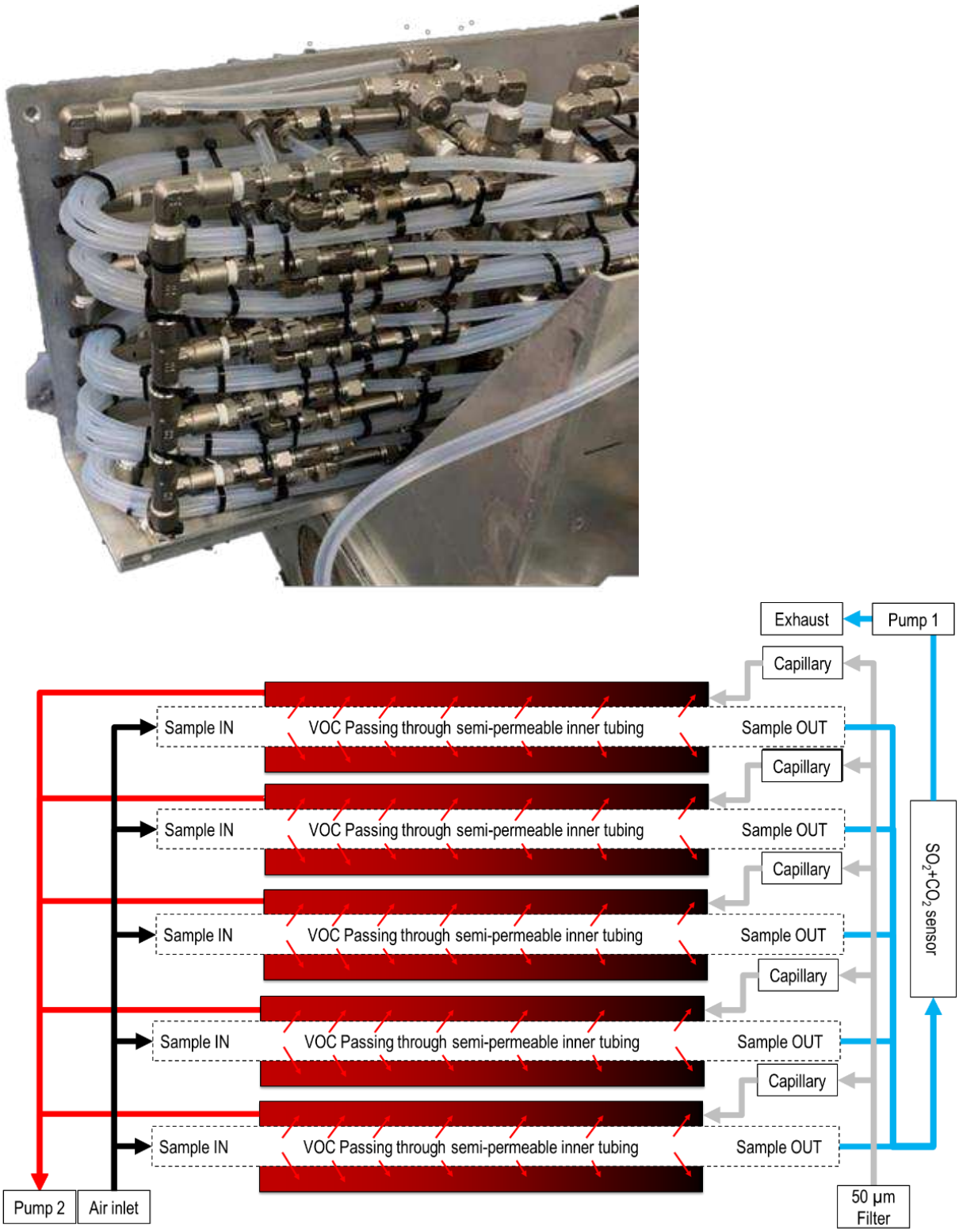


Figure 2. Upper: Picture of the high-volume HC kicker designed to fit the sniffer sensor system. The kicker is composed of ten standard low-volume HC kickers that are connected in parallel creating the high-volume HC kickers in five levels, with two low-volume HC kickers per level. Lower: Scheme of the working mechanism of the HC kicker, which shows only the five levels of one side of the high-volume HC kicker. The air inlet containing VOCs (black line) goes into the inner compartment. A clean (gray) low-pressure airflow flows in the opposite direction in the outer compartment. VOCs pass through the semi-permeable wall and are removed from the airflow that goes to the Thermo

43i TLE and Licor-7200 RS sensors (blue lines). The VOCs are evacuated via the outflow of the outer compartment (red line) to the exhaust of the sniffer system.

In every single standard HC kicker, the airflow was reduced to 0.8 L/min, which is an optimal flow for standard HC kickers. The inner compartment of the novel high-volume HC kicker has a tested total maximum flow of up to 11 L/min at 0.5 bar. However, the maximum flow in the outer compartment at 0.5 bar was limited to 4.5 L/min. Moreover, the original vacuum air pump was not powerful enough to provide the required airflow through the capillaries in combination with the passing of the airflow through the sensors and particle filters. As a result, the standard air pathway through the SO_2 sensor was modified and an additional vacuum pump was installed. The original flow in the sniffer sensor was 6 L/min, but by upgrading the existing one-headed vacuum air pump to a two-headed vacuum air pump the airflow was improved to 8 L/min. The pathway was split into two different pathways. The new two-headed vacuum pump was installed behind the SO_2 and CO_2 sensors, replacing the original one-headed pump. It provided sufficient power to create an airflow through the inner compartment of the HC kickers to meet the increased flow of 8 L/min. However, the pump was not powerful enough to provide the same airflow in the outer compartment due to the capillaries. Accordingly, the original one-headed pump was kept in the system in the form of a second air pathway, providing airflow in the outer compartment and evacuating the VOCs (Figure 2, lower) at 4.5 L/min. This novel design HC kicker with separated airflow had not been applied before and it was unsure if the newly designed high-volume HC kicker would be efficient in removing VOCs at a sufficient rate. Furthermore, it was unsure if the splitting of the air pathways would not result in an unstable pressure or removal of CO_2 or SO_2.

2.4. Updated Sniffer Sensor Software and Sulfur Emissions Measurements

2.4.1. NO Cross Sensitivity

Initially, only the SO_2 and CO_2 concentrations were used for the calculation of the Fuel Sulfur Content (FSC) [31]. For the determination of fuel quantity, the amount of Carbon (C) was first derived from the CO_2 concentration and was subsequently multiplied with a fuel carbon content of 87% [25,32].

$$FSC = 0.232 \times \frac{\int \left[SO_2 - SO_{2,bkg}\right]_{ppb} dt}{\int \left[CO_2 - CO_{2,bkg}\right]_{ppm} dt} [\%\, Sulphur] \quad (1)$$

To correct for the NO cross-sensitivity of the SO_2 sensor, this formula was adapted by subtracting the measured SO_2 from the NO amount in the plume multiplied by the cross-sensitivity factor (CS_{NO}).

$$FSC_{NO} = 0.232 \times \frac{\int \left[SO_2 - SO_{2,bkg}\right]_{ppb} - CS_{NO} \times \left[NO - NO_{bkg}\right]_{ppb} dt}{\int \left[CO_2 - CO_{2,bkg}\right]_{ppm} dt} [\%\, Sulphur] \quad (2)$$

2.4.2. NO Assessment

During the time frame of this study, the NO_x sensor on board the aircraft was mainly used for compliance monitoring of MARPOL Annex VI Regulation 13 which introduced limits on NO_x emissions [27]. The standard operational modus of the NO_x sensor was therefore set to NO_x-mode. To estimate the *NO* concentration from the measured NO_x concentrations a default NO/NO_x In Stack Ratio (*ISR*) of 80% was used [33]. The software was modified in such a way that the ratio could be changed in the configuration settings.

$$FSC_{NO} = 0.232 \times \frac{\int \left[SO_2 - SO_{2,bkg}\right]_{ppb} - CS_{NO} \times ISR \times \left[NO_x - NO_{x,bkg}\right]_{ppb} dt}{\int \left[CO_2 - CO_{2,bkg}\right]_{ppm} dt} [\%\, Sulphur] \quad (3)$$

However, NO/NO_x ratios may vary significantly depending on different factors, such as distance to the stack, UV radiation, ambient ozone concentration,...[27,34] Thus, the NO/NO_x ratio remained a source of uncertainty. To address this uncertainty, the measurement method was to measure by default in NO_x mode. In case the initial NO corrected FSC measurement, based on the NO_x concentration and the default NO/NO_x ratio (80%) exceeded the operational threshold (T_{ops}) (See Section 3.7.1), the sensor was set to NO mode and two new measurements were made with the NO_x sensor in NO mode. Hence, the NO cross sensitivity could be assessed more accurately.

2.4.3. FSC Correction

The FSC measurement was discovered to have a negative bias that consisted of an absolute component (offset) and a relative component (slope) [5]. To be able to calculate the correction factors, two reference points were used to compare the sensor result with the actual value.

For the first set of comparison points (lower FSC values), the median value of all airborne measurements was compared to the median FSC value of 30 randomly selected OGVs that entered Belgian ports. The fuel analysis measurement was executed by the Belgian port inspection authorities using a handheld X-Ray Fluorescence (XRF) scanner (model: Titan S, manufacturer: Bruker).

For the second set of comparison points (higher FSC values), a special gas mixture was ordered from Air Liquide that was utilized to imitate a 1% FSC plume. The ordered concentration was 5000 ppb SO_2 with 1000 ppm CO_2 in synthetic air. Standard air analyzers are not able to check these high concentrations. As only the ratio of SO_2/CO_2 was relevant, a PTFE air sample bag of 50 L (manufacturer: Saint Gobain) was used to dilute the mixture with synthetic air (Figure S1). Afterward, both concentrations of CO_2 and SO_2 could be measured in the measurement range of the gas analyzers at Brussels Institute for Environmental Management (BIM), which demonstrated that the resulting simulated FSC was on average 0.89% FSC (+/− 0.02%), the difference with the ordered concentration is assumed to be a result of the low accuracy of the plume mixture provided by Air Liquide as the error is in the same order of magnitude of the errors of the reference gasses for SO_2 and CO_2. This plume simulation mixture was released for a short interval at a high-volume flow in front of the sampling probe to simulate a passage through an OGV exhaust plume, therefore giving the second set of comparison points.

Based on the two sets of comparison points the correction factors could be calculated (see Section 3.5). To be able to calculate the corrected FSC in flight, the IGPS software was modified in such a way that the correction factors were applied during the calculation step and the corrected FSC was immediately provided to the operator after the measurement of the exhaust plume.

2.5. Sniffer Quality Management System

The Sniffer Quality Management System (SQMS) comprises all standard operational procedures (SOPs) that have been specifically developed for the Belgian Sniffer program to ensure measurement reproducibility and guarantee consistent measurement quality and uncertainty. The SQMS is considered a living document that is upgraded on a regular basis. To include the updated measurement techniques the SQMS has been completely revised. The SQMS contains three sections: (i) an operational procedure (OPS) manual; (ii) a quality assurance (QA) manual; and (iii) a data management manual. The revised SQMS can be found in the supplementary material and can be used by other agencies as a guideline to set up their emission measurement program.

The operational procedures have been adapted to include the procedure to remove the NO cross-sensitivity by switching the NO_x sensor to NO mode when an initial FSC measurement was observed

that exceeded the threshold. In addition, the calibration procedures were adapted to include what was called a quick final check, with the special plume simulation gas mixture of 1% FSC. The SQMS describes that in case the quick final check shows an FSC value deviating more than 10% from the preset value, the calibration procedure is to be repeated, and/or the FSC correction factors are to be adjusted. During the period from 2020–2021, this was never needed during the operations as the factors were regularly monitored and adjusted if needed outside the operations. The adjustments in the QA manual include the maintenance and service of the added hard and software. In addition, the calibration procedure has been described for the special plume simulation gas. The updates to the data management manual include the updated uncertainty calculations and the procedures to measure the actual FSC corrections and how to apply them in the IGPS software. (version 63.99.25.1569)

2.6. Statistical Analysis

The TIBCO Statistica software (version 14.0.0.5) was applied for all statistical analyses in this study. To assess the normality of the SO_2 emission measurement data, a Kolmogorov–Smirnov test for normality was used. This test indicated that the data were not normally distributed ($p < 0.05$). Consequently, the use of parametric tests was not recommended, and nonparametric tests were used. For the comparison of the average emission levels between different monitoring years and ship types, two-tailed Kolmogorov–Smirnov tests were used. Distributions were considered significantly different with p-values < 0.05 [35]. A two-tailed Chi-Square test was used to evaluate frequencies (i.e., compliance rates) between the two groups. Frequencies were considered to be significantly different with p-values < 0.05 [36,37]. When Type I errors are mentioned, they refer to the number of false positives, when Type II errors are used, they refer to the number of false negatives.

3. Results and Discussion

3.1. Monitoring Results

In total, 126 operational flight hours were performed over 83 flights from July 2020 to November 2021. Over 1984 OGV exhaust plume measurement attempts, 1621 successful FSC measurements were made, concerning 1479 OGVs. For 1420 OGVs, the measurements met the quality standards; the others were discarded from the dataset. For 13 OGVs, no NO_x was measured due to sensor issues. For the other 1407 OGVs, NO_x was measured together with SO_2 and CO_2.

For 47 OGVs, both NO and NO_x emissions were measured, this was conducted for the acquisition of test data (15) and in case an initial potential FSC violation was observed (35) with the sensor in NO_x mode. In these cases, after completing an initial measurement with the NO_x sensor in NO_x mode, the NO_x sensor was set to the NO mode for one or two more measurements.

3.2. NO Interference

To assess the NO interference of the SO_2 sensor, the sensor was taken to the air quality lab of the BIM, a gas mixture device (MCZ CGM 2000) was used to create airflow with seven different NO concentrations ranging from 0 to 1666 ppb NO (mixed with synthetic air), which indicated that the SO_2 sensor had a NO cross-sensitivity of 0.45% and followed a linear pattern with a very high correlation ($R^2 = 0.9994$). The gas mixing device was only able to create gas mixtures of up to 1666 ppb NO at a flow of 8 L/min, falling perfectly in the range of the mean NO concentration of all analyzed OGV plumes (480 ppb). However, the highest observed NO concentrations were higher than the tested maximum concentration (ca. 2200 ppb). Due to the linearity of the measurement principle of the SO_2 sensor, this NO cross-sensitivity ratio could be extrapolated to the high end of the measurement range of NO concentrations that were observed with the NOx sensor (Figure 3).

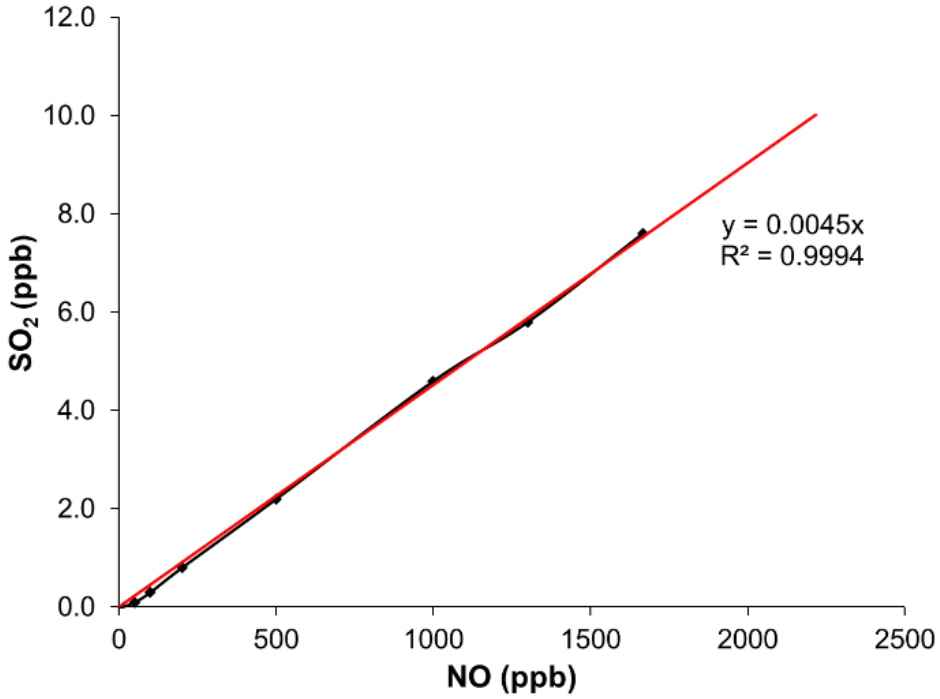


Figure 3. Sensitivity to NO of the Thermo 43i TLE sensor used in this study.

3.3. NO/NOx in Stack Ratio (ISR)

The *NO/NO$_x$ ISR* could not be measured directly as the NO_x sensor could only be used to measure either NO or NO_x with a time resolution of 1 s. An indirect approach was used to calculate the *ISR* based on multiple measurements, which measured either the NO or the NO_x. As the absolute measurement of NO_x and NO is useful due to the high dilution, the *NO/NO$_x$ ISR* ratio was derived indirectly. With this regard, the *NO/CO$_2$* ratio was compared to the *NO$_x$/CO$_2$* ratio, providing a reliable estimation of the actual NO/NO_x ratio.

$$^{NO}/_{NO_x}\,ISR = \frac{\frac{NO}{CO_2}}{\frac{NO_x}{CO_2}}\,[\%] \tag{4}$$

This illustrated that the *NO/NO$_x$ ISR* ratio had a large variation, going from 25% to 96% (Figure 4, left). The average value was 78% and the median value was 84%. As the median value is very close to the default of 80%, the latter was not adjusted. However, the large variety of these measurements is in line with the previous findings [34], confirming the importance of using the actual NO concentration to rectify the cross-sensitivity for possible violations, instead of solemnly relying on the default *ISR* of 80%. By looking at the *ISR* ratios per OGV type, it was observed that tanker OGVs have generally a higher *ISR* compared to cargo OGVs (Figure 4, right). As the actual NO is used for possible violations, the risk of Type I errors is removed. The risk of Type II errors however might be considered for OGVs with a low *ISR*. In terms of these vessels, a NO cross-sensitivity correction that is too high may be applied resulting in low FSC values. This impact is nevertheless limited for OGVs that are compliant with the NO_x emission limits (MARPOL Annex VI Reg. 13) with a relative uncertainty of ca. 10% for Type II errors. The risk of Type II errors increases when there is also non-compliance for NO_x observed. To avoid Type II errors in these situations, it is recommended to perform an FSC measurement with the NO_x sensor in NO mode, whenever an FSC value is observed close to the threshold, in combination with a possible NO_x non-compliance.

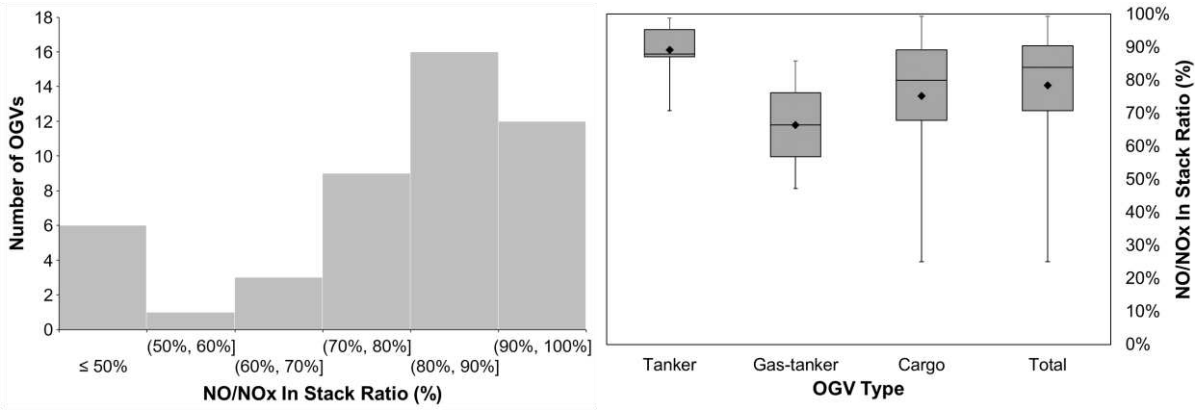


Figure 4. Left: Histogram of the NO/NO_x ratios calculated based on NO/CO_2 and NO_x/CO_2 ratios. Right: Comparison of NO/NOx ISR values between different OGV types.

3.4. Hydrocarbon Kicker

The effectiveness of the custom-built HC kicker was tested in the lab using solvent-based paint, which is known to contain large amounts of VOCs [38], sprayed on a clod. First, the sniffer sensor was tested without the HC kicker. When the sensor air inlet tubing was held above the paint-sprayed cloth, SO_2 values increased to high levels (>20 ppb). Furthermore, a clear SO_2 tale was observed that lasted for ca. ten minutes. Then the HC kicker was connected before the sensor air inlet and the procedure was repeated. In this configuration, the SO_2 values still produced an increased concentration, but the level was drastically lower (<3 ppb) and within the order of magnitude of the noise of the sensor signal. Moreover, it cannot be excluded that the SO_2 peak is not resulting from SO_2 released from the paint itself. Within less than three minutes, the smaller SO_2 tail was also much shorter than the one without the HC kicker (Figure 5). In addition, the average measured SO_2 value was significantly different from the measurements without the HC kicker ($p = 0.0$). However, it was observed that even with the HC kicker installed, the average value during the VOC exposure (2.2 ppb) was—albeit very limited—significantly higher than the average value before and after its exposure (1.5 ppb) ($p < 0.001$).

The HC kicker thus showed to be very effective in reducing the VOCs from the airflow in a lab environment. Likewise, the HC kicker, in the field, performed as anticipated. From the moment the HC kicker was put into use, no more tails were observed on the SO_2 signal. It can therefore be concluded that, even if the effects of VOCs were perhaps not completely eliminated, the VOCs were more than sufficiently removed and could no longer produce any possible significant effect on the FSC measurements.

3.5. Improvement of Measurement Quality and Reduced Uncertainty

In the previous sniffer campaigns, emission measurements were considered to meet the high-quality standards if the following requirements were met: (i) a distinct link of the plume to a single OGV; (ii) comparable T90 response times for the Thermo 43i TLE and the Licor-7200RS; (iii) ample plume sampling time; (iv) a high to very high Signal to Noise Ratio (SNR); and (v) absence of interference from land-based emission sources [5]. With the increased airflow of 8 L/min instead of 6 L/min, owing to the upgrade of the vacuum pump, the response time and SNR were improved allowing a higher quality of the sniffer measurements. The other quality requirements were not impacted. By improving the airflow, not only the quality was improved, but also the uncertainty was reduced. In addition, by applying a NO correction and removing the impact of VOCs the uncertainty was further reduced.

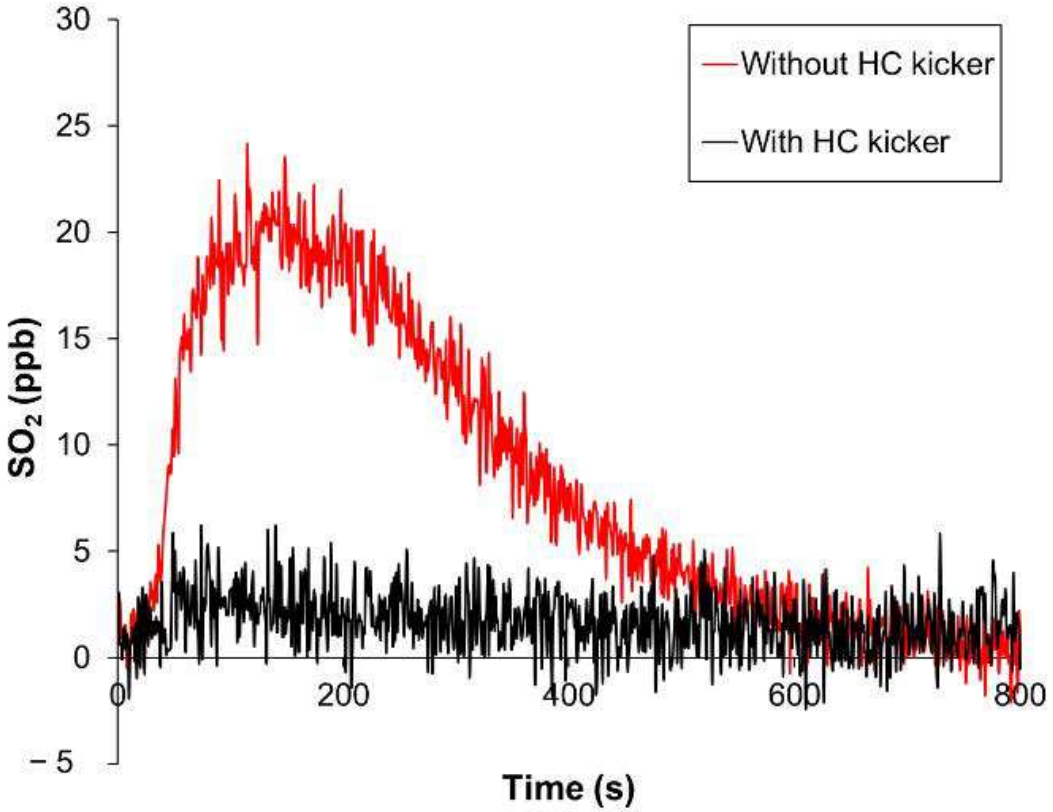


Figure 5. Erroneous SO_2 measured concentration indicates the effect VOCs (using spray paint in a lab environment) have on the SO_2 measurement signal. The red line shows the erroneous indicated SO_2 sensor reading without an HC kicker and the black line shows the erroneous sensor reading when the HC kicker was installed in the airflow before the SO_2 sensor.

3.5.1. Improvement of Response Time

Similar to the initial determination of the response time with the previous sniffer version, response times were redetermined by using calibration gases. This allowed the simulation of a concentration–difference (ΔC) that is comparable to the measurement of OGV plume exhausts. The *T90* response time was defined as the time difference (ΔT) between T_{10}, which is the time where the gas concentration is 10% of ΔC above the initial concentration (C_b), and T_{90}, being the time where the gas concentration is 10% of ΔC below the end concentration (C_e)) [5,27].

$$\Delta T = T_{90} - T_{10} \tag{5}$$

where

$$\Delta C = C_2 - C_1 \tag{6}$$

$$C_1 = C_b + 0.1 \times \Delta C \tag{7}$$

$$C_2 = C_e - 0.1 \times \Delta C \tag{8}$$

Both linear and non-linear interpolations were used to find the exact T_{10} and T_{90} times [5]. In terms of the Thermo 43i, TLE the non-linear interpolation was considered to be the most appropriate due to the lower signal frequency (1 Hz), which demonstrated that the *T90* time was reduced from 3.7 to 3.4 s, an improvement of 9.2% (Figure S3, upper), and well within the average plume sampling time of 8 s (and median of 7 s) [5]. For the Licor-7200RS, no substantial difference was observed between the linear interpolation and non-linear interpolation due to the high-signal frequency (5 Hz). The *T90* was reduced

from 3.5 s to 3.3 s, also offering an improvement of 9.2% (Figure S3, lower). The T90 times of both sensors were therefore still very comparable with an equivalent improvement of 9.2% as a result of the improved flow of 8 L/min instead of 6 L/min [5].

3.5.2. Improved Signal-to-Noise Ratio (SNR)

The SNR was defined as the ratio of the amplitude of the concentration during plume exhaust measurements (A_{plm}) over the amplitude of the noise (A_{bkg}) [5].

$$SNR = \frac{A_{plm}}{A_{bkg}} \tag{9}$$

A minimum SNR of 20 was previously required for high-quality measurements [5]. In practice, this corresponded to a minimum peak amplitude of 5 ppm, a threshold that was not adjusted. However, the average amplitude of the CO_2 measurements increased from 37.3 ppm to 38.5 ppm. As a result, the average SNR of the CO_2 measurements was improved from 149 to 154, corresponding to an improvement of 3.4%. The assessment of the average SNR of the SO_2 signal is not relevant as this is highly dependent on the average FSC level. The minimum A_{plm} for SO_2 for potential non-compliant OGVs was set at 3 ppb resulting in an SNR of 6.7 which is considered as low, but if a potential non-compliant OGV is observed, in most cases a second measurement will be made. For high-quality non-compliant measurements, a minimum A_{plm} of 7 ppb SO_2 is required. For the large majority of the potential non-compliant vessels, this minimum A_{plm} was easily reached during one of the measurements with an average A_{plm} of 51.74 ppb.

3.5.3. Reduced Uncertainty

The combined uncertainty of the FSC measurements (U) was described as the sum of the measurement bias (b) and the standard deviation (u_{tot}) [5,39].

$$U = |b| + \sigma . u_{tot} \tag{10}$$

The measurement bias as described above was defined as an offset in the FSC correction. The average bias for the period from 2020–2021 was 0.0039% FSC, and is 4.6 times smaller than the previous bias of 0.018 +/− 0.005% FSC [5], although it was assumed that the actual negative bias was even lower as the absence of the NO cross sensitivity correction largely eliminated the bias.

The standard deviation was, as for the previous sniffer campaigns, calculated based on the intra-assay coefficient of variability and the sum of all supplementary uncertainty factors ($u_{sup,i}$) [5,39]. The intra-assay coefficient of variability is a measure of the variance of replicate values. The supplementary uncertainty factors include all additional uncertainties for the sensors and methods used for the calculation of the emission factors and are available in Table S.1. By using calibration gasses with a lower uncertainty level and with a higher calibration frequency for the reference gasses, the supplementary uncertainty was reduced from 6.15% to 4.36%.

$$u_{tot} = \sqrt{(CV_{RW})^2 + \sum \left(u_{sup,i}\right)^2} \tag{11}$$

$$CV_{RW} = \frac{1}{\sqrt{2}} \sqrt{\frac{\sum_{i=1}^{n} \left(\frac{x_{i1} - x_{i2}}{0.5(x_{i1} + x_{i2})}\right)^2}{n}} \times 100(\%) \tag{12}$$

The CV_{RW} was calculated for three newly defined subsets of FSC values: low FSC values (0.13–0.2% FSC), medium FSC levels (0.2–0.3% FSC) and high FSC values (>3% FSC). The new CV_{RW} values for the different FSC levels are given in Table 1. Due to low degrees of freedom, the normal distribution could not be used and the t-distribution was used instead to replace the σ values.

Table 1. Intra-assay coefficients of variability, freedom of degrees, total uncertainty, bias and used t-values for the new FSC ranges.

FSC range	0.13–0.2%	0.2–3%	>3%
CV_{RW}	18.0%	8.04%	4.82%
n	20	12	14
u_{tot}	25%	20%	18%
|b|	15%	14%	12%
t	2.086	2.179	2.145
U (95% CI)	67%	58%	51%

Based on the updated bias and updated total uncertainties, the combined uncertainties were calculated for the three new FSC levels. When comparing the new combined uncertainties with the previous uncertainty calculation, the updated values may appear to be higher [5]. However, it must be clarified that this is a misconception, as the bias in the previous calculation was underestimated. The bias was most likely much higher but was on average largely removed by the cross-sensitivity to NO. A VOC cross-sensitivity assessment was also not included in the previous uncertainty calculation. Due to the fact that it was not possible to assess the exact bias without the NO cross-sensitivity effect, the negative bias was not applied on an individual measurement level.

3.6. Measurement Results

3.6.1. FSC Correction

In terms of the offset and slope correction, two sets of comparison points were used, similar to the calibration factors for air analyzers. For the first set of comparison points, the median value of the airborne measurements was compared to the median value of the 30 random fuel analyses in port using a handheld XRF scanner. The differences between the two median values were very small with a median value for the airborne measurements of 0.05% FSC and a median value for the XRF measurements of 0.06% FSC. The 25 and 75% percentiles of the airborne measurements were respectively 0.04 % FSC and 0.08% FSC, while the 25 and 75% percentiles of the XRF measurements were respectively 0.05 % FSC and 0.08% FSC.

In terms of the second set of comparison points, the measured FSC of the special calibration gas mixture was compared to the lab analysis. On average, the simulated plume gas mixture gave a value of 0.80% FSC compared to the 0.89% FSC that was measured in the lab using the PTFE sample bag. For 2020, the resulting slope correction was 10.1% and the offset correction was 0.0097% FSC. For 2021, the slope correction was 10.5% and the offset correction corresponded to 0.0063%. When calculated for the overall period, the slope correction was 10.4% and the offset correction was 0.0074% (Figure 6). These factors were calculated after every check using the mixture gas before every mission and can be updated in the

software when a significant variation is observed. The average slope and offset were also applied to reprocess all measurements using the raw data.

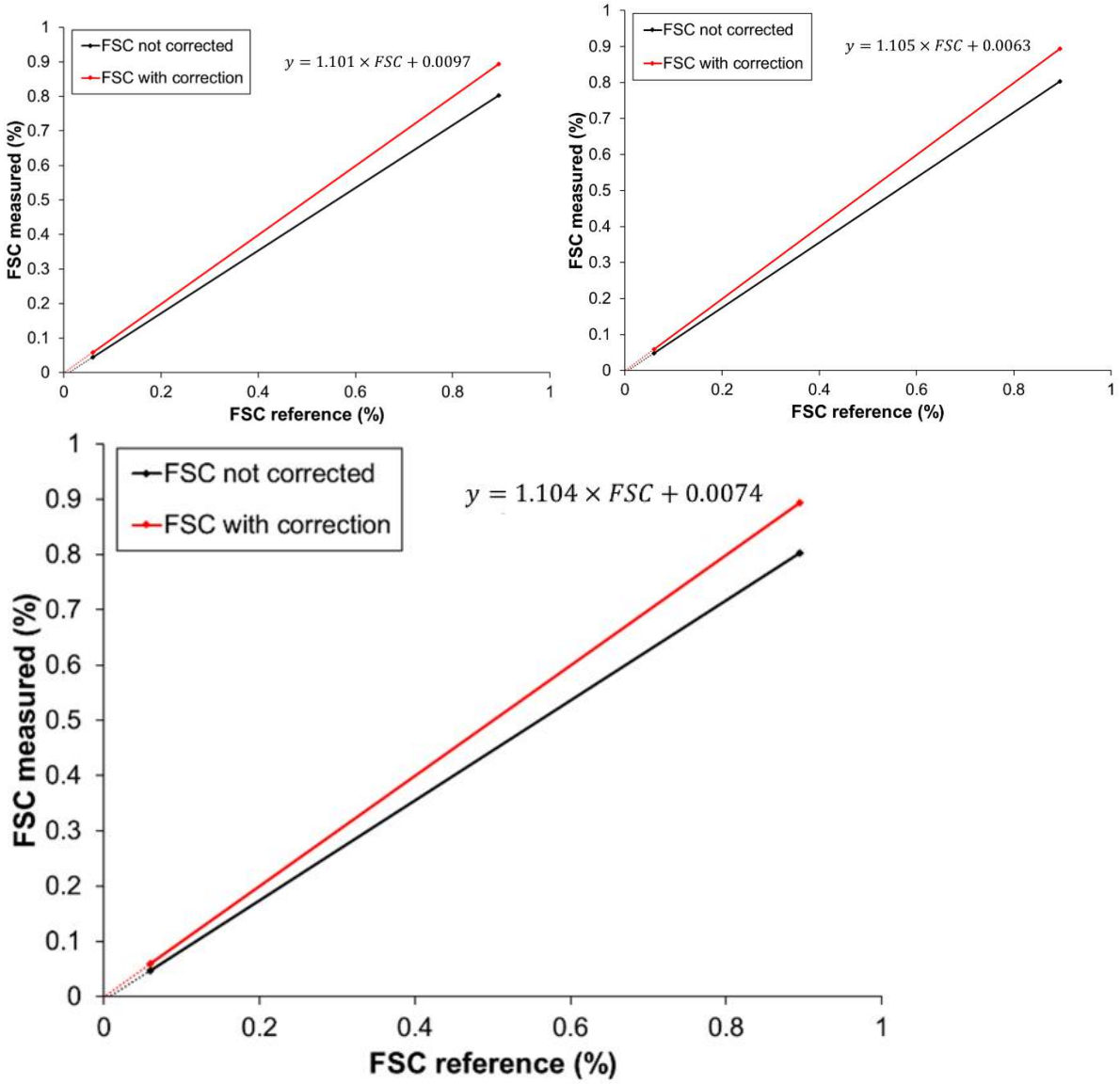


Figure 6. Calculation of the average slope and offset correction for the FSC measurements for 2020 (upper left) and 2021 (upper right) and the combined period from 2020–2021 (lower).

3.6.2. Average FSC

The average corrected FSC over the 2020–2021 period was 0.07% FSC, with a median of 0.06% FSC. The annual average FSC for 2020, with an FSC of 0.06%, was significantly lower than the annual average FSC for 2021 of 0.07% FSC ($p < 0.01$) (Figure 7). The median values, however, are not that different, which indicates that the used fuel does not seem to vary between 2020 and 2021. The higher average is most likely a result of higher extreme values in 2021. When comparing the average FSC between the periods of 2020 and 2021 with the period of 2019 (0.08%), a significant decrease in average FSC was observed for both 2020 and 2021 ($p < 0.001$). This is even without applying a bias correction for the 2019 data. When the bias of 0.0189% FSC [5] was applied, the actual average FSC for 2019 increased to 0.10% FSC.

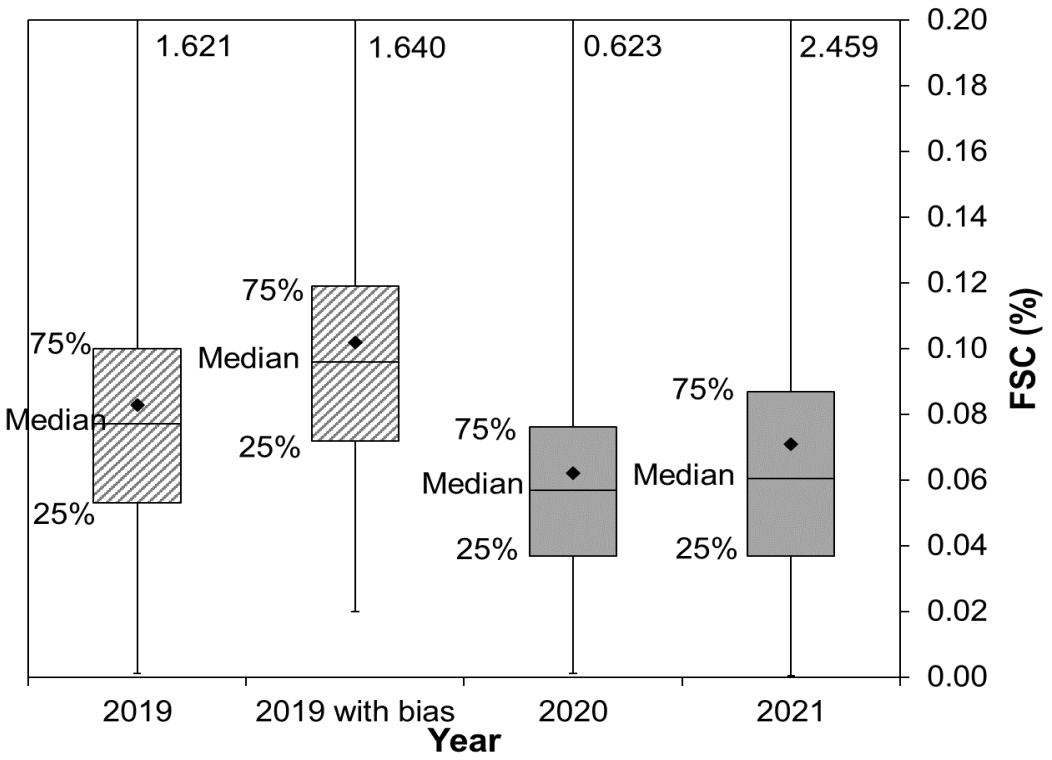


Figure 7. Box plot with 25, 75% percentiles medians and annual average (♦) of the monitored OGVs for the years 2019, 2020 and 2021. The data for 2019 is arched as the measurement for 2019 and were conducted with another measurement methodology with higher uncertainty. Both the uncorrected and corrected data for 2019 are visualized (bias of +0.0189% FSC).

3.7. OGV Compliance Analysis

Thanks to the improvement of the measurement quality and the reduction of the uncertainty, it was possible to improve the assessment of OGV compliance with MARPOL Annex VI Regulation 14. For the assessment of compliance during the surveillance operations, a set of three operational reporting thresholds (T_{OPS}) with corresponding color flags were created in 2016 [5]. These T_{OPS} were updated with reduced uncertainty levels.

3.7.1. Lowered Compliance Thresholds

The T_{OPS} used for different non-compliance alert levels are based on the combined measurement uncertainty (U) and sulfur limit (S). In comparison with the previous method, the bias was integrated into the FSC calculation and could therefore be removed from the equation for the threshold calculation [5].

$$S\,(\%FSC) = T_a(1 - \sigma \times u_{tot}) \tag{13}$$

The actual threshold (T_a) was described as the FSC value for which the difference between its value and its combined uncertainty exceeded a pre-defined S which depends on the color flags [5,27]. The value for S is based on the legal follow-up applied in Belgium. A warning is given from 0.11% FSC, and an administrative penalty is applied from 0.15% FSC [5]. As the degrees of freedom of the datasets per FSC level were not sufficient to allow the use of a normal distribution, t values were used instead of σ values

$$T_a = \frac{S}{1 - t \times u_{to}} \tag{14}$$

The same three color flags were used for creating the new thresholds. However, the thresholds were reassessed due to the updated uncertainties. The yellow flag represented the lowest alert level with a confidence interval (CI) of 60% ($t = 0.86$). Its operational reporting threshold was lowered from 0.15% to 0.13% FSC. As in the FSC calculation before 2019, the positive bias was not included in the actual threshold and was 0.17% FSC, hence the improvement of the threshold was 0.04% FSC or an improvement of 23%. The orange flag indicated a medium alert level, with a CI of 95% ($t = 2.179$). Its threshold remained at 0.2% FSC, but as the bias was not included in the previous orange flag, the actual improvement was 0.02% FSC or 10%. Red flags represented high non-compliance alerts with a CI of 99% ($t = 2.528$); the red flag threshold could be reduced from 0.4% to 0.3% FSC. Likewise, the bias was not taken into account with the threshold. In case the bias was to be included, the previous threshold would in fact be 0.42%, and the actual improvement would therefore be 0.12% FSC, which represents an improvement of 30%. The thresholds for the orange and red flags are in fact even lower, but were rounded up to create operational thresholds (T_{OPS}) that are easy to memorize and apply in surveillance and enforcement operations, whilst remaining on the safe side for avoiding Type I errors (Table 2).

Table 2. Updated flag thresholds as of 2020.

Color flag	t	U	CI	Sulfur limit	T	T_{OPS}
Yellow	0.86	22%	60%	0.10%	0.13%	0.13%
Orange	2.179	38%	95%	0.11%	0.19%	0.20%
Red	2.528	48%	99%	0.15%	0.28%	0.30%

When a sulfur limit of 0.11% FSC would be applied for the red flag instead of 0.15% FSC, with the updated uncertainty, the CI increases even to 99.99% for the same threshold (0.295% FSC).

In the aforementioned uncertainty calculation, the uncertainty was calculated for individual measurements. When conducting multiple measurements, the uncertainty of the average value can be divided by the square root of the number of measurements (n).

$$u_n = \frac{u_{tot}}{\sqrt{n}} \tag{15}$$

For possible non-compliant OGVs, a confirmation measurement was made in almost all cases, which means that in the case of alerts, the actual uncertainty was even lower and uncertainty thresholds could potentially be further reduced (Table 3).

Table 3. Alert flag thresholds based on two subsequent measurements.

Color flag	t	$U_{n=2}$	CI	Sulfur limit	$T_{n=2}$	$T_{OPS\_n=2}$
Yellow	0.86	15%	60%	0.10%	0.12%	0.12%
Orange	2.179	30%	95%	0.11%	0.16%	0.16%
Red	2.528	33%	99%	0.15%	0.22%	0.25%

By taking two measurements it is possible to state that observed non-compliant values of more than 0.198% FSC (orange flags) are above the sulfur limit of 0.11% with a CI of 99.99%.

3.7.2. Evaluation of Non-Compliance

An OGV was considered to be non-compliant when it was measured with a value exceeding the yellow threshold. As non-compliance can, strictly speaking in accordance with the EU Sulfur Directive (2016/802) [3] and the European Commission Decision (2015/253) [7], only be legally proven with a positive fuel sample taken in port. All non-compliance detections at sea referred to in this evaluation are expressed as alleged non-compliance. In nearly all instances when a measured OGV was found to be

potentially non-compliant, a second and third measurement was performed to confirm the initial measurement, with the NO_x sensor in "NO mode". As the initial measurement was performed with the NO_x sensor in "NO_x mode", and was therefore characterized by a higher uncertainty due to the uncertainty in the NO/NO_x ratio, it was chosen to not rely on this first measurement but only use the measurements made with the NO_x sensor in "NO mode" for the assessment of alleged non-compliance. This implied that, after the NO_x sensor was switched to the "NO mode", two additional measurements were required. If the second measurement (first in "NO mode") did not confirm the initial value, the OGV was reported as compliant to avoid Type I errors. In case the second and third measurements confirmed the first measurement, only the latter values were reported. If the two latter measurements were assigned to different alerting color flags, the lower alert level of the two was used as a precautionary measure to avoid overestimating the FSC value.

For 2020 and 2021, the FSC measurements were recalculated using the overall offset (0.0074% FSC) and slope correction (10.4%). These FSC values were compared to the updated compliance thresholds and resulted in 35 alleged non-compliant OGVs. In the same period, only 22 OGVs had been reported to port inspection authorities. For 13 OGVs, the initial measured FSC value was below the threshold, but by applying the span and offset, the corrected FSC value slightly exceeded the yellow color flag threshold.

3.7.3. Compliance Rate Comparison

The overall compliance rate was 97.3% for both 2020 and 2021. When looking in more detail at the distribution of the compliance levels between 2020 and 2021, it was observed that the number of red flags was slightly higher for 2021 (0.7%) compared to 2020 (0.5%). Furthermore, the number of yellow flags was higher for 2021 (1.7%) compared to 2020 (1.5%) and the number of orange flags was higher for 2020 (0.7%) compared to 2021 (0.3%). None of these frequencies were significantly different between 2020 and 2021. However, when comparing the compliance over the period 2020–2021 with the compliance for the year 2019 (95.9%), the difference was found to be significant ($p = 0.0445$). This is remarkable since the thresholds for 2019 were higher. If the same updated thresholds were to be applied to the 2019 data, the compliance level for 2019 would be 93.0%. If in addition, the bias of 0.0189 were to be applied, the compliance in 2019 would even fall to 85%. When looking at the red flags only, the 0.6% red flags in 2020–2021 were lower compared to the 0.9% in 2019, but this difference was not significant ($p = 0.5$). Consequently, it can be concluded that the compliance rate was substantially improved between 2019 and 2020, but concerns remain about the minor number of gross polluters (red flags).

3.7.4. Global Sulfur Cap and Global Bunker Fuel Prices

An explanation for this drastic improvement in compliance levels can be located in the implementation of the 'Global Sulfur Cap' and 'Carriage Ban'. Before 2020, OGVs were allowed to use Heavy Fuel Oil (HFO) of up to 3.5% FSC outside a SECA. As the fuel cost can contribute up to 50% or more of the operating costs of OGVs [40,41], the fuel prices and especially the price difference between compliant and non-compliant fuel may be an important driving force for non-compliance.

From 1 January 2020, the Global Sulfur Cap entered into force, as a result of which the FSC was limited worldwide to 0.5% [42]. Shortly after, from 1 March of the same year, the carriage of non-compliant fuel oil (i.e., HFO) for combustion purposes for propulsion or operations on board OGVs became prohibited, unless the OGV was equipped with an EGCS [43]. At the start of 2020, the price for Very Low Sulfur Fuel Oil (VLSFO), i.e., fuel oil with an FSC of 0.5%, was 598 $/ton in the port of Rotterdam (price on 6/01/2020). The price for Ultra Low Sulfur Fuel Oil (ULSFO), fuel oil with an FSC of 0.1%, was at that moment slightly lower at 593 $/ton. The price for Low Sulfur Marine Gas Oil (LSMGO) was 623

$/ton and thus very comparable with the price of VLSFO. At that moment, the price difference between SECA-compliant fuel and Global Cap Compliant Fuel was small. Therefore, it was economically speaking not profitable for OGVs to be non-compliant in a SECA. The HFO price was at that moment 304 $/ton much lower

From the start of 2020, prices decreased gradually until March 2020. From that moment onwards, due to the impact of the global Covid-19 pandemic, all fuel prices dropped by about 60%. On 28 April 2020, the fuel prices were reduced to 150 $/ton for VLSFO, 160 $/ton for ULSFO and 180 $/ton for LSMGO. The price difference in this period was still very small and also the price for HFO decreased, but less dramatically to 123 $/ton.

Due to the slow economic recovery following the aftermath of the global Covid-19 pandemic, fuel prices gradually started to increase again. The main turning point was the start of 2021; from that moment the price difference between ULSFO and VLSFO generally increased. By the summer of 2021, prices were again at the same level as at the beginning of 2020. The largest price difference in 2021 was observed on 18 October 2021 at a price of 606 $/ton for VLSFO, 710 $/ton for ULSFO and 724 $/ton for LSMGO, resulting in a price difference of 104 $/ton between VLSFO and ULFSO. For an OGV with fuel consumption of 200 tons/day, the potential economic gain of non-compliance was 20,800$ per day.

Recent dramatic developments in 2022, however, changed the global economic context so profoundly that the demonstrated improvement of OGV compliance levels for 2020 and 2021 would probably be stopped or reversed. Since the Russian invasion of Ukraine on 24 February 2022, the price difference increased to unseen record heights. On 3 May 2022, the price was 647 $/ton for HFO, 822 $/ton for VLSFO, 1270 $/ton for ULSFO and 1338 $/ton for LSMGO. The price difference between VLSFO and ULSFO was at that moment a staggering 517 $/ton (Figure S4). For a large container OGV (+10,000 Twenty-foot Equivalent Unit (TEU)), the average daily fuel consumption is in the range of 124 up to 367 tons/day [41]. This led to a potential economic gain of up to 190,000$ per day. (All prices above are for the port of Rotterdam and were provided by Ship & Bunker).

With this important price difference in 2022, a decrease in the compliance rate in 2022 was expected. Although at the moment of publication, the data for 2022 was still incomplete, the preliminary results for the compliance rate for the period 14 March 2022 until 3 August 2022 have thus far shown a significant decrease in the compliance rate to 95.2% ($p = 0.0246$). This confirms the negative compliance prognosis. Additionally, the average FSC was with 0.078% higher in this period than the average of 2021, although this difference was not found to be significant ($p > 0.1$).

The graphs in Figure S.4. demonstrate the impact of the absolute fuel price for MGO and the spread between ULSFO and MGO on the monthly average FSC and the non-compliance rate. The correlation between the monthly average FSC and the price for MGO is nevertheless low ($R^2 = 0.294$). The correlation between FSC and the price difference between ULSFO and MGO is slightly higher ($R^2 = 0.330$). A stronger correlation was found between the non-compliance rate and the price for MGO ($R^2 = 0.816$) and a slightly higher correlation was found when comparing the fuel price difference with the non-compliance rate ($R^2 = 0.818$). Furthermore, the slope of the linear regression is higher when the price difference is plotted against both the average FSC and non-compliance rate, compared to when the absolute price of MGO is plotted against the average FSC and non-compliance rate. This indicates that the price difference between high-sulfur fuel oils and low-sulfur fuels plays a more important role in compliance behavior than the absolute fuel price.

Another important explanation for the improved compliance from 2020–2021 is that it follows a downward non-compliance trend that has been initiated long before the implementation of the Global Sulfur Cap. This trend shows that the monitoring and enforcement efforts in Belgium and other European countries are paying off.

3.7.5. Compliance of OGVs with a Scrubber Installation

MARPOL Regulation Annex VI provides the possibility to use scrubbers, to continue using fuel with higher sulfur content, under the condition that emission limits are comparable to the SO_2/CO_2 emission ratios of OGVs running on compliant fuel [13–15]. Table S.2. provides the ratios corresponding to the allowed FSC, which are in fact based on the same emission factor calculation as provided in Formula 1.

$$\frac{SO_2(ppm)}{CO_2\,(\%\,VV)} = 10 \times \frac{SO_2(ppb)}{CO_2(ppm)} = \frac{10 \times FSC\,(\%)}{0.232} \tag{16}$$

OGVs equipped with a scrubber are allowed to use fuel oil with a very high percentage of sulfur (i.e., HFO). It has already been demonstrated that open-loop scrubbers create significant risks for the marine environment due to the release of scrubber wash water, in particular in densely navigated coastal waters [15,16,18]. But paradoxically they may also pose a significant risk of more air pollution in certain cases. Non-compliance may occur intentionally; for instance, the scrubber may be under scrubbing or may be switched off altogether, to lower the fuel consumption and/or energy demand from the scrubber. The pumps of a scrubber system have a very high power demand and may consume up to 10% of the generated electricity capacity [24,44,45]. Non-compliance may also occur due to negligence, when no action is taken after technical failures, or system-generated alarms. Non-compliance may furthermore occur unintentionally when the emission monitoring system on board is malfunctioning. These gas emission sensors are only calibrated occasionally (i.e., once per year). If in between calibrations a sensor is no longer providing the correct gas measurements, the SO_2/CO_2 ratios are no longer correct and may result in under or over scrubbing. Finally, "allowed" non-compliance can also occur either during the commissioning phase (a short period after the installation of the scrubber on board the OGV) or even for short periods during regular operations. The IMO guidelines allow for a one-hour non-compliance, and if in that short time window the situation cannot be resolved, the coastal state, port state and the OGV flag state must be informed [14]. However, if non-compliance occurs by OGVs equipped with a scrubber, this will almost always result in higher sulfur emissions compared to non-compliant OGVs without a scrubber, since the latter will, in most cases, be using VLSFO of 0.5% FSC.

In the period from 2020 and 2021, 38 possible non-compliant OGVs have been observed, of which 15 of these OGVs were equipped with a scrubber. When focusing on the higher observed FSC levels, six OGVs were observed with an FSC higher than 0.5% and five of these OGVs were using a scrubber system, as was indicated in the Thetis–EU database. The other OGV was most likely also equipped with a scrubber system, but this could not be confirmed. When focusing on all observed red flags, it can be concluded that at least six (but most likely seven) out of the total observed nine red flags from 2020–2021 concerned OGVs with scrubbers (i.e., 67%). In the case of yellow and orange flags, 10 out of 29 OGVs were equipped with a scrubber. This is in line with the global ratio of OGVs equipped with a scrubber, as by the end of 2021 ca. 30% of the global fleet was equipped with a scrubber system [21], which indicates that OGVs with scrubbers have a comparable amount of low to medium non-compliance levels as non-scrubber OGVs, but are twice as much observed with high non-compliance levels. It must be highlighted that the higher amount of non-compliant scrubber OGVs may be a temporary issue due to the limited experience a seafarer may have with the technology. Several shipping companies, such as Stenalines and Bore, operating in the surveillance area with scrubber OGVs have been observed frequently, and

although there were some initial non-compliant observations at the start of the scrubber operations (during the commissioning phase), these OGVs now have a very high (up to 100%) level of compliance.

3.7.6. Geospatial Analysis

When comparing non-compliance levels between the different zones (NHTSS, WHTSS, Westerschelde, Rotterdam and the zone between WHTSS and Rotterdam) that were identified in the 2015–2019 study [5] (Figure 8), there were no significant differences observed ($p > 0.05$); although the non-compliance was slightly higher for the NHTSS, especially when focusing on non-compliance levels from 0.2% FSC. The average FSC level for the Westerschelde was 0.08%, significantly higher than in the other zones ($p < 0.05$); although this result was biased by a single OGV equipped with a scrubber that was observed with an FSC of 2.35%. However, even when this vessel was excluded from the data, the average is still significantly different ($p < 0.05$).

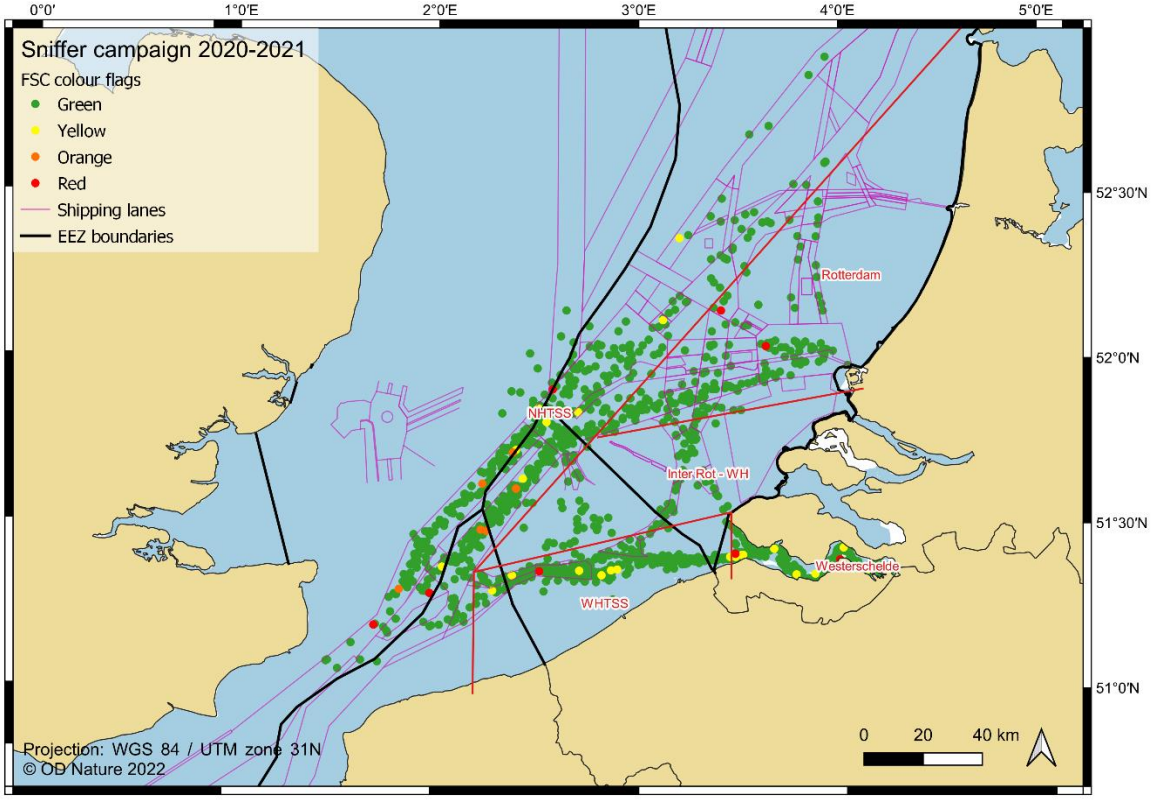


Figure 8. Spatial distribution of FSC measurements based on the color flags in the period from 2020–2021, with the location of the different zones: North–Hinder Traffic Separation Scheme (NHTSS), West–Hinder Traffic Separation Scheme (WHTSS), Westerschelde, Rotterdam and the area between WHTSS and Rotterdam Inter WH-Rot).

When comparing the spatial distribution of non-compliant OGVs in the period from 2020–2021, there were slightly higher non-compliance levels observed in the WHTSS and NHTSS shipping lanes compared to the Westerschelde, with non-compliance levels ranging between 1% and 18% per grid cell of 5 km, with one outlier at the West Hinder Anchorage area (WH) (Figure 9A). This is in line with the spatial analysis of the compliance data from 2015–2019 [5] that was performed with the previous thresholds and methodology. The data from 2019 have been reanalyzed using the lowered thresholds of 2020 (Figure 9B) and resulted in overall higher non-compliance levels, confirming the spatial distribution with higher non-compliance in the main offshore shipping lanes. When the 2019 data is further corrected with the bias of 0.0189% FSC (Figure 9C), the difference in compliance compared to 2020–2021 is striking, with non-compliance levels between 6% and 30% per grid cell. Although caution needs to be applied in the

interpretation of the 2019 data for the measurements that fall between the old and new thresholds, the OGVs were at that moment deemed compliant and therefore only one measurement was made. From 2020–2021, two measurements were made and in case one of the two was below the threshold, the lowest of the two was withheld to assess compliance. Furthermore, as was demonstrated in Section 3.2, there is a potential impact of the NO cross-sensitivity. This cross-sensitivity was included in the calculation of the bias. However, this was based on average NO emissions comparable to the Tier I emission levels. It was established that about 4% of the OGVs are not compliant with MARPOL Regulation 13 [27] and, therefore, emit significantly higher levels of NO. For these reasons, the non-compliance levels in Figure 9C are certainly an overestimation, the actual non-compliance levels must therefore lie between Figure 9B, C.

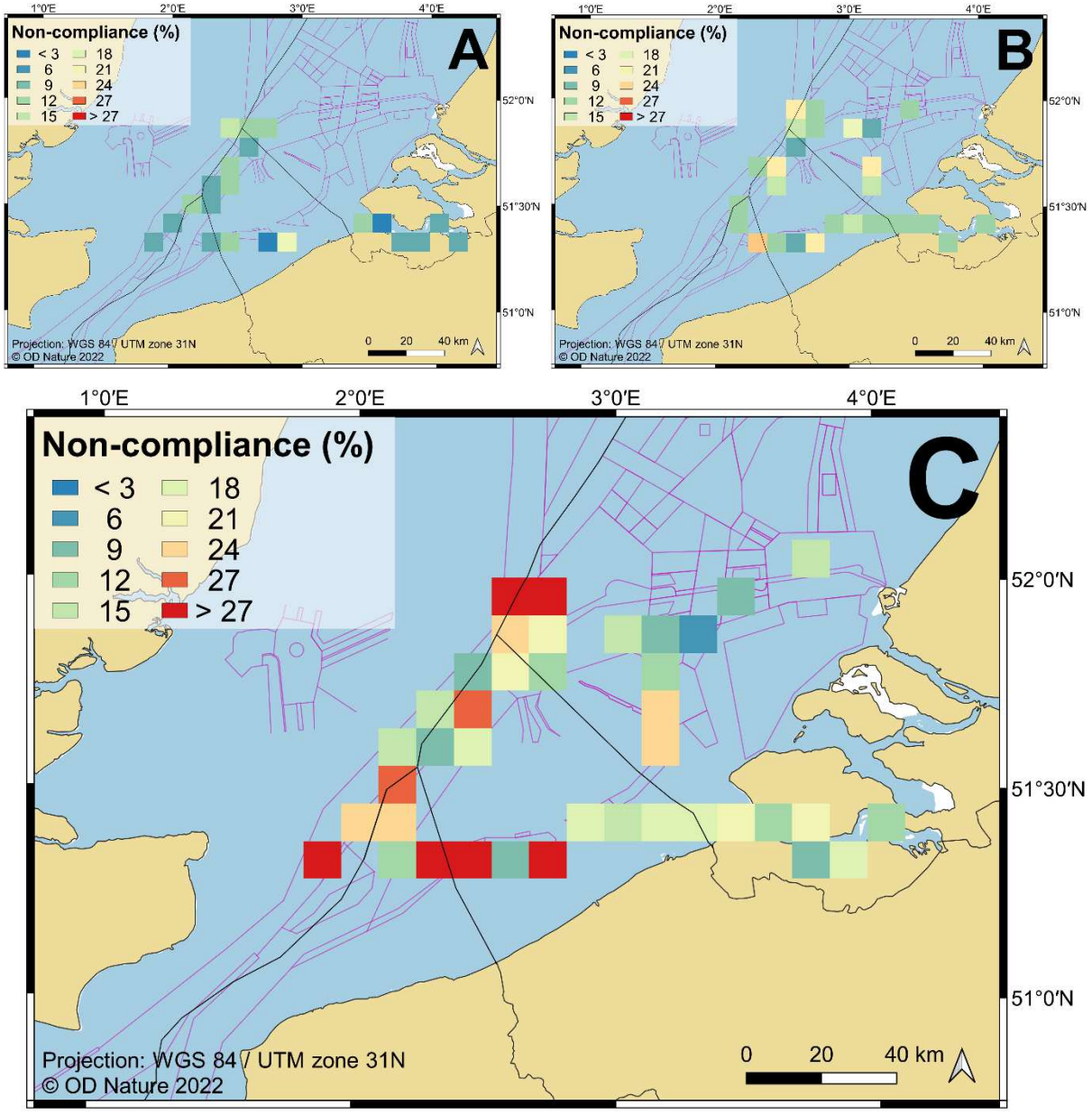


Figure 9. Non-compliance grid map with a grid size of 5 km, for the period of 2020–2021 (A), for 2019 applying the lowered thresholds (B) and for the 2019 data applying the bias and the lowered threshold (C). A filter of a minimum of ten OGVs per grid cell was used for assessing compliance levels.

4. Conclusions

Airborne measurements of FSC are not yet used as official and conclusive evidence for prosecution and sanctioning OGVs for violations of MARPOL Annex VI Regulation 14. However, these measurements provide a valuable non-compliancy indication that can be used to target potential violators for further inspections in the port. This paper demonstrates that the previous airborne sniffer methodology for the monitoring of compliance to sulfur regulation by OGVs, based on the SO_2/CO_2 ratio, has been substantially improved by applying novel features. Thanks to the upgraded vacuum air pump, the updated sniffer sensor system has a shorter response time (−9.2%), a higher SNR (+9.6%) and an increased flow, which drastically improved the quality of the sniffer measurements. Additionally, by including the NO_x sensor and measuring the NO concentration after an initial potential non-compliance was observed, the cross-sensitivity to NO was removed. With the introduction of a novel high-volume HC kicker with separated airflow, the impact of VOCs on the SO_2 measurements was removed. Finally, a procedure was developed to assess the proportional bias and absolute bias before ever using a special plume simulation mixture. Thanks to these modifications in the sniffer hardware and SOPs, uncertainty was considerably reduced. Owing to this reduced uncertainty, compliance thresholds could be lowered to 0.13% FSC for yellow flags and 0.3% FSC for red flags.

The average observed FSC of 0.07% for the period from 2020–2021 was significantly lower than the average FSC of 0.08% for 2019. If the bias were to be applied to this average FSC, the average FSC for 2019 could even be as much as 0.10%. The application of the improved thresholds resulted in an overall compliance rate of 97.3% with MARPOL Annex VI Regulation 14 for 2020–2021, which is significantly higher in comparison to the compliance rate of 2019 (95.9%). However, we need to take into account that the measurements in 2019 used a different methodology making it difficult to accurately compare compliance levels. In case the data in 2019 were to be assessed according to the 0.13% FSC threshold, compliance levels would be 93%; and in case the data in 2019 were to be corrected with the bias of 0.0189% FSC, compliance levels for 2019 could even be as low as 85%—although the latter is probably an overestimation (for aforementioned operational reasons).

Regardless of a potential comparison bias between the 2019 data and the 2020–2021 data, compliance levels improved drastically from 2020 onwards. This positive development coincided with the implementation of the Global Sulfur Cap in January 2020. Therefore, this regulatory measure can be seen as a crucial driving force for the improvement in compliance behavior and a further reduction of air pollution from OGVs. Nevertheless, the collapse of fuel prices in 2020 due to the global Covid-19 pandemic and the equal price for high- and low-sulfur fuels in this period need to be taken into account as well. Additionally, the monitoring and enforcement activities conducted by different European member states should be considered as a potential driver in the increased compliance rate. It should be noted that although the number of red flags also reduced between 2019 and 2020–2021, this was not regarded to be significant. This means that gross polluters remain a reason for concern in the future.

The annual average FSC of 0.06% for 2020 was significantly lower than the annual average FSC of 0.07% for 2021. The increased FSC values for 2021 and improved compliance in 2020 and 2021 can be explained by the evolution of fuel prices. As a result of the Global Sulfur Cap, OGVs were forced from 2020 onwards to operate on VLSFO. In 2020, the average price spread between VLSFO and LSMGO of 39$ was relatively low, but in 2021 the price difference increased to 65$. The largest price spread that year was observed on 18 October 2021, with a price difference of 104 $/ton between VLSFO and LSMGO. This could explain the higher observed average FSC for 2021. For an OGV with fuel consumption of 200 tons/day, the potential economic gain of non-compliance contributed to 20,800$ per day. Unfortunately, the war in Ukraine pushed the price difference between high and low sulfur fuels to

unseen heights with an average price spread of 231$ in 2022 (until 12 May 2022), and an unprecedented maximum price spread of 517 $/ton on 3 May 2022, creating a potential economic gain of more than 100,000$ per day for that same OGV with daily consumption of 200 tons/day. Accordingly, it can be expected that the average FSC and non-compliance for 2022 will increase again (as already indicated by preliminary sniffer flight results for the first part of 2022). The new techniques described in this research provide a solution for effective and more refined offshore compliance monitoring in the future.

Another important benefit of the airborne monitoring method lies in its potential to effectively monitor and target scrubber OGVs. Special attention should be paid to these scrubber OGVs as, in case of non-compliance, they generally have much higher FSC levels (>0.5%) compared to OGVs that are not equipped with a scrubber. Inspections of these systems are laborious, time-consuming and not highly effective. The targeted information resulting from airborne monitoring has the potential to drastically improve scrubber inspection efforts in port. This is not only important for port inspection authorities, as shipping companies that abide by the rules will profit, because compliant OGVs will be less likely to be targeted by an inspection in port. This will save time and money for the shipping company and also contribute to the creation of a level playing field.

The airborne OGV emission measurement dataset is available on:
https://doi.org/10.24417/bmdc.be:dataset:2687.

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6. Supplementary figures and tables

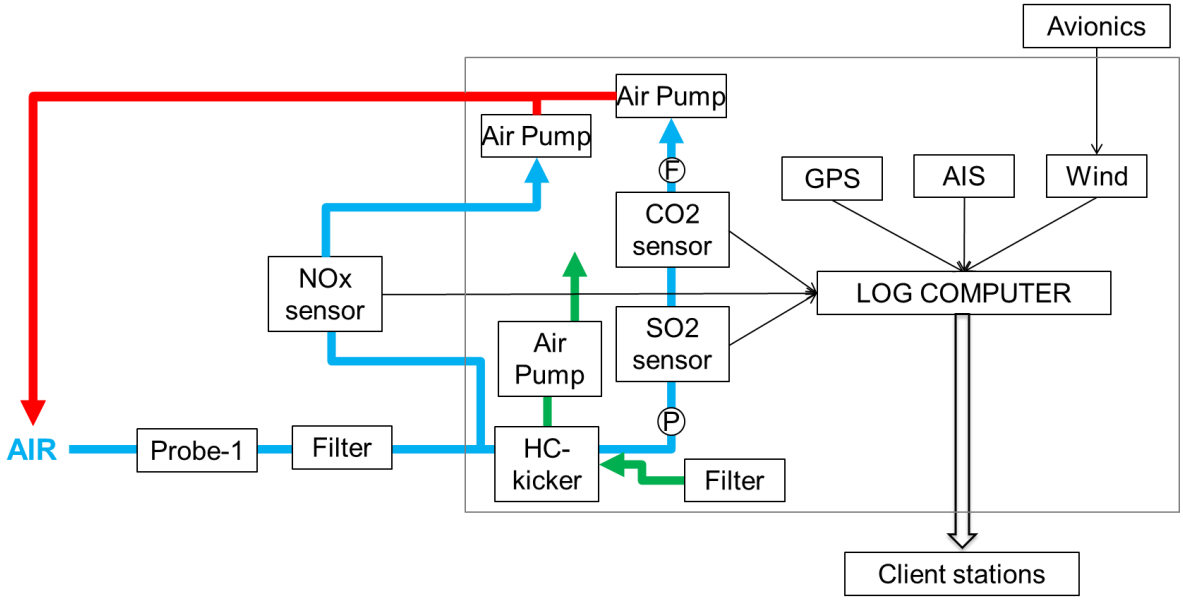


Figure S.1. Schematic overview of the updated sniffer sensor system, with NO_x sensor and HC kicker.



Figure S.2. PTFE sample bag of 50 l filled with 2.5 l of the plume simulation gas mixture and further filled with synthetic air.

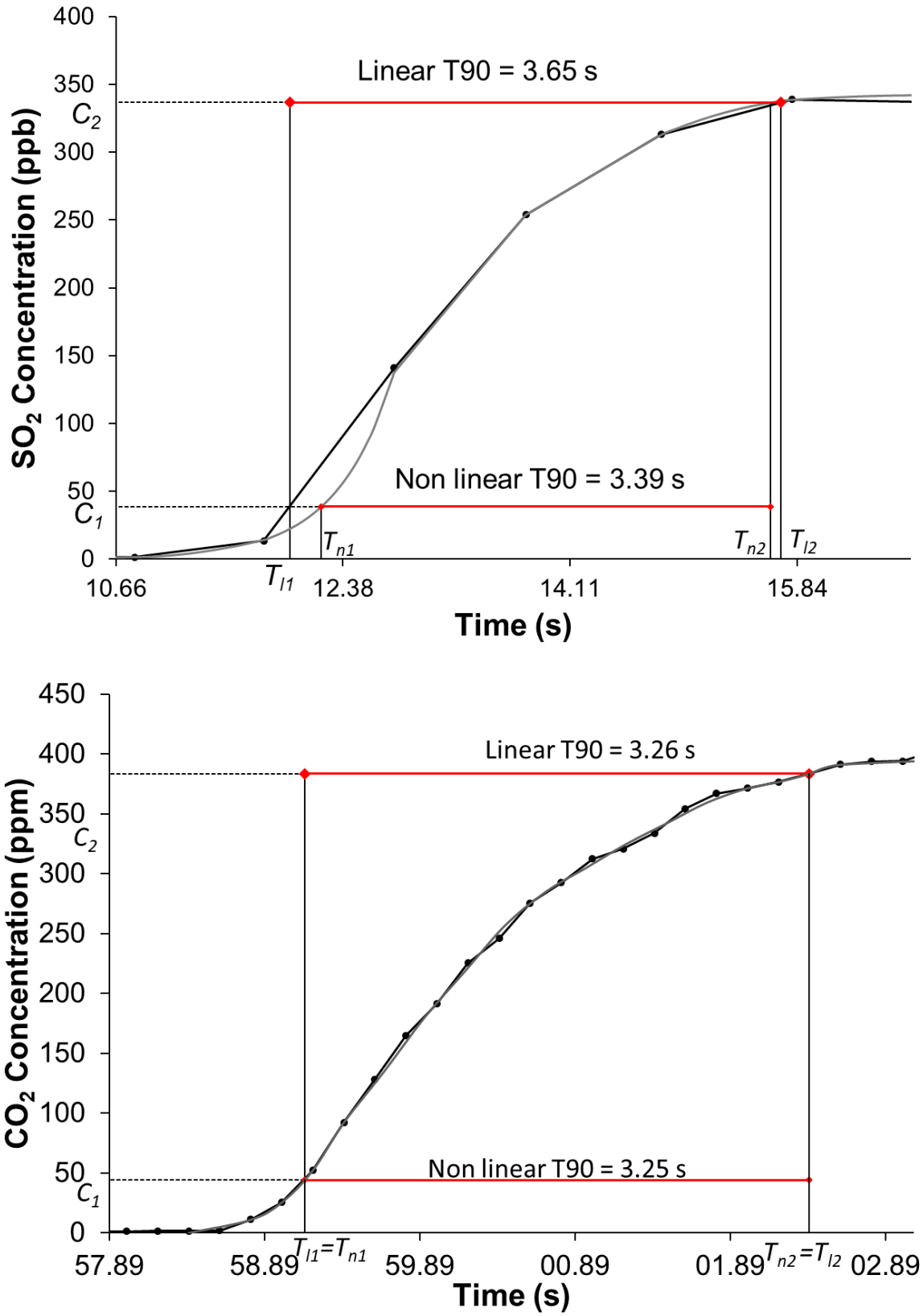


Figure S.3. Upper: T90 response times for the Thermo 43i TLE sensor. Lower: T90 response time for Licor 7200 RS. At airflow of 8 l/min.

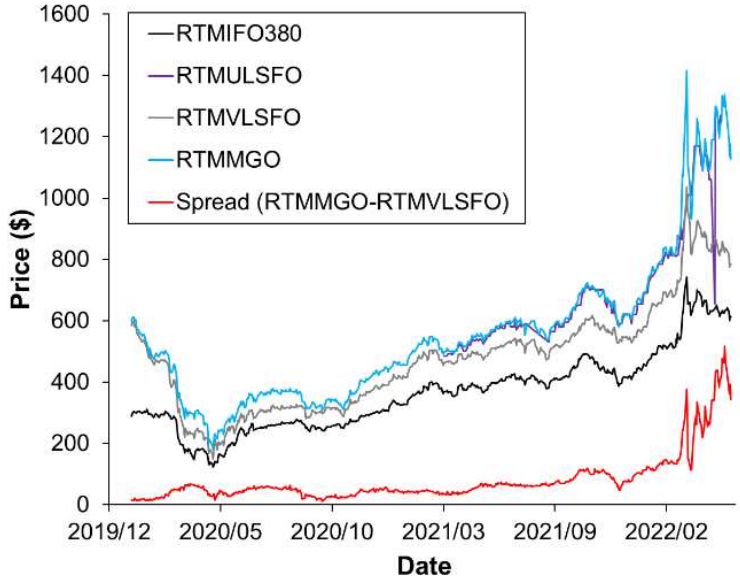


Figure S.4. Evolution of the bunker fuel prices for Rotterdam (own visualization based on data provided by Ship and Bunker).

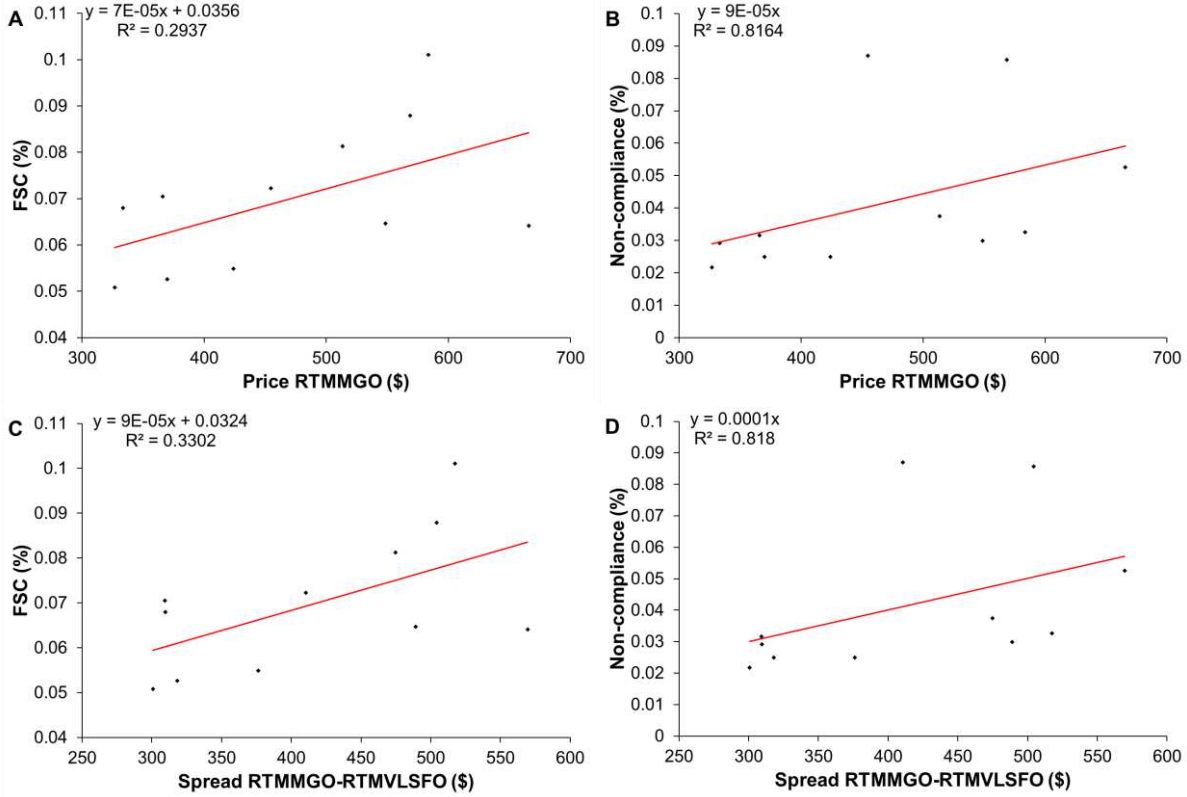


Figure S.5. The upper graphs demonstrate the relation between price of MGO in Rotterdam compared to the monthly average observed FSC (A) and the monthly observed non-compliance rate (B). The lower graphs demonstrate the relation between the price difference or spread between MGO and VLSFO in Rotterdam compared to the monthly observed FSC (C) and the monthly observed non-compliance rate (D). For the non-compliance rate an intercept at zero was chosen assuming a zero non-compliance when either the absolute price or the spread is zero.

Table S.1. Supplementary uncertainty factors and the combined supplementary standard uncertainty. The uncertainty on the NO/NO_x ISR (80%) is not included as the uncertainty factors as described below are only applied for the non-compliance thresholds (not for the uncertainty on the compliant OGVs). For the potential non-compliant OGVs, NO will be assessed directly without using of the NO/NOx ISR.

Supplementary uncertainties	Max
SO_2 span gas drift (3 months)	2.77%
SO_2 span gas concentration*	0.20%
CO_2 span gas drift (6 months)	0.92%
CO_2 span gas concentration*	0.05%
Measurement accuracy SO_2 sensor	0.40%
Measurement accuracy CO_2 sensor	0.05%
Error on FSC correction (offset reference)	2.35%
Error on FSC correction (offset measured)	2.17%
Error on FSC correction (Slope reference)	2.79%
Error on FSC correction (Slope measured)	4.26%
Uncertainty molar mass S	2.49E-06
Uncertainty molar mass O	1.88E-05
Uncertainty molar mass C	0.01%
Uncertainty molar mass N	2.49E-06
Uncertainty C content in marine fuel	0.83%
Combined supplementary standard uncertainty $\sum u_i^2$	3.17%

** According to gas certificate*

Table S.2. Emission ratios for EGCS systems [18].

Fuel oil sulphur content (% m/m)	Ratio emission SO2(ppm)/CO2(% v/v)
4.5	195
3.5	151.7
1.5	65
1	43.3
0.5	21.7
0.1	4.3

Table S.3. Observed color flags and non-compliance levels for the different zones

2020-21	Average FSC	Green flags	Yellow flags	Orange flags	Red flags	Non-Compliance	Non-compliance orange and red flags
NHTSS	0.064	527	8	6	2	3.0%	1.5%
WHTSS	0.064	291	6	0	2	2.7%	0.7%
Westerschelde	0.080	310	9	0	2	3.5%	0.6%
Rotterdam	0.063	158	0	0	2	1.3%	1.3%
Inter Rot-WH	0.073	96	0	0	1	1.0%	1.0%

Part II

Chapter 4: The Role of Belgian Airborne Sniffer Measurements in the MARPOL Annex VI Enforcement Chain.



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The Role of Belgian Airborne Sniffer Measurements in the MARPOL Annex VI Enforcement Chain

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Abstract

The Royal Belgian Institute of Natural Sciences launched its airborne sniffer program in 2015 whereby a custom-built sniffer sensor was installed onboard the Belgian coastguard aircraft enabling the measurement of SO_2 and NO_x emitted by ocean-going vessels (OGVs). The data gathered on non-compliant OGVs were subsequently sent to port inspection authorities, who were then able to trigger inspections more rapidly than had they not had the data from the aircraft. This study reveals the added value of airborne alerts on port inspection effectiveness, a subject that had not been previously documented. This article demonstrates that airborne alerts have not only led to increased sanctions but have also drastically improved the efficiency of port inspection authorities, leading to a 50% reduction in the enforcement cost per confirmed violation. Port inspection authorities were able to follow up on 46% of the generated Fuel Sulphur Content (FSC) alerts. Of the alerts that were followed up, 43% were confirmed as non-compliant after inspection. This means that 20% of the total number of generated airborne alerts, which includes those that were not able to be followed up, met conditions for legal sanctioning. In contrast, for NO_x alerts, only limited follow-ups were conducted by port inspection authorities. None of the alerts were confirmed with those inspections, mainly due to the lack of inspection mechanisms for real-world NO_x emissions under IMO and EU regulations. In addition, for this study, a large-scale remote FSC measurement validation analysis was conducted for the first time, comparing airborne FSC measurements and FSC reference data. In order to obtain FSC reference data, onboard measurements from exhaust gas cleaning systems (EGCSs) were collected, together with fuel samples from Belgian port inspection authorities. The validation analysis revealed that the empiric deviation in the airborne FSC measurements with the FSC reference data was 9%, which was significantly lower than the 25% uncertainty used in the reporting of the alerts. This study helps pave the way for an increased role of airborne monitoring in the MARPOL Annex VI enforcement chain.

1. Introduction

1.1. Background to MARPOL Annex VI

The SO_x and NO_x emission limits from ocean-going vessels (OGVs) are laid down by the International Maritime Organization (IMO) in the MARPOL Protocol of 1997 (MARPOL PROT 1997, as amended), described in the MARPOL Annex VI. Reference to Annex VI in this article will be to the Revised MARPOL Annex VI in 2008 and not to the 2021 Revised MARPOL Annex VI because airborne emission measurements took place before entry into force of the 2021 revision [1]. In MARPOL Annex VI, designated emission control areas (ECAs) were defined with more stringent standards for SO_x and NO_x.

MARPOL Annex VI Regulation 14 defines the SO_x emission limits. As of 2008, the Baltic Sea and the North Sea were designated as sulfur emission control areas (SECAs) (Figure S1, upper). The maximum fuel sulfur content (FSC) of the marine fuels used by OGVs in SECAs was reduced in successive steps

until it reached the current limit of 0.1% FSC. Instead of using compliant fuels, OGVs can also use natural gas or an exhaust gas cleaning system (EGCS) to achieve the same emission level as low-sulfur fuels (Table S1) [2–5]. The sulfur limit outside SECAs, initially set in 2005 to 3.5% [1,4,6], was reduced in 2020 to 0.5% by the so-called 'Global Sulfur Cap' [7] (Figure S1, middle). On 1 March 2020, the so-called "Carriage Ban" came into force, prohibiting the carriage of non-compliant fuels in the bunker tanks, unless the OGV is equipped with an EGCS [8].

Moreover, at the European level, SO_x emissions from OGVs are regulated by the EU Sulphur Directive ((EU) 2016/802) and the Commission Implementing Decision ((EU) 2015/253), which lay down the rules regarding sampling and reporting of the sulfur content of marine fuels [9–12]. The latter stipulated that Member States must carry out documentary inspections on at least 10% of the total number of individual OGVs calling at Member States' ports (Art 3.1, Implementing Decision). In addition, 40% of the inspected ships will be checked using approved (laboratory) fuel sampling methods for Member States that fully border the SECA area (Art 3.2(a)). However, the number of fuel samplings can be reduced by up to 50%, by subtracting the number of OGVs that have been checked for compliance using remote sensing or the rapid scan analysis (Art 3.3(a)) [11]. At the national level, Belgium further implemented MARPOL Annex VI and the Sulfur Directive ((EU) 2016/802) in 2020 [13].

MARPOL Annex VI Regulation 13 introduced NO_x emission limits for OGVs and described dedicated NO_x emission control areas (NECAs) where stricter limits apply for recently built OGVs (Tier III, see further in this section) [5]. Five years after the enactment of the North American and US Caribbean NECA on 1 January 2016 [14], the SECA in the Baltic Sea and the North Sea was expanded in 2021 with a NECA and renamed emission control area (ECA) [15,16]. To reduce NO_x emissions in the OGV exhaust gases, engine manufacturers have the option to either tackle the combustion processes in the engine or to install NO_x abatement systems such as a selective catalytic reduction (SCR) and/or exhaust gas recirculation (EGR) [17].

MARPOL Annex VI divides the merchant fleet into four categories, from tier I to tier III, and before tier I (tier 0), according to the construction of the ship based on the keel-laying date (KLD) or a similar stage of construction (Reg. 2.19). The emission limits per tier follow a decreasing curve in the function of the engine-rated speed (ERS or n), expressed in rotations per minute (RPM) (Figure S1, lower). In order to obtain the required Engine International Air Pollution Prevention (EIAPP) Certificate, a verification test is executed before the installation of the engines onboard the OGV, in accordance with the NO_x Technical Code, MEPC.1/Circ.679 [18,19]. After the installation of the engines onboard, an International Air Pollution Prevention (IAPP) Certificate is issued by a classification society. In addition, the NO_x Technical Code stipulates that all interchangeable parts that exert an influence on the NO_x emissions, described as "engine components" (1.3.3, NO_x Technical Code), must be listed in the NO_x technical file and all modifications must be recorded and stored onboard together with the EIAPP Certificate and the IAPP Certificate [18,20]. Substantial modifications mean all modifications to the engine components that may cause NO_x emissions to exceed the limit, in which case a new verification test is required (6.4.16.1, NO_x Technical Code). In contrast, the replacement of engine components that do not alter the NO_x emissions are not considered a substantial modification (1.3.2 NO_x Technical Code). The verification tests are based on five different engine test cycles with four to five engine loads and corresponding weighting factors (WFs) (Table S2). It is crucial to highlight that only for Tier III, a "not to exceed" (NTE) limit is defined, which states that the NO_x emission may not exceed the limit by more than 50% at any of the individual engine loads [18]. Another critical aspect of the Technical Code to highlight is that currently, no restrictions are described under the 25% main engine loading point for any of the tiers.

In contrast to the sulfur regulations, NO_x emissions from ships are currently not regulated by an EU directive. However, discussions are ongoing to evaluate if MARPOL and its Annexes, thus including NO_x emissions, can be included under a future revision of the Ship Source Pollution Directive (2005/35/EC) [21]. More importantly, on 18 December 2022, the European Commission, the European Parliament, and the Council of the EU finalized a Provisional Agreement on a broad set of policy proposals for the "Fit for 55" climate package, including a landmark reform of the EU Emissions Trading System (ETS) and the milestone introduction of the Carbon Border Adjustment Mechanism (CBAM), which still requires formal approval from the Parliament and the Council before entering into force. Particularly, once formally adopted, the new ETS system will, for the first time, integrate emissions from the maritime sector into its scope, with the obligation to surrender allowances rising from 40% of verified emissions in 2024 to 100% in 2026. Moreover, in addition to the gradual implementation of CO_2 emission retributions, OGVs will also have to pay for their non-CO_2 emissions, such as N_2O and CH_4, from 2027 [22–24]. At the end of 2024, it will be decided if other greenhouse gasses, such as NO_x, and certain particles, such as Black Carbon (BC), will be included in the ETS [25–27].

1.2. Research Questions

In order to create an adequate compliance level for the MARPOL Annex VI Regulation 13 and 14, an effective enforcement strategy is required that incorporates a reasonable non-compliance detection rate. The legal sanctions need to be in proportion to the economic benefit that would result from an OGV being non-compliant to discourage violations. Such an effective enforcement strategy will not only contribute to environmental protection, human health, and economic benefits but will also contribute to a level playing field for the maritime transport sector [28–32]. Therefore, ensuring that all market actors follow the same set of rules and conditions is considered one of the backbones of international trade [33–36].

Remote measurements from either fixed stations or airborne platforms have been shown to provide an efficient solution to monitor the compliance of OGVs with regard to the emission regulations and, therefore, have the potential to contribute to the enforcement strategy and level playing field [37–60]. Even so, the use of airborne measurement data has not yet been recognized as independent legal evidence for observed possible non-compliant OGVs and is thus far merely used for risk-based targeting of inspections in ports. However, the impact of the provision in these airborne alerts on the effective results of port inspections of OGVs has not been examined in detail to date. The main research question of this study was to evaluate how and to which extent airborne measurement alerts have already contributed to the efficiency and results of inspections in Belgian and North Sea ECA ports. Looking ahead, this study also examines the full potential role of airborne monitoring for the targeting of inspections.

In addition, to increase the enforcing effect of airborne monitoring, the airborne measurements would need to obtain a legal evidence status, not only to serve as an alerting mechanism but also to become a direct enforcement action. An essential part of the process for receiving the status of legal recognition of airborne measurements is the validation of airborne measurement reliability in real-world conditions. So far, several studies have been executed comparing onboard measurements with remote measurements. However, these studies were limited to one or two OGVs and concerned only one OGV type [37,38,53,61–64]. The third research question of this study was therefore to evaluate how airborne measurements would relate to real-world emissions for a larger amount and more diverse sample of OGVs.

Finally, airborne operations and airborne measurements, in particular, are known to be costly endeavors. Previous studies have already demonstrated the advantage of scale in airborne measurements [31,42,43]. The third research question focuses on evaluating the overall cost-effectiveness of airborne operations compared to other remote measurement methods and onboard inspections.

2. Methods and Materials

2.1. Airborne Measurements

The Scientific Service of the Management Unit of the Mathematical Models of the North Sea (MUMM) of the Royal Belgian Institute of Natural Sciences (RBINS) is recognized by Belgian Law as one of the legally competent authorities for the monitoring and enforcement of MARPOL regulations at sea [65]. Since 1991, MUMM has been responsible for airborne surveillance of the Belgian North Sea area and neighboring waters in the so-called Bonn Agreement (BA) Quadripartite Zone of Joint Responsibility (BAQPZJR) (Figure S1, upper).

Since 2015, the RBINS has been conducting airborne surveillance operations to monitor sulfur emissions from OGVs in accordance with MARPOL Annex VI Regulation 14 [39]. In addition, from 2020 onwards, the RBINS has been conducting airborne surveillance operations to monitor NO_x emissions from OGVs in accordance with MARPOL Annex VI Regulation 13 [39–41].

Based on the measurement uncertainty, thresholds were described that reflect not only the uncertainty level but also the level of non-compliance. Three flags of color were defined for both SO_2 and NO_x. For the lowest alert level, the yellow flag with a confidence interval (CI) of 68% ($\sigma = 1$) was used. For the orange flag, a CI of 95% was used ($\sigma = 1.96$); for the most excessive pollution alerts, a red color flag was defined based on the 99% CI ($\sigma = 2.576$.) (Table 1). The uncertainties align with the results of other organizations and previous measurement campaigns using similar techniques [38,42,46–48, 54].

Table 1. Applied thresholds for FSC and NO_x compliance monitoring.

Color Flag	CI	σ	FSC		NO_x		
			$T_{ops<2020}$ (%)	$T_{ops>2020}$ (%)	$T_{ops\ Tier\ I}$ (g NO_x/kWh)	$T_{ops\ Tier\ II}$ (g NO_x/kWh)	$T_{ops\ Tier\ III}$ (g NO_x/kWh)
Yellow	68%	1	0.15	0.13	25	20	6
Orange	95%	1.96	0.20	0.20	35	30	8
Red	99%	2.576	0.40	0.30	55	45	9

Once a possible violation was observed, a flight report was sent to the port inspection authorities. In addition, the alert was shared in the Thetis–EU database and became accessible to all EU Member States (Section 2.3) [39,40,46]. The provision of airborne alerts may therefore be considered the first step in the enforcement chain. The onboard inspection executed by the port inspection authorities is the second step in the enforcement chain (Figure 1).

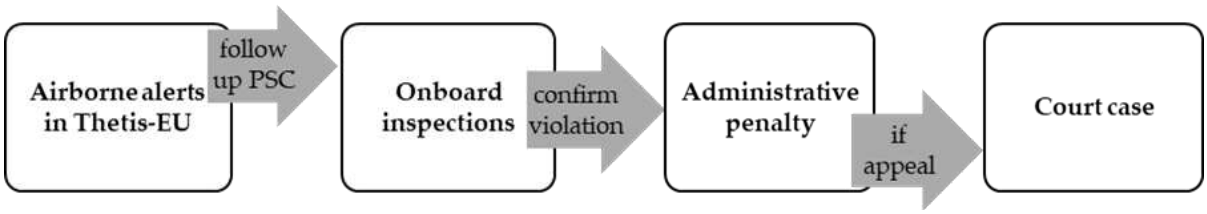


Figure 1. Flow chart illustrating the 4 steps of the MARPOL Annex VI enforcement chain.

2.2. Port Inspections

The various international emission regulations for OGVs are mainly enforced by onboard inspections in ports. In general, this is done under the jurisdiction of port state control (PSC). In Belgium, inspections regarding the sulfur regulations are the responsibility of a separate service called 'Environmental Safeguarding and Dangerous Goods' within the department 'Shipping Control' of the Federal Public Service (FPS) Mobility and Transport. This separate service has eight environmental inspectors, which operate next to PSC and control compliance with the EU Sulfur Directive (EU) 2016/802. Not being

part of PSC means that those inspectors cannot arrest vessels, but in the case of breaches in the sulfur regulations, they make police reports based on documentation requirements and fuel controls. These inspectors have no access to the Paris MoU Thetis database (PSC) but only to the Thetis–EU database (Section 2.3).

Inspections are executed in accordance with the IMO and EU guidelines, whereas fuel samples are collected from a location in the fuel supply lines as close to the main engine as possible. This location is always decided in close cooperation with the chief engineer and is most often either from a dedicated sampling point or close to the last booster filter. A fuel sample is collected in one sampling bottle (1 L), and after mixing, is dispersed over two other bottles; one bottle remains onboard to be used as counter-expertise if necessary. The other two bottles are taken along by the inspector, one of them is sent to an accredited laboratory for analysis using an X-ray fluorescence (XRF) spectrometer (accuracy of 0.01% FSC), and the other sample is stored and kept as a reference sample in case a violation was observed in the first sample [11,66].

In the case that an onboard inspection demonstrates non-compliance with an FSC above 0.15% FSC, the environmental inspectors shall make a police report. On the basis of this report, the administrative sanctioning department of FPS Mobility can impose an administrative fine. This sanctioning step can be considered the third step in the enforcement chain. If the accused party does not agree with the proposed administrative fine, this party can appeal using a suspending petition before the Court of First Instance, which can be considered as the fourth and final step in the enforcement chain, without a possibility of appeal (Art. 16, Law of 25/12/2016) [67] (Figure 1).

2.3. Thetis–EU

A dedicated webtool, called Thetis–EU, was created by the European Maritime Safety Agency (EMSA) to record information on the results of individual compliance verifications carried out by Member States' competent authorities under the Sulphur Directive (EU) 2016/802. Thetis–EU also serves as a platform to exchange information on remote measurements from and between EU Member States. Thetis–EU should not be confused with Thetis, which is the ship inspection database of the Paris MoU. Thetis–EU was established following the Commission's Implementation Decision, which stipulates that a system for the reporting of inspection results is mandatory. However, Member States have the discretionary power to choose whichever reporting system they prefer, and the use of Thetis–EU is therefore on a voluntary basis [11,12,68]. The inspection results and alerts in Thetis–EU are accessible to all EU Member States and two EEA EFTA States—Iceland and Norway. Data on inspections and compliance levels can be publicly accessed [68]. For detailed inspection results of specific OGVs, authorization has to be granted by the Thetis–EU National Competent Authority (NCA). For Belgium, this NCA lies with the FPS Mobility and Transport, and a request for read-only access is granted to the crewmembers of the coastguard aircraft.

When an OGV with an alert enters a port in another EU Member State, local port inspection authorities can see this alert and start an inspection. Therefore, Thetis–EU facilitates the link between step one and step two of the enforcement chain (Figure 1). It is noteworthy that the local authorities do not receive an active warning from Thetis–EU when an alerted OGV is heading to their jurisdiction. Instead, authorities have to check manually if alerted ships are calling at their ports. Consequently, there is no prioritization system for inspections as is the case with the Thetis system under the Paris MoU on PSC.

For optimizing the reporting to Thetis–EU and improving the efficiency of port inspections, in 2019, RBINS implemented an automatic upload of the airborne measurements to Thetis–EU. By doing so, Belgium was the first Member State to upload monitoring data directly into Thetis–EU. In addition to

non-compliant alerts, these data also include compliant data. This compliant information is highly valuable for port inspectors as it allows a more efficient targeting of the inspections by ignoring OGVs that were recently found to be compliant.

2.4. FSC Data Validation with Reference Data

A validation analysis has been carried out to compare the airborne measurements with real-world reference FSC data. Two types of data were used for the collection of reference FSC data. For the first type, FSC information was collected from fuel samples. For the second type, SO_2/CO_2 ratios were collected from vessels equipped with an EGCS.

2.4.1. FSC Comparison with Fuel Samples

For the large majority of the airborne alerts, data were submitted to Thetis–EU. In the case that an onboard inspection was carried out in the next port of call, the fuel sampling results were entered in Thetis–EU by the port inspection administration. The results of those fuel sample analyses have been retrieved for warnings generated by the aircraft. As the alerts concerned mainly non-compliant data, this can create a bias in the data comparison. Therefore, additional fuel samples were taken by the Belgian environmental inspectors for airborne measurements of compliant OGVs.

2.4.2. EGCS Data

OGVs that are equipped with an EGCS are required to have a continuous emission measurement system (CEMS) that logs specific emission-related data (7, Data recording) [2]. This system is a vital part of the proper functioning of the EGCS, which is used to provide SO_2 removal rate feedback to the EGCS control unit. This feedback is essential to ensure, on the one hand, that the emissions are never over the limits defined by IMO [2]. On the other hand, this also allows the OGV to optimize the EGCS capacity to avoid over-scrubbing, which would cause higher fuel consumption and discharge water with lower PH levels. Discharges of wastewater with low PH levels are not only corrosive for the piping but moreover, may also not be in accordance with the regulations. The IMO guidelines for EGCS stipulate that the minimum PH of the discharge wastewater is 6.5 or no less than 2 PH levels different from the inlet water (10.1.2) [2]. The CEMS data are logged according to the IMO guidelines for EGCS [2] and can be requested for verification by port inspection authorities. CEMS data include measurements of SO_2 (in ppm) and CO_2 (%Vol), which are used to calculate the SO_2/CO_2 ratio (1.3). In accordance with the 2015 IMO guidelines for EGCS, this ratio must be below 4.3 in the SECA (1.3) (Table S1) [2], which corresponds to an identical conversion used by the sniffer software (with the difference in the units). This procedure is described in Appendix II of Resolution MEPC. 259 (68) [2].

$$FSC = \frac{SO_2}{CO_2} \times 0.0232 \left[\frac{\text{ppm}}{\%\ \text{vol}}\right] \quad (1)$$

The data from the EGCS logs, therefore, provided an excellent set of reference data to validate the airborne measurement data. For this purpose, seven shipping companies were contacted to request if CEMS data from their OGVs could be provided for the times when they were measured with the aircraft. The shipping companies were selected based on the number of airborne measurements and OGV type (container, RoRos, tanker, and bulk carriers). Four companies agreed to cooperate and provided CEMS information for the period 2018–2022. Unfortunately, no tanker and no container OGVs were among the participating companies, as one of the companies requested to remain anonymous, and no information was shared with the other participating companies.

Although the IMO guidelines recommend that UTC time be used for the data logging (Art 7.2) [2,69], often a time correction had to be applied as it was observed that for some OGVs, the time and location of the log files did not match with the coordinates from the Automatic Identification System (AIS) of

the OGV at the moment of the measurements. To correct for any short-term differences, an average SO_2/CO_2 ratio has been applied for the two CEMS measurements before and the two CEMS measurements after the moment of the airborne measurement. Some OGVs were equipped with multiple EGCSs, for which the average values of the different EGCSs were calculated. Most of the voluntarily provided information concerned compliant data. However, some non-compliant measurements were also included for which CEMS log data was obtained after a port inspection, including from container OGVs. As a consequence, only tanker OGVs were missing in the final dataset.

2.5. Statistical Analysis

A Kolmogorov–Smirnov test was used to assess the normality of the emission measurement data. With a $p < 0.05$, the data were considered not normally distributed. Therefore, non-parametrical tests were used. A two-tailed Kolmogorov–Smirnov test was used to compare the distribution in the measurements of different sources (i.e., ship inspection data versus airborne data). Distributions were discovered to be significantly different when $p < 0.05$ [70]. To determine a difference in the compliance rate between two distributions, a two-sided chi-square test was used. Statistical significance was defined when $p < 0.05$ [71,72]. When Type I errors are used, they refer to the number of false positives; when Type II errors are used, they refer to the number of false negatives [70].

To compare the correlation between (n) reference FSC (FSC_{ref}) and airborne measurements (FSC_{AC}), a Pearson correlation coefficient (r) was used in addition to a modified Bland Altman (B&A) visualization. A B&A visualization is commonly used for the comparison of two measurement methods and provides an alternative for a correlation or linear regression with a corresponding coefficient of determination (R^2). The main advantage is that it provides a quantification of the agreement between two methods based on the determination of Limits of Agreement (LOA) that can be evaluated according to a user predefined Maximum Allowable Difference (MAD). The B&A visualization furthermore allows for the evaluation of the absolute and proportional bias [73,74]. For a B&A visualization, the difference between the results of the two measurement methods is plotted against their average. The LOA are generally defined by the ±Standard Deviation (SD) (±LOA). For the LOA with the Confidence Interval (±LOA + CI), the SD is multiplied by the sigma value (σ) for which generally 1.96 is used. If the ±LOA and/or the ±LOA + CI are within the $\pm MAD$, both measurement methods can be considered comparable.

For the modified B&A visualization in this study, the difference between the reference measurements and the airborne measurements was plotted against the average FSC. The standard B&A was modified for the use of the SD in combination with the Relative Standard Deviation (RSD). To create the MAD, the sulfur limit (S) was used as defined within the thresholds, for yellow flags (0.13–0.2% FSC), S is 0.1% FSC; for orange flags (0.2–0.3% FSC), S = 0.11% FSC; for red flags (>0.3% FSC), S is 0.15% FSC. The MAD was defined to ensure that the difference between the airborne measurement and the reference data is never more than S, avoiding, therefore, Type I errors.

$$RSD\ (\%) = \frac{SD_{Diff}}{\frac{\sum_i^n (FSC_{ref_i} + FSC_{AC_i})}{2 \times n}} \tag{2}$$

$$SD_{Diff} = SD\left(FSC_{ref} - FSC_{AC}\right) = \sqrt{\frac{\sum_i^n (FSC_{ref_i} - FSC_{AC_i})^2}{n}} \tag{3}$$

$$FSC_{Diff}\ (MAD) = S + FSC_{average} \tag{4}$$

3. Results and Discussion

3.1. Follow-Up on Airborne FSC Alerts by Port Inspection Authorities

3.1.1. Results of Onboard Inspections

For Belgium, it was defined, in accordance with the EMSA, that ca. 5500 OGVs are calling Belgian ports every year. According to the Commission Implementing Decision ((EU) 2015/253), inspections must be carried out on 10% of these port calls (Art 3.1), which amounts to 550 inspections per year. Belgian inspection authorities started with sulfur inspections in 2015, but as they only carried out five inspections in that year, 2016 is used as the starting point. In total, 12,148 onboard inspections were completed between 2016 and 2022 (Figure 2A). With an average of 1735 inspections per year, this is substantially higher than the 550 mandatory inspections. The Commission's Implementation Decision further indicates a 40% fuel sampling effort for MS bordering a SECA (Art 3.2.), representing 220 fuel samples. However, a reduction of up to 50% may be applied when remote monitoring is used (Art 3.3), which comes down to 110 mandatory fuel samples per year [11]. In total, 871 fuel samples were taken between 2016 and 2022, or 124 fuel samples per year on average, therefore amply fulfilling the required number of fuel samples.

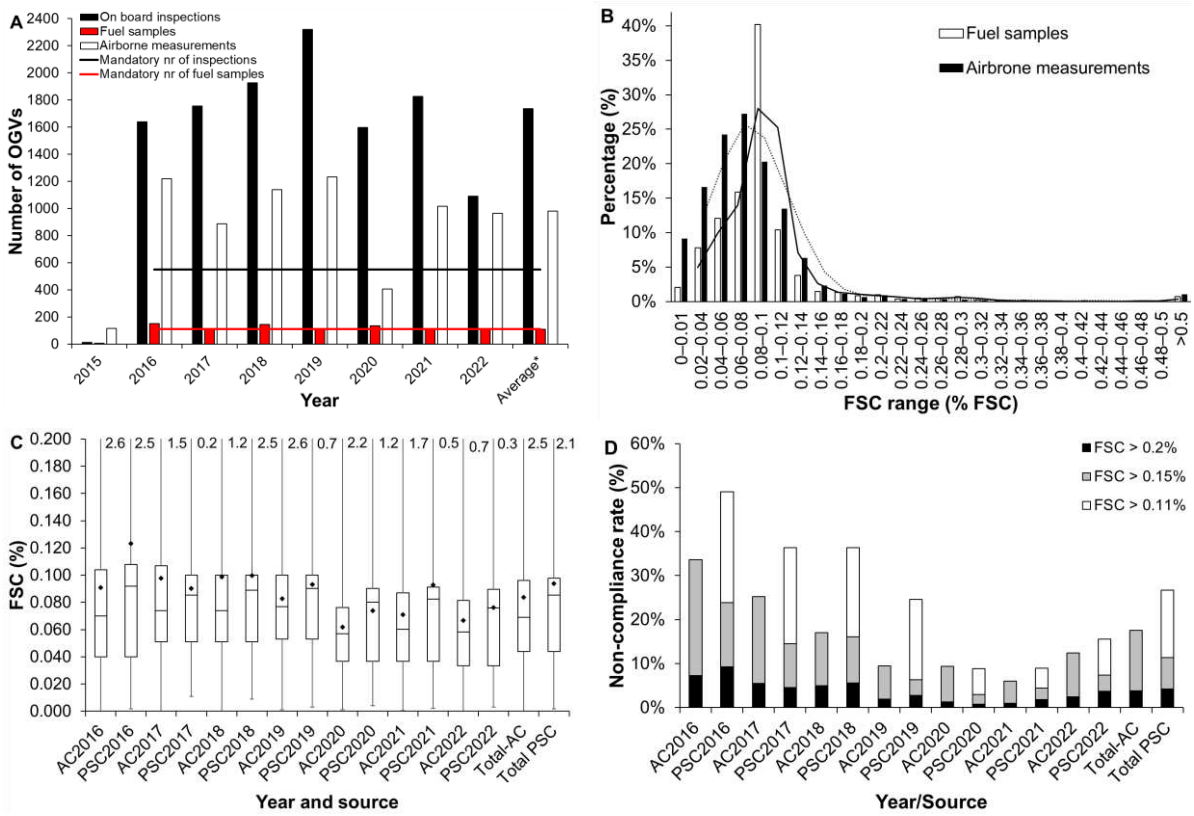


Figure 2. Overview of the number of mandatory and executed onboard inspections (black) and fuel samples (red) undertaken by Belgian port inspection authorities and airborne measurements (white) (A). Comparisons of observed FSC values and moving averages of fuel samples with airborne measurements between 2016 and 2022 (B). Boxplot comparison of FSC between fuel samples and airborne measurements with 25, 75% percentile, median values, and average values (♦) (C). Comparison of compliance rates between port inspections and airborne monitoring between 2016 and 2022 (D).

During the global COVID-19 pandemic, the number of port calls in Belgian ports decreased by 8% in 2020 and by 5% in 2021 compared to 2019 [75]. Despite this, Belgium still managed to meet the pre-

COVID set number of inspections and fuel samples, which contrasts with the impact of the pandemic within the Paris MoU, for which a 27% reduction in the number of PSC inspections was reported [76].

When in port, the overall FSC non-compliance is assessed based on the document inspections, and the compliance rate is very high; 99.5% of the OGVs had an FSC under 0.15%. When looking at the compliance rate based on fuel samples alone, compliance is substantially lower, with 92.2% of the OGVs under 0.15% FSC. The average FSC from the collected fuel samples was 0.096% FSC.

3.1.2. Results of Onboard Inspections

Regarding airborne monitoring, between 2016 and 2022, 6961 OGVs were checked for FSC, with an average of 978 OGVs per year. A total of 626.5 flight hours were spent on MARPOL Annex VI surveillance or an average of 89.5 flight hours per year, and of the measured OGVs, 93.6% were considered compliant, and the mean observed FSC was 0.084% FSC.

The Belgian average FSC and non-compliance levels are slightly higher when compared to other studies and measurement campaigns [42,51,52, 54, 77–85]. This is most likely related to 1) the closer distance to the SECA border, leading to a higher likelihood of observing OGVs who either delayed (outgoing traffic) or advanced (ingoing traffic) their fuel change-over procedures; 2) the closer proximity of the Belgian coastguard aircraft to the OGVs during the measurement, resulting in higher gas concentration peaks; and 3) the use of special plume simulation mixtures during the calibration, eliminating the measurement bias [39,40,86,87]. When looking at other NO_x studies, similar NO_x emission factors have been observed. Like the Belgian results, other studies have also indicated lower non-compliance levels for NO_x compared to FSC. The most important finding, indicating higher non-compliance levels for Tier II and Tier III compared to Tier I, has also been confirmed in other studies [50,85,88–93].

Some authors have elaborated that environmental factors such as temperature (T) and relative humidity (RH) may influence the remote measurements of FSC [42,44, 54]. In addition, both T and RH are known to have an impact on NO_x emissions and are therefore included as a correction factor in the NO_x Technical code [17,18,41,94]. For this reason, the seasonal and environmental effects on the airborne measurements were analyzed using an evaluation of the monthly average, median, and non-compliance levels. For the calculation of these monthly values, a total of 100 measurements were set as the minimum per month. For FSC, the months of March–November provided sufficient data, whereas for NO_x, the months of March–October were used. The monthly averages, median, and non-compliance levels for FSC showed very little variation, with an SD of 0.01% FSC for both the average and median FSC and an SD of 1.8% for the FSC non-compliance level. For the monthly average and median NO_x, an SD of 0.6 g NO_x/kWh was found, and the SD of the NO_x non-compliance was 1.4%. The visualization of the average, median, and non-compliance FSC showed higher levels in the summer compared to the winter (Figure S4A). However, the effect is weak, with a large variation in non-compliance between the summer months. For NO_x, no seasonal relation could be observed (Figure S4B).

To evaluate the impact of the T and RH on the FSC and NO_x measurements, the monthly average T and RH were normalized and plotted together with the normalized median and non-compliance rate for FSC and NO_x [95]. This showed hardly any impact of the T and RH on the median FSC; however, a limited T effect on the FSC non-compliance rate was observed, and this effect corresponds with the observed seasonal effect (Figure S4C). The T and RH did not have any impact on either the median NO_x or the NO_x non-compliance rate (Figure S4D). In addition, the R^2 values for the linear regression between these monthly FSC and NO_x values and the monthly average T and RH were calculated to evaluate the impact of environmental factors on the airborne measurements (Table S3). This showed low to very low R^2 values, with 0.3–0.4 for the median and average FSC and 0.02–0.2 for the median

and average NO_x. A higher but still low R^2 of 0.6 was found for the non-compliance of FSC with T, confirming the seasonal effect. On the other hand, the R^2 for the FSC non-compliance with RH was 0.00. The R^2 was also 0.00 for the linear regression between the NO_x non-compliance and T, as well as for the RH.

Due to the limited or lack of seasonal and environmental effects on the airborne measurements, their impact was not taken into account during the further data analysis in this study. This does not imply that there are no environmental or seasonal effects to be considered for the remote measurement of FSC and NO_x. Merely, it can be stated that these factors had no significant impact on the remote measurement data in this study. This could be due to the relatively high measurement uncertainty and/or the limited seasonal variation over the Belgian waters from spring until fall.

3.1.3. Comparison of Port Inspection and Airborne Results

The significant difference in the number of fuel inspections between port inspections and airborne inspections immediately demonstrates the scale advantage of airborne monitoring. It takes 275-man hours per year to carry out 110 fuel samples in the port (only including the time of the inspection), while for 110 measurements, 10 flight hours would suffice, with a crew of four on board or 40-man hours, so almost 7 times more time efficiency.

When comparing the FSC measurement distribution between the aircraft and fuel inspections, they broadly show the same patterns. The aircraft measurements have the highest proportion in the 0.06–0.08% FSC interval (median = 0.086% FSC), and the fuel samples have a higher proportion in the 0.08–0.1% FSC interval (median = 0.069% FSC) (Figure 2B). This difference is also observed in the average FSC values, which indicates that the average FSC of the airborne measurements is 0.084% FSC, significantly lower than the average measured FSC in the port of 0.094% FSC ($p < 0.001$) (Figure 2C). To exclude the effect of the airborne alerts, the average FSC was calculated for the fuel samples excluding the samples carried out after airborne alerts, which was 0.087% FSC. Although the difference was already much smaller, it still appeared to deviate significantly from the average FSC from airborne measurements ($p < 0.001$) (Figure S2, upper), which indicates the presence of a slight negative measurement bias for the airborne measurements. This average FSC for the fuel inspections without alerts was furthermore compared with the average FSC for the fuel inspections that followed up on an alert, which was with 0.21% FSC significantly higher ($p < 0.001$) and even exceeding the 0.1% FSC legal limit substantially (Figure S2, lower), therefore demonstrating the added value of the airborne surveillance.

It is not easy to draw conclusions about the compliance rates between the airborne results and the results of either the onboard inspections or the fuel samples (Figure 2D). Onboard inspections may miss non-compliance if no suspicious aspects in the documents are observed (Type II errors). Fuel samples, on the other hand, may be biased as they are not taken randomly but are taken after suspicious aspects in the documents, after an alert from airborne monitoring, or due to previous deficiencies. When the overall compliance based on the document inspections is compared to the airborne compliance rate, the airborne compliance rate is significantly lower ($p = 0.000$). When the compliance rate based on the fuel samples is compared to the airborne results, the airborne compliance is significantly higher ($p = 0.0281$).

However, to compare the compliance rate of the airborne measurements with the unbiased fuel sampling, the number of fuel samples greater than 0.15% FSC, excluding the fuel samples initiated after the airborne alert was calculated as 94.1%. The number of airborne measurements exceeding 0.15% FSC was 94.2%, which is highly comparable. In general, the difference was not found to be significant ($p = 0.8691$).

3.1.4. Follow-Up on Alerts Based on Thetis–EU

All possible non-compliant OGVs observed with the coastguard aircraft were reported to the Belgian port inspection authorities by email. Only about 1/3 of the observed potentially non-compliant OGVs went to a Belgian port. In the case that the non-compliant OGVs were sailing to a Belgian port, inspectors of FPS Mobility prioritized these OGVs for inspection and carried out an inspection on board whenever it was operationally feasible. In case the non-compliant OGV was not sailing to a Belgian port, an alert was made in Thetis–EU. Initially, this was completed manually using FPS Mobility, but from 2019 onward, the results were automatically uploaded to Thetis–EU after each flight. Once an OGV was inspected in a Belgian or another EU port, inspectors reported this in Thetis–EU. For all airborne alerts, a manual check was carried out to see whether actions had been taken, as Thetis–EU does not (yet) contain a tool that can generate those exports. For the evaluation of the follow-up, a qualitative approach was used to see if the OGV was followed up within a reasonable time. For OGVs operating only in the ECA, a limit of 14 days was used; for OGVs operating on international routes, it was checked if the OGV was inspected upon their return to the ECA (within a maximum of 3 months).

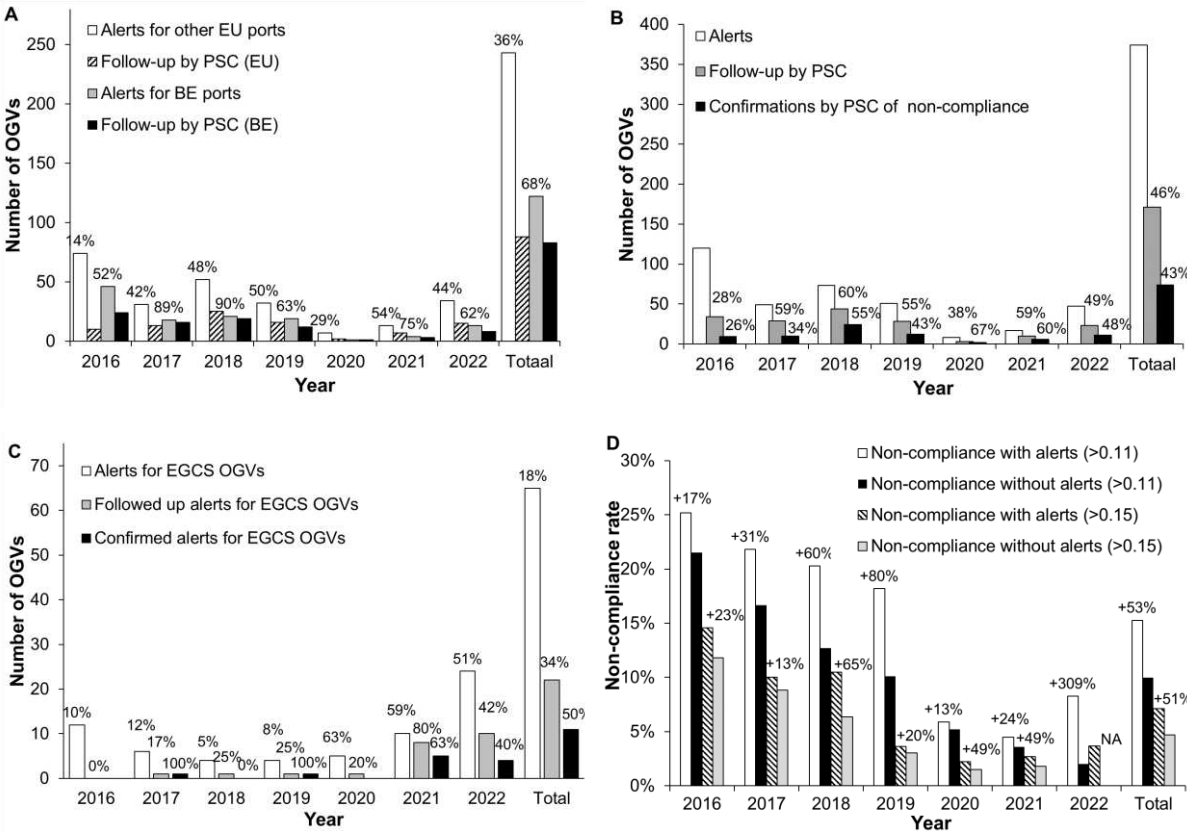


Figure 3. Follow-up of alerts for OGVs in Belgian ports and follow-up of alerts for OGVs in other EU ports (A). Number of alerts send to port inspection authorities, number of alerts followed-up, and number of confirmations (B). Alerts for EGCS OGVs (% of the total number of alerts), number of alerts followed-up with port inspection, and number of EGCS OGVs confirmed after inspection (C). Improvement in the efficiency of PSC inspections (D).

In terms of analyzing the follow-up on airborne alerts by port inspection authorities, a distinction was made between Belgian and other EU ports of destination (Figure 3A). In 2015, only five inspections were carried out in Belgium. Moreover, the airborne measurement was taken in a test period without the results put into Thetis–EU, and thus 2015 is omitted from the analysis. In 2016, only 34 of 120 alerts were followed up (28%). This low follow-up was mainly due to the limited follow-up on alerts in Thetis–EU, as 24 alerts out of 46 alerts for Belgian ports were followed up, and only 10 out of 74 alerts

for other EU ports were followed up. In 2017, the overall follow-up improved to 59%, with 16 out of 18 alerts followed up in Belgian ports and 13 out of 31 alerts in other EU ports. In 2018, the overall follow-up increased further to 60%. Again, the follow-up in Belgium was very high with 19 out of 21 alerts. In addition, the follow-up in other EU ports increased with 25 out of 52 alerts followed-up. In 2019, there were fewer alerts reported, resulting in a limited decrease in the follow-up to 55%, with 12 out of 19 alerts in Belgium, and 16 out of 32 alerts in other EU ports. In 2020, due to the global COVID-19 pandemic, the global follow-up fell substantially back to 38%: one alert was delivered to Belgian ports, which was followed up, and two out of seven alerts were followed up by other EU ports. In 2021, the overall follow-up increased again to 59%, three out of four alerts in Belgian ports were followed up, and in other EU ports, 7 out of 13 alerts were followed up. In 2022, more alerts were generated, whereas the follow-up fell back to 49%, with 8 out of 13 alerts followed up in Belgian ports and 15 out of 34 in other EU ports. During 2016–2022, 83 out of 122 reported FSC alerts to a Belgian port were followed up (68%), and 88 out of 243 alerts were followed up in other EU ports (36%) (Figure 3A). The overall follow-up of airborne alerts for OGVs with all ports of destinations combined is 46%, which can still be considered relatively high, as 20% of the observed OGVs had a port of destination outside the SECA.

3.1.5. Confirmation Rate of Airborne Alerts in Ports

The confirmation of the airborne alerts was analyzed based on the results of the fuel sampling, entered in Thetis–EU after an alert was followed up by port inspection authorities. An alert was considered to be confirmed as soon as the measurement of the fuel sampling was above 0.11% FSC. In Belgium, a public statement and financial penalty are only applied above 0.15% FSC, and this limit was investigated separately.

In the period 2016–2022, port inspection authorities in Belgium and in other EU countries were able to confirm the alert in 43% of the cases, after an inspection had been carried out onboard the OGV (Figure 3B). Noteworthy is that the confirmation rate is lower for Belgian ports (39%) compared to other ports (48%), which is likely due to the fact that most alerts for OGVs with a Belgian port of destination went to Antwerp (22% of the observed OGVs), while OGVs with another country as a destination went to Rotterdam (17% of the observed OGVs) (Figure S3). OGVs going to Antwerp must sail on the river Scheldt, which takes 5–6 h, adding several hours to the time lap between the measurement and the fuel sampling, hence decreasing the chance of confirming the non-compliance.

The reason why the port inspection authorities did not always confirm the initial alerts may be due to several factors. One of the factors is time: on average, the time between the alert and the onboard inspection was 49 days. In the meantime, the OGV might have completed the fuel changeover procedures or switched to compliant fuel. The median time to successfully confirm the non-compliance was 2 days. The high follow-up time was often a result of alerts for OGVs with a destination at a port outside the EU, and the OGV could only be inspected after entering an EU port. In other cases, the OGV was only in port for a very short time or arrived in the evening (or the weekend), and the inspectors did not have sufficient time or staff to organize an onboard inspection. In some cases, the lack of confirmation could be the result of a false positive alert (Type I error). One of the reasons for obtaining a false alert was high emissions of VOCs, resulting in higher SO_2 readings. These false positives were eliminated from 2020 on after installing a customized hydrocarbon kicker [40]. Very high NO_x non-compliances may also have impacted FSC measurements between 2016 and 2019. From 2020 on, this NO cross-sensitivity was also eliminated with the installation of the NO_x sensor [40,41]. Nevertheless, both NO and VOCs have most likely only impacted the yellow flags. In some cases, ship incinerators may also affect SO_2 readings. However, it is unlikely that this would result in multiple false readings as these are highly temporal events. By taking multiple measurements, these Type I errors are significantly reduced [40]

3.1.6. Follow-Up on EGCS OGV Alerts

The number of OGVs equipped with an EGCS or so-called scrubber increased drastically over the years. At the end of 2021, 30% of the global fleet was equipped with an EGCS system [96]. As OGVs equipped with an EGCS are able to use Heavy Fuel Oil (HFO) with an FSC of up to 3.5% or more, they pose a significant risk for high SO_2 emissions in the case of non-compliance. Non-compliance may occur intentionally, for instance, to lower fuel consumption or when no action was taken after technical failures or system-generated alarms. Non-compliance can also occur unintentionally if the onboard emission monitoring system is not functioning properly. If non-compliance occurs, this will result in SO_2 emissions that can be multiple times higher than emissions from non-compliant OGVs that are not equipped with an EGCS but most likely operating on Very Low Sulfur Fuel Oil (VLSFO) of 0.5% FSC outside the ECA. This means that, when observed as non-compliant, these non-EGCS OGVs are generally observed with FSC values between 0.13% FSC and 0.5% FSC.

A wide variety of shortcomings with EGCS OGVs are also observed by other EU Member States, such as Germany and the Netherlands. In order to draw awareness to these issues, in 2022, the Netherlands submitted an information document at MEPC 79 to address certain inspection issues of EGCS OGVs in ports [97].

Since the start of the Global Cap in 2020, the number of EGCS OGVs observed has increased dramatically. This shift was also clearly observed in the number of alerts generated for EGCS OGVs (Figure 3C). Before 2020, there were very few alerts for EGCS-OGVs, excluding some OGVs that were emitting higher levels of SO_2 in their commissioning phase in 2015 and 2016. However, of the 2363 monitored OGVs in the period 2020–2022, 21% were equipped with an EGCS. In the period 2020–2022, 44 non-compliant EGCS-OGVs were observed, representing 59% of the total number of observed non-compliant OGVs, which indicates that the proportion of EGCS-OGV in the non-compliance observations is almost three times as high as the relative amount of observed EGCS OGVs. The overall rate of non-compliance observations for EGCS OGVs was 15% over the period 2020–2022, while the overall rate of non-compliant observations for non-EGCS OGVs was 1.8%, which is significantly lower ($p = 0.000$). When focusing on the higher observed FSC levels over the period 2020–2022, 12 out of 12 observed OGVs with an FSC above 0.5% were equipped with an EGCS. From a flag color perspective, 16 out of 21 red flags were EGCS OGVs, and 12 out of 18 orange flag OGVs were equipped with an EGCS. For yellow flags, 16 out of 38 were equipped with an EGCS.

EGCS OGVs are not only observed more often to be non-compliant they also provide more challenges for the onboard inspections. In accordance with the IMO guidelines on EGCS, OGVs are required to keep data logs on regulated parameters, which are among others: SO_2/CO_2 ratios, PH values of water in- and outlets, the concentration of Polycyclic Aromatic Hydrocarbons (PAHs), and suspended matter in the discharged water. OGVs are required to keep these logs for a minimum of 18 months onboard (7.4, 2015 EGCS Guidelines) [2–5,69]. Nevertheless, checking these logs is very time-consuming and has low efficiency in detecting deficiencies. Even with the use of airborne alerts, the sanctioning of EGCS OGVs is not easy. In some cases, the logs showed compliant values, and in some cases, the non-compliant values lasted only for a short time, and in one case, the non-compliance was confirmed but the OGV owners provided information that showed due diligence.

From 2016–2022, a total of 55 alerts were generated from OGVs with EGCS. For 39% of these alerts, an onboard inspection was initiated (with 40% in Belgian ports and 39% in other ports), which is 6% lower than for non-EGCS OGVs but with no significant difference ($p = 0.6178$). For 41% of the inspections following an alert, non-compliance was confirmed, which is 16% lower than for the non-

EGCS OGVs but also not statistically different ($p = 0.4154$). This demonstrates that airborne monitoring provides an important added value in the enforcement of the EGCS regulations.

3.1.7. Improvement in Port Inspections

As mentioned in Section 3.1.1, the compliance rate of neither the fuel sample results nor the onboard documentary inspections reflected the actual random non-compliance rate of OGV at the port. It was therefore not easy to determine the direct benefits of aerial monitoring for port inspections. In Section 3.1.1, it was already demonstrated that the average FSC of all onboard fuel samples, including the fuel samples initiated after an airborne alert, was higher than the average FSC of the fuel samples that were executed without an alert. In addition, fuel sample compliance rates, including those taken after an airborne alert, were significantly higher than the airborne non-compliance rate. Furthermore, no difference was observed in the compliance rate between the fuel samples and the airborne measurements after omitting the fuel samples that were taken after an airborne alert. In Section 3.1.2, it was furthermore demonstrated that 43% of the airborne alerts were confirmed.

To demonstrate that airborne measurements have a positive effect on the efficiency of the inspections in ports, different approaches are used to support this link. In the first approach, the relative increase in the observed compliance percentage during port inspections, with or without the use of airborne alerts, is examined. Experience with the EU-funded CompMon project [43] shows that random non-compliance in the port is around 3%. With a confirmation rate of 43%, this would mean an improvement with factor 13 in the case that port inspection authorities would rely only on airborne monitoring alerts. With the relatively low number of alerts, Belgian port inspection authorities cannot rely solemnly on alerts from the aircraft to initiate an investigation (as shown in Section 3.1.2 only ca. 1/3 of the fuel samples are taken after an airborne alert). To examine the actual realized benefits of the airborne alerts for the Belgian port inspection authorities, the non-compliance rate from all port inspections, including the inspections initiated after an alert, is compared with the non-compliance rate of the port inspections excluding those initiated after an alert. This analysis shows an overall significant increase in the observed non-compliance in port inspections of ca. 53% ($p = 0.0035$) above 0.11% FSC, and a significant increase of 51% above 0.15% FSC ($p = 0.044$) (Figure 3D). If we look at the increase in violations above 0.2% FSC, the increase is still 48%, while the difference is not significant ($p = 0.1342$), which is purely a result of the lower number of high non-compliances.

In a second approach, the level of non-compliance was examined with a comparison of three compliance levels (0.11% FSC, 0.15% FSC and 0.20% FSC). The non-compliance level of OGVs above 0.11% FSC in port inspections initiated without airborne alert was 10.0%, while the non-compliance of inspections resulting from an alert was 84%. The non-compliance level above 0.15% FSC in the port inspections taken without airborne alert was 6%, while the inspections initiated after an airborne alert was 38%. The observed non-compliance level above 0.2% FSC in port inspections without an airborne alert was 4%, and the non-compliance of the inspections after airborne alerts was 22%. The improvement in the non-compliance rate by port inspections after an alert is significant for all levels ($p = 0.000$). This analysis shows that airborne monitoring can address both high and low FSC levels and can therefore be applied to identify large and small emitters where other warning mechanisms may be less successful.

For inspections of EGCS-OGVs, the added value of airborne monitoring in the enforcement chain is even more relevant. In total, 974 EGCS-OGVs have been inspected, representing 4% of the total number of inspections. Of all these inspections, six were executed after an alert was generated with airborne monitoring. All port inspections lead to three confirmed violations of EGCS-OGVs, of which two were a result of an alert and only one was found without the help of airborne alerts, therefore increasing the efficiency of port inspections of EGCS-OGVs by a factor of three.

3.1.8. Administrative Fines Imposed in Belgian Ports

Exhaustive information was collected from public statements (which is a statement of a criminal fact and a ticket for a fine issued by a law enforcement officer) and administrative fines issued for OGVs after an inspection in Belgian ports. The public statements and administrative fines imposed by Belgian port inspection authorities in the period 2016–2022 are shown in Table 2. It is crucial to highlight that not all public statements were subject to a fine. In 2016, the regime of administrative fines for violations of shipping laws was not yet in force in Belgium [67]. More importantly, it must be noted that not all confirmed non-compliances resulted in a public statement. No public statement was made if the FSC was between 0.1% FSC and 0.15% FSC and, as a consequence, no fine followed. For one confirmed case, the reference sample was contaminated and could not be re-analyzed, which was therefore dismissed. One case for an EGCS OGV was confirmed as non-compliant, but due diligence was proven, and the case was dismissed. In total, 32 public statements have been made for violations of MARPOL Annex VI, for a total amount of EUR 1,425,200. Among these, 12 violations (41%) resulted from an alert made by the Belgian Coastguard aircraft and one from an alert from the German Federal Maritime and Hydrographic Agency (BSH), resulting in an amount of EUR 482,800 (34%) (the total amount of the fines for 2022 was not available at the time of submission). In the period 2016–2022, no perpetrators appealed against the fines, so no cases went to court. Of the 32 public statements, three involved an EGCS-OGV, totaling fines of EUR 216,000; two of these OGVs were reported by the aircraft and represented a total fine of EUR 200,000.

Table 2. Public statements and fines issued by Belgian port inspection authorities in the period 2016–2022.

Year	Total Public Statements	Public Statements after Remote Measurement	%	Total Amount of Fines (EUR)	Amount of Fines after Remote Measurement (EUR)	%
2016	3	3	100%	-	-	-
2017	7	2	29%	112,400	21,600	19%
2018	13	4	31%	668,800	261,200	39%
2019	4	1	25%	452,000	200,000	0%
2020	1	0	0%	136,000	0	0%
2021	2	1 *	50%	56,000	0	-
2022 ***	2	2 **	100%	0 ***	0 ***[1]	100%
Total	32	13	41%	1,425,200	482,800	34%

* The public statement was dismissed after due diligence was proven.

** One of the two sanctions in 2022 was after an alert from a German fixed sniffer station, managed by BSH.

*** the total amount of the fines for 2022 was not available at the time of submission

In comparison: the total operational cost for the implementation of the sniffer program in 2016–2022 was EUR 981,848 (Table S4). The fines generated with the help of remote measurements account for approx. 50% of government expenditure on airborne monitoring.

3.2. Follow-Up Airborne NO_x Alerts by Port Inspection Authorities

The IMO regulations regarding NO_x emission are complex and do not include compliance checks in ports. Therefore, currently, it is practically impossible for port inspection authorities to check effective compliance in ports. In contrast to sulfur emissions from ships, there are no EU implementation regulations for NO_x emissions from OGVs and no common European mandatory number of inspections have been defined. There is also no system for exchanging information on NO_x inspection results and remote measurements.

There is no exhaustive information about compliance or non-compliance with the MARPOL NO_x standards based on NO_x inspections of OGVs in Belgian ports. The results of NO_x inspections remain fragmentary and incomplete because these inspections by the Belgian PSC department and the Environmental Safeguarding and Dangerous Goods department are limited to an evaluation of the EIAPP and the IAPP certification documents issued by classification societies on behalf of the flag state authority (Recognized Organizations). This means that the only assessment of NO_x compliance is based on remote measurements.

In the period 2020–2022, the Belgian Coastguard aircraft monitored NO_x emissions of 2375 vessels of which 97.3% were found to be compliant. In the period of 2020–2022, 35 alerts for possible non-compliance were sent to port inspection authorities. More specifically, nine of these concerned OGVs with a Belgian port of destination, one Tier 0 OGV, one Tier I OGV, and seven Tier II OGVs.

Port inspection authorities in Belgium followed up on two of these alerts and carried out a documentary inspection. However, none of these inspections could confirm if the OGV was non-compliant or not. As Thetis EU does not yet include the possibility to share NO_x alerts, no detailed follow-up statistics of NO_x alerts by other countries could be obtained. No fines have been imposed for NO_x emission violations to date.

In other ECA countries, for instance, in the United States, a more rigorous inspection regime is already in place, although the inspections are merely based on a profound documentary analysis by technical NO_x experts from the US Coastguard. Possible non-compliant NO_x alerts for OGVs with the US as a destination have been forwarded to the US Coastguard and resulted in two inspections. However, these inspections did not lead to any legal follow-up as the documents did not reveal any suspicious findings.

The very low follow-up on the alerts generated and the lack of any confirmation of non-compliance are due to the regulations themselves. In the case that the regulations would have included mandatory CEMS systems, port inspection authorities would have had considerably more possibilities to check for effective NO_x compliance during onboard inspections. On top of this, the use of an NTE limit for Tier I and Tier II would provide even more potential for effective onboard inspections. Unfortunately, based on these results, it can be concluded that the NO_x regulations are not enforceable by port inspection authorities within the existing international and European legal frameworks.

3.3. FSC Validation

3.3.1. Fuel Samples

During onboard inspections in Belgian ports, a fuel sample was taken for 145 airborne alerts. Unfortunately, not all fuel sampling data were useful, as in several cases the inspection was carried out several days to several months after the initial alert. In some cases, the sampling data could not be applied because the OGV was still performing a fuel change procedure at the time of the measurement, so the FSC values were not comparable on arrival at the port. However, a total of 51 fuel samples have been selected for comparison. Overall, the fuel sampling data relates very well to the airborne measurement data. With a low standard deviation of the difference between the reference data and the airborne measurements (SD_{Diff} = 0.006% FSC), the relative standard deviation is also very low (RSD = 3%). The Pearson correlation coefficient (r) between the fuel samples and the airborne measurement is very high (r = 0.88) (Table 3).

Table 3. Comparison of airborne data with reference data from EGCS and Fuel samples.

Reference data	*Degrees of freedom* (n)	Average (% FSC)	SD_{Diff} (% FSC)	*RSD*	T_{ops}-S	r
Fuel samples	49	0.20	0.007	3%		0.873
EGCS	56	0.10	0.005	4%		0.997
Combined	105	0.15	0.004	3%		0.991
Green flag	41	0.06	0.014	23%		0.934
Yellow flag	18*	0.14	0.026	18%	*0.03*	
Orange flag	15*	0.22	0.043	19%	*0.09*	0.989*
Red flag	11*	0.60	0.097	16%	*0.25*	

* r for combined non-compliant measurements as the $n < 30$ for the different color flags.

3.3.2. EGCS Data

EGCS data were collected from 16 different OGVs for 71 airborne measurements, However, also for the EGCS data, a comparison was not always possible due to several reasons. For one OGV, the time reference in the EGCS logs was not reliable and the GPS position was missing; for these airborne measurements, the exact reference measurement time could not be identified. For two OGVs, the EGCS logs contained only zero values, which could have been a result of either a problem with the gas analyzers of the CEMS or a result of the technical characteristics, such as the detection limit or measurement resolution of the CEMS system. In total, reference data were found suitable for 56 measurements from 13 OGVs. Similarly, the EGCS reference data related very well to the airborne data. The standard deviation of the difference was slightly lower (SD_{Diff} = 0.004% FSC) compared to the fuel sampling data comparison, which was likely a result of the lower average FSC levels. The relative standard deviation, on the other hand, was marginally higher (RSD = 4%), thus demonstrating the proportional bias. The Pearson correlation coefficient was even higher than the fuel sampling data comparison (r = 0.997) (Table 3).

3.3.3. Combined Results

Both reference datasets (fuel samples and EGCS data) were combined to perform a comparison over the full measurement range. The combined dataset contained 107 measurements in total. A plot of the airborne measurement data against the combined reference data is provided in Figure 4A,B, which show the overall high correlation of both reference datasets with the airborne measurements. These plots also demonstrate that the fuel samples differed more from the perfect fit compared to the EGCS data, which is most likely a result from the longer time span between airborne measurement and the fuel sampling. Nevertheless, the fuel samples provided an important added value as they covered the higher section (non-compliant) of the FSC range for which only limited CEMS data were obtained.

The combined SD_{Diff} was similar to that for the EGCS data (SD_{Diff} = 0.004% FSC). The combined RSD was the same as that for the fuel samples (RSD = 3%). The combined Pearson correlation factor fell in between the individual correlation coefficients (r = 0.991). To validate the uncertainty levels used in the different color flag thresholds, the data were divided according the FSC level of the color flags. For the green flag, a minimum of 0.02% FSC was used to avoid errors due to the detection limit of either the sniffer sensor or the CEMS. This indicated that the SD_{diff} and RSD were below the applied uncertainty levels for all non-compliant thresholds, which was defined by the operational threshold (T_{ops}) minus the sulfur limit (S) (Table 3). A modified B&A graph is provided in Figure 4 (C and D). For these graphs, the difference in the two measurement methods were plotted against the average value together with: (1) the Limits of Agreement (+LOA); (2) the LOA added with the confidence interval (+LOA + CI); and (3) the maximum allowable difference (+MAD).

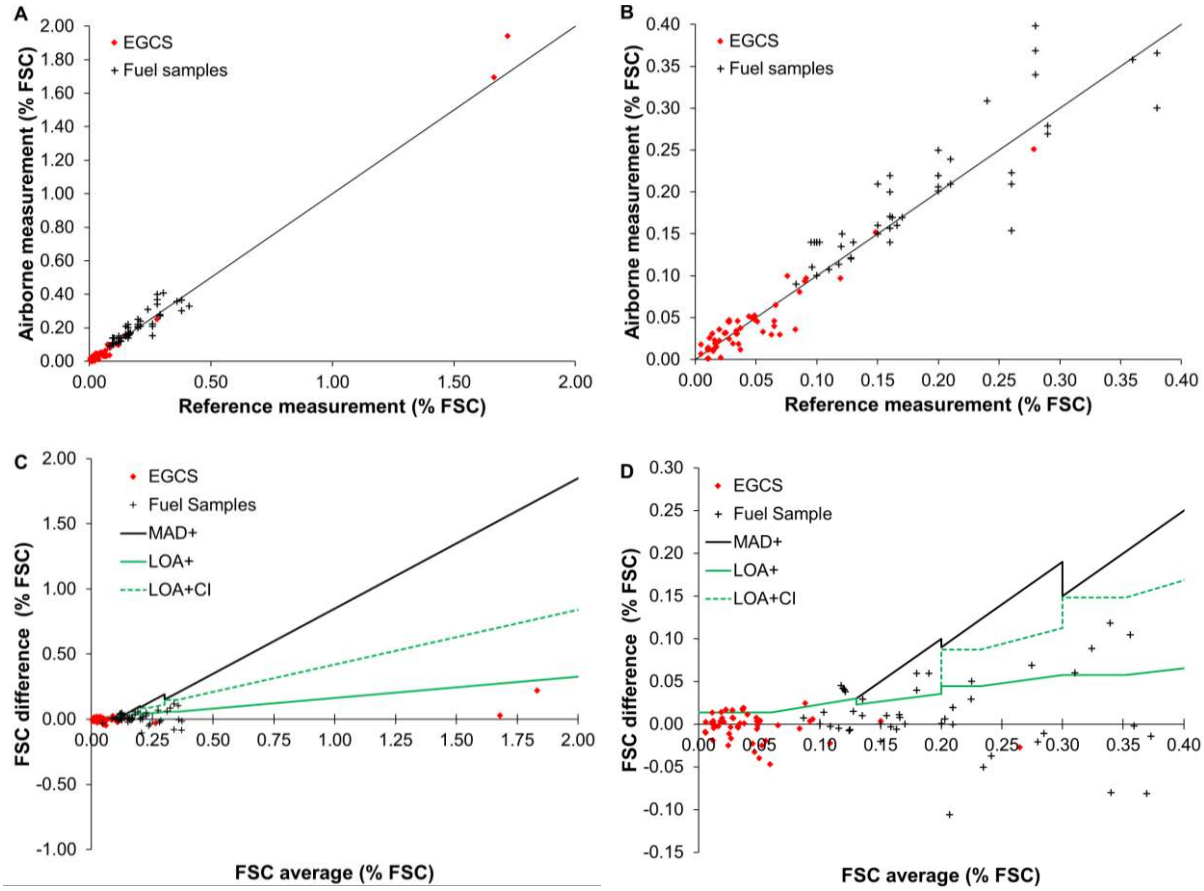


Figure 4. Comparison of reference data from EGCS (in red ♦) and fuel samples (in black +) with the airborne measurement for the full FSC range; the perfect fit is visualized with a black line (x = y) (A). Comparison of reference data with airborne measurement for FSC values < 0.4% FSC (B). Modified B&A graph comparing the reference values with the airborne measurements for the total FSC range. The Limits of Agreement (LOA) are based on either the standard deviation or the relative standard deviation (the highest of the two applies), the confidence interval is added to the LOA in accordance with the CI as defined by the thresholds (LOA + CI) (C). Modified Bland Altman graph comparing the reference values with the airborne measurements for FSC values < 0.4%FSC (D).

The standard B&A was modified using the *RSD* where this was larger than the *SD*. In addition, the different σ values were used for the *CI*s as defined in the thresholds instead of the standard 1.96 (with $\sigma = 1$ and a *CI* of 68% for yellow flags; $\sigma = 1.96$ and a *CI* of 95% for orange flags; and $\sigma = 2.576$ and a *CI* of 99% for red flags).

Finally, only the positive +LOA, +LOA + CI, and +MAD were visualized as the objective was to check for Type I errors and to evaluate the extent to which potential alerts have been sent for compliant vessels. This analysis showed that the +LOA + CI was well below the +MAD for all color flags. Moreover, all measurements were below the +MAD. Based on this analysis, it can be concluded that the effective uncertainty in the sniffer sensor is well below the calculated uncertainty used for the alert thresholds. It also demonstrates the existence of a proportional bias (higher alerts differed more than lower alerts), whereas this error remained well within the MAD. The systematic bias that was found in previous studies was, however, sufficiently removed with the application of the FSC correction [40].

3.4. NO_x Validation

To validate NO_x measurements, cooperation has been sought with the maritime industry. One Belgium engine manufacturer was willing to provide measurement data from CEMS systems installed on their OGVs. Unfortunately, these OGVs did not pass in the surveillance area of the Belgian coastguard aircraft during the airborne surveillance missions. NO_x alerts of ships with destinations other than Belgium have also been reported by email to other European monitoring agencies using fixed sniffers. These fixed sniffer sensors are currently also measuring NO_x but are not generating alerts such as those from the Belgian coastguard aircraft as they have no possibility to contact the OGV to request its Specific Fuel Consumption (SFC). Without this SFC information, the measurements have a large uncertainty. Moreover, the lack of EU regulations on NO_x makes this a low priority for the inspection authorities of EU member states. For instance, in Germany, the BSH did take the initiative to follow up on some alerts for OGVs that were inbound to Germany. The comparison of these pairwise measurements is not as accurate as the comparison with EGCS or fuel samples as both sensors use the same measurement method. Nevertheless, for the concerned alerts, a relatively good comparison was found with the measurements in Germany (SD_{diff} = 5.55 g NO_x/kWh and RSD = 22%), demonstrating that the NO_x measurements used by fixed stations and airborne stations are useful for alerting high NO_x non-compliant OGVs (Figure 5).

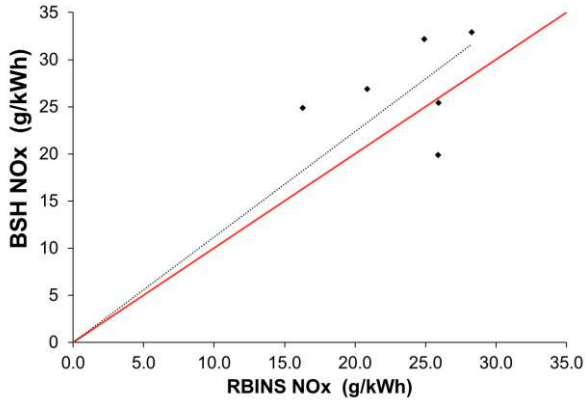


Figure 5. Comparison of NO_x measurements of RBINS (BE) with BSH (DE) (♦); the black dotted line represents the linear regression, and the red line represents a perfect correlation (x = y).

3.5. Cost Benefit Analysis

3.5.1. Comparison of Remote Compliance Monitoring with Port Inspections

An important aspect of the enforcement chain is the implementation cost. One of the incentives for the use of remote compliance monitoring is an improvement in the overall cost efficiency of the enforcement chain. The high labor effort is the most important cost factor in onboard inspections, followed by the cost of fuel sampling analyses by a certified laboratory (EUR 20–100) [43]. The total cost for the Belgian port inspection authorities amounted to approx. EUR 540 per FSC inspection in 2022. For NO_x, no practical real-world emissions test is possible in port unless the OGV is equipped with a CEMS with a data logger. For these vessels (generally Tier III OGVs), the inspection effort can be compared to an inspection of an EGCS OGV. For the OGVs that are not equipped with a CEMS, the use of remote emission measurements can be considered as the only practical way to control real-world NO_x emissions, as engine emission verification tests are too labor intensive to perform on a regular basis, and these tests are beyond the scope and capacity of port inspection authorities.

To calculate the cost per airborne measurement, a distinction is made between: (1) the net cost or the effective supplementary cost for RBINS for the sniffer flights per flight hour, including fuel costs, a

breakdown of aircraft maintenance cost per flight hour, personal costs for the execution of the flights, amortization of sniffer hardware and software, gas calibrations, and sensor maintenance (Table S4) and (2) the full cost of the airborne operation program per hour, including overhead, among which are: all costs, including personal costs related to the program management and administration, fixed platform costs (such as insurance, aircraft stalling, and avionics data subscriptions), crew trainings, office computer hard- and software, and communication costs. The net cost can be regarded as the cost for RBINS to meet its national commitments, whereas the full cost is the "commercial" cost used when executing sniffer flights contracted by other countries. The overall cost per airborne FSC measurement was estimated to be EUR 122 for the net costs and EUR 188 for the full cost. From 2020 onward, both SO_2 and NO_x are measured, which resulted in a slightly lower number of inspections per hour. However, from that time, not one but two regulations were inspected for each OGV, thus decreasing the cost per inspected regulation to EUR 71 for the net cost and to EUR 109 for the gross cost (Table 4).

Table 4. Cost efficiency calculation for different remote measurement techniques.

	Fixed Station [a]	Aircraft (FSC Only) [b]	Aircraft (FSC + NO_x) [c]	Helicopter [d]	Port Inspections	RPAS [e]
Hours of operation per year	2450	96.1	94.8	60	200	425
Average number of OGVs per hour	1.85	12.8	10.3	10	0.6	0.8
Average number of inspected ships per year	4500	1232	980	600	110.0	325
Average price per inspection	20–25 €	122 [f]–188 [g] €	71 [f]–109 [g] €	380 €	550 €	3923 €

[a] based on data obtained from the TNO and Danish Maritime authorities [82–84].
[b] based on RBINS data for the year 2019 (FSC only); net and full cost price per inspection are given.
[c] based on RBINS data for the years 2021–2022 (FSC + NO_x).
[d] based on data from the Danish Maritime authorities [77–81]. [e] based on data from the SCIPPER project [31,42] and the exploitation of drones in France. [f] net cost for RBINS. [g] full cost or commercial cost for external partners of RBINS.

3.5.2. Comparison with Other Enforcement Methods

The outcome of the EU funded SCIPPER (Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations) and CompMon (Compliance Monitoring) projects showed that airborne monitoring using fixed wing platforms is significantly more cost-effective than inspections in port and also when compared to airborne operations using medium range drones (vertical take-off and landing) and helicopters [31,43,91]. Based on the number of inspections and the costs of the operations in French waters, medium range drones are more expensive per inspection compared to onboard inspections. The reason why EU Member States prefer drones given their high cost per inspection lies in the EMSA Remote Piloted Airborne Systems (RPAS) program. The EU Member States are not charged for the deployment of the RPAS but only have to provide the facilities and the legal authorizations. By centralizing the RPAS operations, the prices quoted by EMSA are lower than if a Member State would implement this type of operations individually. It should be noted that the EMSA RPAS program only started in 2019, and with the experiences gained, the operational costs can be reduced in the coming years. The cost per inspection already showed a significantly reduced price of EUR 700–1000 per OGV according to the SCIPPER project outcome [31]. Fixed stations, on the other hand, are found to be the most cost-effective but have limited operational capabilities as they can only be used when shipping lanes pass close to the shore. The cost comparison made in the SCIPPER project demonstrated that this cost varied between EUR 20 and EUR 770 per OGV depending on the shipping density and the wind conditions at the location of the fixed station [31]. The cost for fixed stations used in this

comparison is based on the cost of the fixed station operated by the TNO in the Netherlands on behalf of the Human Environment and Transport Inspectorate of the Ministry of Infrastructure and Water Management of the Netherlands (ILT) and the fixed station operated by Chalmers University in Denmark on behalf of the Danish Environmental Protection Agency (EPA). The operating cost and likewise the cost per inspection in the Netherlands in Rotterdam is substantially lower than the cost for the fixed station used in Denmark on the Great Belt Bridge due to the optimal wind orientation in Rotterdam, the higher maritime traffic density, and the easily accessible location.

3.5.3. Cost per Detected Violation

The cost efficiency of the airborne operations can also be expressed in the cost price per confirmed violation, which clearly demonstrated the added value of airborne monitoring (Table 5). The number of mandatory inspections according to the EU Directive is based on the number of port calls. For Belgium, the quota is 220 inspections with fuel sampling per year. However, as Belgium used remote monitoring, a reduction of 50% can be applied. For the non-compliance percentage of random fuel inspections, 2.7% was used. Therefore, 5.9 non-compliant OGVs would be identified. The total enforcement cost, in this case, would be EUR 118,000, thus resulting in a cost of EUR 20,000 per detected violation. In the case that port inspection authorities rely solemnly on airborne alerts, the confirmation rate would increase to 43%. With a reduced quota of 110 inspections, this would provide 47 confirmed non-compliant OGVs. To be able to provide sufficient alerts, the aircraft would need to operate for approx. 211.5 h. The resulting cost per confirmed violation would be EUR 8304, an improvement of almost 60%. However, the implementation of 211.5 flight hours would not be operationally or budgetary feasible. In addition, port inspection authorities also have to follow up on other types of alerts and cannot fit their planning completely based on the aircraft operations. With an allocated 70 flight hours per year, the aircraft would be able to provide approx. 1/3 of the alerts, resulting in a combined number of detected violations of 18.4 OGVs, which is already a drastic improvement. When looking at the total price per confirmed violation, this would amount to EUR 9622, which is an improvement of more than 50% compared to the base scenario without remote measurements. This would require all aircraft alerts to be followed up on by an onboard inspection, which for operational reasons may not always be possible. However, even with a follow-up rate of 80%, an improvement of 42% can be realized.

Table 5. Cost calculation per confirmed violation.

	No Remote Measurements	100% Based on Remote Measurements	1/3 Based on Remote Measurements
Number of port inspections	220	110	110
Random inspections	*220*	-	*74*
Inspections after alert from aircraft	-	*110*	*36*
Confirmation rate	2.7%	43%	16%
Number of confirmations	5.94	55	17.6
Cost port inspections	EUR 118,800	EUR 59,400	EUR 59,400
Number of flight hours	0	264.4	70
Non-compliance rate	-	*4.0%*	*4.0%*
Number of inspection/hr	-	*13*	*13*
Price/flight hour	-	EUR 1576*	EUR 1576
Cost airborne monitoring	-	EUR 333,385	EUR 110,320
Combined cost	EUR 118,800	EUR 392,785	EUR 169,720
Cost/confirmed violation	EUR 20,000	EUR 8304	EUR 9622
Improvement	0%	−58%	−52%

* The price per flight hour would be lower as fixed operational costs are spread over more flight hours.

4. Conclusions

Previous studies on airborne sniffer measurements, including recent sniffer improvements, have already demonstrated the reliability of airborne monitoring techniques for the enforcement of MARPOL Annex VI regulations 13 and 14. However, the effective improvement in enforcement of non-compliant OGVs remained unknown, and only limited field validation studies have been performed. This study makes the first ink between airborne sniffer measurements and the results of port inspections, which shows that about 46% of the alerts generated with the airborne monitoring are followed-up on by an inspection of the OGC, and about 43% of the alerts followed-up are confirmed by port inspection authorities. This study furthermore demonstrates that by including airborne alerts in the enforcement chain, the number of non-compliant detections in Belgian ports increased by 53%. When examining the sanctions issued by the FPS Mobility and Transport, 41% of all MARPOL Annex VI sanctions appear to be the result airborne alerts, which corresponds to 34% of the total amount of fines.

Compliance and follow-up on EGCS OGVs was also examined in this study. Due to the introduction of the Global Cap, the number of EGCS OGVs increased drastically, which coincided with a steep increase in the number of non-compliant EGCS-OGVs. The number of non-compliant EGCS OGVs was even higher than the number of non-compliant non-EGCS OGVs for the period of 2020 until 2022, while the frequency of observed EGCS OGVs in that period was only 30%. However, the onboard inspection of these OGVs poses major challenges for the port inspection authorities. The results clearly demonstrate that inspections of EGCS OGVs after airborne alerts improved the inspections drastically. Looking at sanctions, airborne alerts accounted for 2/3 of the sanctioned EGC-OGVs.

The results of this study also indicate that up to 80% of the observed potential non-compliant OGVs were not followed up or, if followed up, could not be confirmed with a fuel sample analysis. These results highlight the strong incentive to further explore the use of sniffer measurements as legal evidence for further tightening the MARPOL Annex VI enforcement chain. Therefore, a field validation was performed, demonstrating real-world measurement reliability. For that field validation, FSC measurements in the air are compared to FSC reference values from fuel samples and EGCS CEMS measurements. This analysis shows that the accuracy of the sensor is even better than expected.

For NO_x, the situation is entirely different. Due to the lack of a mechanism for a practical compliance check by port inspection authorities in the IMO regulations and the absence of EU regulations in this regard, only very limited NO_x inspections are carried out in ports. Moreover, these inspections are only based on documentary checks and cannot assess real-world NO_x emissions and compliance, as would be the case with the use of remote measurements. In order for the real NO_x emissions to be assessed by port inspection authorities, CEMS should become mandatory in international or European regulations. Consequently, the non-compliances observed by the aircraft remain only indicative and cannot be compared with the results of port inspections. In addition, no large-scale field validation could be conducted, but the comparison of high NO_x alerts with other measurements in Germany have confirmed the Belgian NO_x alerts and demonstrated the need for a more effective enforcement based on real-world emission measurements.

This study also analyzed the cost effectiveness of airborne monitoring and compared it to the cost of onboard inspections. Airborne measurements have been proven to be significantly cheaper than onboard inspections. Using airborne monitoring, the cost per detected violation can potentially be reduced by 40–50%. Although airborne monitoring is less cost-effective than fixed stations per inspection, airborne measurements provide more flexibility as they can operate over a full ECA. Airborne monitoring also

provides more opportunities to obtain legal evidence, as it is possible to collect multiple measurements, dramatically increasing the reliability of non-compliance alerts.

This study has also demonstrated that airborne measurements can play a first role in the enforcement chain as scientifically proven sound legal evidence for further legal actions. The field validation performed in this study can be regarded as an initial assessment, while further large-scale field validation experiments for compliance with both SO_2 and NO_x emissions from a legal evidence perspective remain highly advisable. These large-scale field validation experiments require a substantial organization and are therefore best organized in the framework of an EU-funded project with the participation of other EU Member States.

The airborne monitoring dataset is available at: https://doi.org/10.24417/bmdc.be:dataset:2687

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6. Supplementary figures and tables

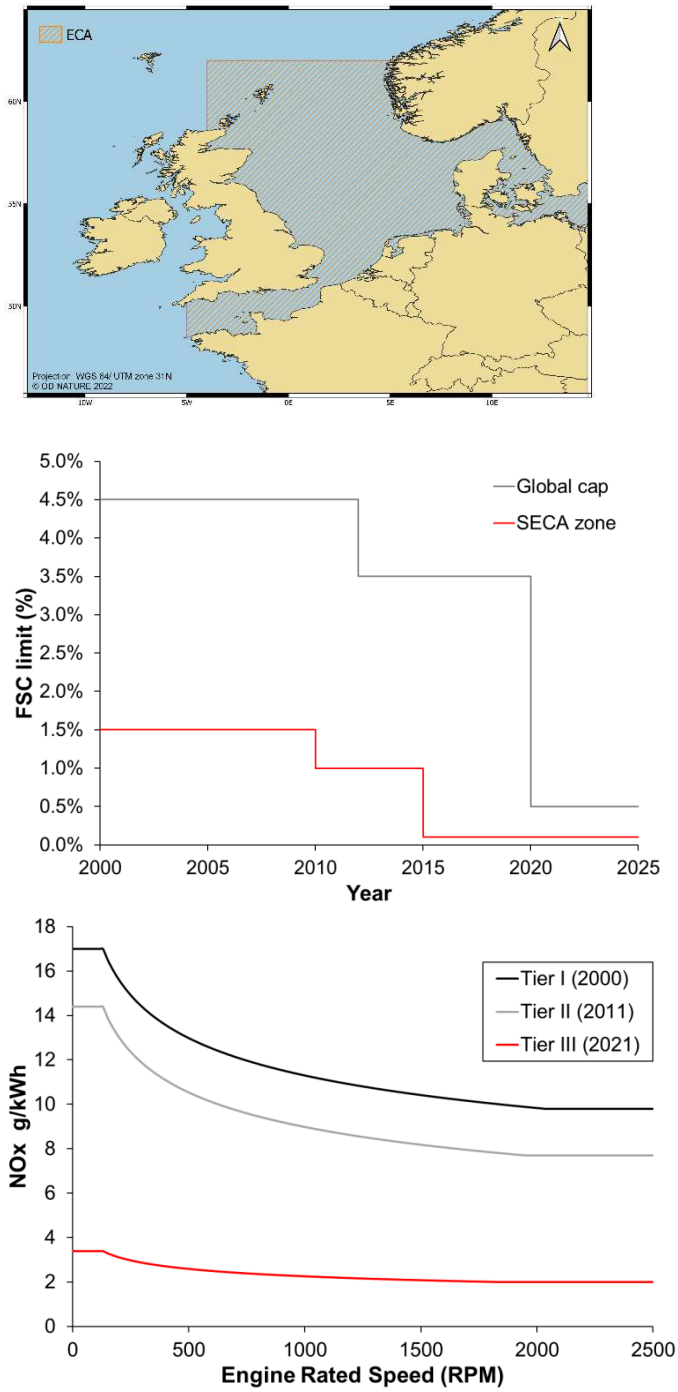


Figure S.1. Emission Control Area (ECA) as defined by MARPOL Annex VI (Upper). Limits on the Fuel Sulfur Content of marine fuels according to the MARPOL Annex VI regulation 14 (Middle). NOx emission limits according to MARPOL Annex VI Regulation 13 (Lower).

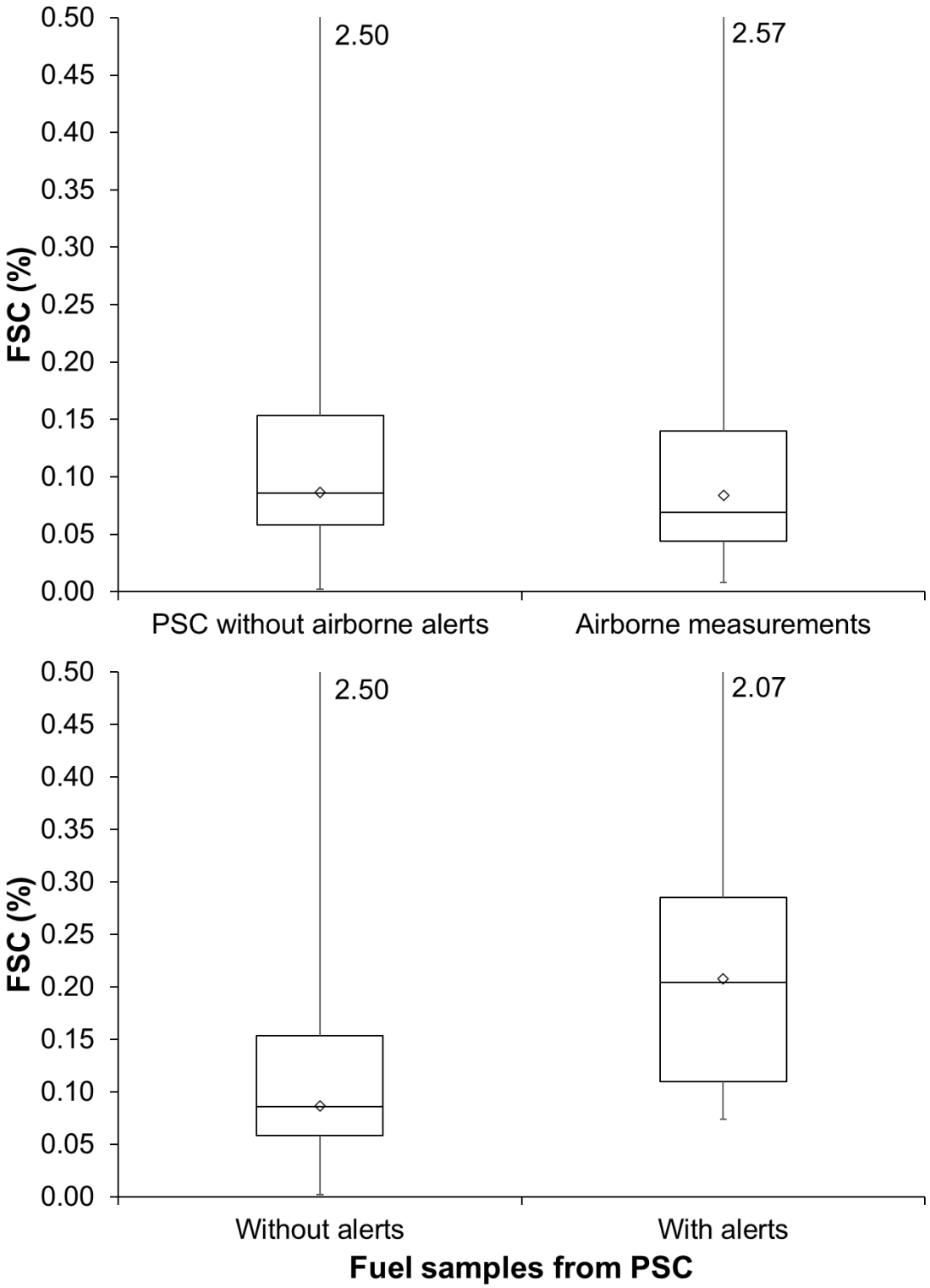


Figure S.2. Boxplot comparison of results of fuel samples executed without airborne alerts and the results of the airborne measurements, with minimum, maximum median, average (♦) , 25 and 75 percentiles (Upper). Comparison of results of fuel sample analysis executed by Belgian port inspection authorities initiated without and with the use of airborne alerts (Lower).

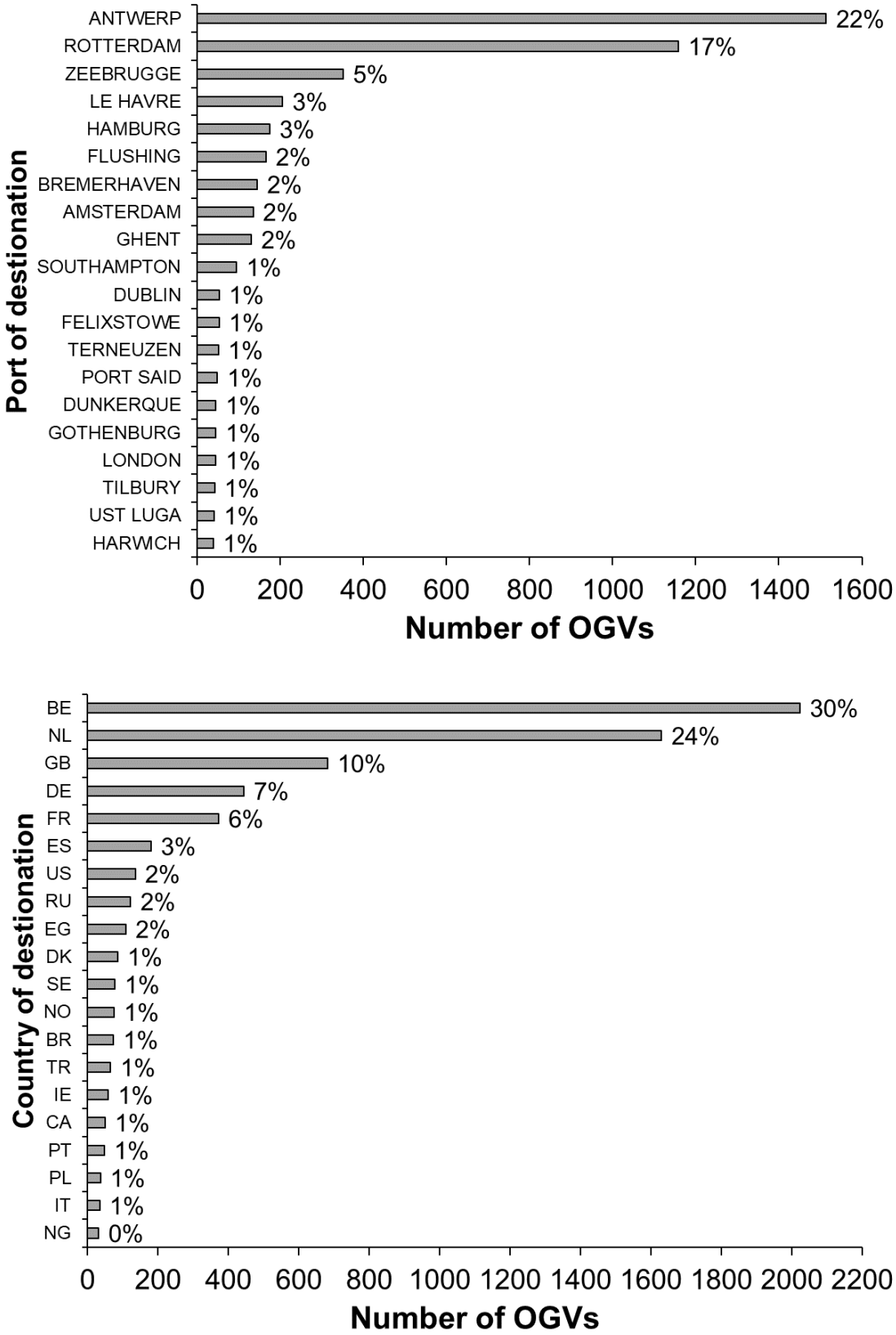


Figure S.3. Number OGVs and relative amount of 20 most observed ports of destionation (Upper) and country of destination (Lower).

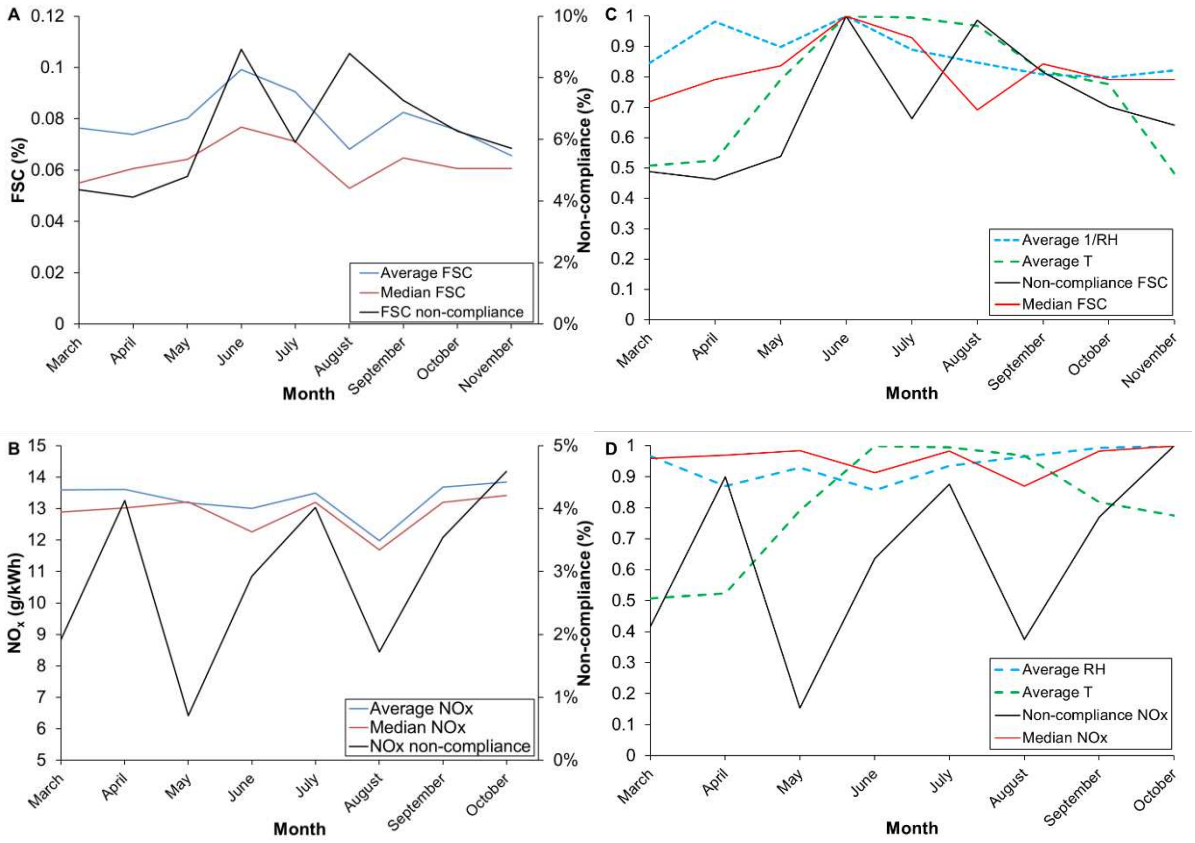


Figure S.4. Monthly average, median and non-compliance values for FSC (A) and NO_x (B). Normalized values for median and non-compliance for FSC (C) and NO_x (D) compared to the normalized monthly values for T and RH. The months January, February and December were not included for FSC and additionally the month of November was not included for NO_x due to the low amount of measurements for these months.

Table S.1. Emission ratios for EGCS systems (MEPC, 2015).

Fuel oil sulfur content (% m/m)	Ratio emission SO2(ppm)/CO2(% v/v)
4.5	195
3.5	151.7
1.5	65
1	43.3
0.5	21.7
0.1	4.3

Table S.2. Test cycles and weighting factors according to the NOx Technical code (MEPC, 2008b).

E2	Speed	100%	100%	100%	100%
	Power	100%	75%	50%	25%
	WF	0.2	0.5	0.15	0.15
E3	Speed	100%	91%	80%	63%
	Power	100%	75%	50%	25%
	WF	0.2	0.5	0.15	0.15

Table S.3. R^2 values for the linear regression between the monthly values for: average FSC, median FSC, FSC non-compliance, average NO_x, median NO_x, NO_x non-compliance, relative humidity (RH) and temperature (T).

R^2	RH	T	Average NO_x	Median NO_x	FSC non-compliance	NO_x non-compliance	Average FSC	Median FSC
Average FSC	0.28	0.38	0.03	0.05	0.10	0.03	-	-
Median FSC	0.29	0.26	0.01	0.03	0.08	0.08	-	-
FSC non-compliance	0.00	0.55	0.37	0.45	-	0.00	0.10	0.08
Average NO_x	0.02	0.20	-	-	0.37	0.32	0.03	0.05
Median NO_x	0.06	0.08	-	-	0.45	0.17	0.01	0.03
NO_x non-compliance	0.00	0.00	0.32	0.17	0.00	-	0.03	0.08

Table S.3. Cost breakdown of the Belgian Sniffer program 2016-2022.

Cost Category	Year							
	2016	2017	2018	2019	2020	2021	2022	Total
Instrumentation								
Sensor and installation	€ 233,010.00	€ 1,624.00	€ -	€ 63,479.49	€ 23,587.77	€ 51,263.64	€ 15,542.19	€ 388,507.09
Calibration and gases	€ 9,509.97	€ 4,651.87	€ 7,829.61	€ 9,913.42	€ 6,966.36	€ 12,676.03	€ 9,800.25	€ 61,347.51
General Equipment	€ 2,614.76	€ -	€ 639.83	€ 1,809.47	€ 1,167.47	€ -	€ 744.93	€ 6,976.46
Software	€ 23,000.00	€ -	€ -	€ 501.83	€ -	€ -	€ 1,689.16	€ 25,190.99
Hardware	€ 20,790.04	€ 1,007.65	€ 561.74	€ 717.35	€ -	€ 6,795.52	€ 162.87	€ 30,035.17
Total Instrumentation cost	€ 288,924.77	€ 7,283.52	€ 9,031.18	€ 76,421.56	€ 31,721.60	€ 70,735.19	€ 27,939.40	€ 512,057.22
Platform								
Fuel for sniffer Flight Hours (FH)	€ 31,219.67	€ 17,167.05	€ 20,301.17	€ 68,753.38	€ 7,751.34	€ 23,005.80	€ 28,771.99	€ 196,970.40
Regular Maintenance	€ 98,915.52	€ 99,792.92	€ 78,709.51	€ 89,076.17	€ 78,210.00	€ 74,301.00	€ 87,656.54	
Part Regular Maintenance for sniffer FH	€ 39,199.93	€ 27,497.48	€ 23,774.49	€ 27,221.00	€ 12,583.22	€ 23,147.09	€ 25,810.64	€ 179,233.85
Major Maintenance (unit cost per flight hour)								
Engine overhaul (2800 EH)		€ 48.70						
Propeller overhaul (2800 EH)					€ 3.93			
Repaint (2800 EH)		€ 15.04						
500 (EH) maintenance	€ 56.61			€ 30.61				
1000 (EH) maintenance			€ 27.25			€ 33.62		
Other unscheduled major parts (2800 EH)		€ 4.97	€ 14.53		€ 9.73		€ 7.04	
Part Major Maintenance for sniffer FH	€ 7,693.62	€ 5,496.73	€ 3,687.30	€ 2,941.12	€ 502.20	€ 3,323.24	€ 638.26	€ 24,282.47
Total Platform cost	€ 78,113.22	€ 50,161.25	€ 47,762.96	€ 98,915.50	€ 20,836.76	€ 49,476.14	€ 55,220.89	€ 400,486.72
Labour								
Operator cost for sniffer FH	€ 10,552.95	€ 5,356.83	€ 7,096.89	€ 7,627.37	€ 2,219.92	€ 8,739.20	€ 8,197.59	€ 49,790.76
Part Mission cost for sniffer FH	€ 1,641.67	€ 979.87	€ 1,080.92	€ 1,215.30	€ 475.24	€ 1,278.08	€ 1,338.40	€ 8,009.48
Pilot cost for sniffer FH	€ 1,090.34	€ 1,403.61	€ 2,253.68	€ 2,305.11	€ 725.62	€ 1,783.25	€ 1,942.41	€ 11,504.02
Total Labour cost	€ 13,284.95	€ 7,740.32	€ 10,431.49	€ 11,147.78	€ 3,420.78	€ 11,800.53	€ 11,478.41	€ 69,304.26
Total	€ 380,322.94	€ 65,185.09	€ 67,225.63	€ 186,484.84	€ 55,979.14	€ 132,011.86	€ 94,638.70	€ 981,848.20
Total/flight hour	€ 2,798.21	€ 814.81	€ 761.76	€ 1,940.87	€ 1,523.24	€ 1,335.70	€ 1,043.81	€ 1,567.20
Number of measurements	1219	887	1138	1232	405	1015	965	6975
Total/measurement	€ 312.00	€ 73.49	€ 59.07	€ 151.37	€ 138.22	€ 130.06	€ 98.07	€ 140.77

Part III

Chapter 5: Assessment of the Effect of International Maritime Regulations on Air Quality in the Southern North Sea.



RBINS-MUMM © picture taken during flight 22083 (22/06/2022)

Assessment of the Effect of International Maritime Regulations on Air Quality in the Southern North Sea.

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Abstract

Air pollution is a leading cause of death worldwide, and it has a profound impact on the planet's climate and ecosystems. A substantial portion of air pollution is attributable to Ocean Going Vessels (OGVs). In light of this, international regulations have been put in place to mitigate air pollutant emissions from OGVs. While studies have indicated that these regulations can create significant health, environmental, and economic benefits, there remains a research gap regarding their specific impact on enhancing air quality. The aim of this study is to investigate how the implemented regulations have affected air quality in the Southern North Sea. The study found that the international regulations on ship emissions have successfully led to a decline in SO2 emissions from OGVs in the Southern North Sea, which resulted in a reduction of ambient SO2 concentrations inland, leading to positive effects on public health and the environment. However, the proportion of shipping's contribution to SO2 emissions is projected to increase in the future. Moreover, the study revealed that the use of Exhaust Gas Cleaning Systems (EGCS) presents significant concerns. They were more frequently found to be non-compliant, and, more alarmingly, they emit higher mean levels of SO2. It also emerged that international regulations in the southern North Sea have less of an impact on the reduction of NOx emissions from OGVs than expected, which is all the more important given that NOx emissions from OGVs are expected to account for 40% of the total domestic NOx emissions for the northern region of Belgium by 2030.

1. Introduction

99% of the world's population is exposed to air containing high levels of pollutants that exceed the limits of the World Health Organization (WHO) guidelines [1]. The negative health effects of air pollution are well documented, with an estimated 9 million annual deaths worldwide attributed to exposure to ambient air pollution [2]. Despite significant reductions in emissions for many air pollutants over the past two decades, concentrations of air pollutants in the European Union remain too high. In 2020, the European Environment Agency (EEA) reported that 96% of city residents were exposed to harmful concentrations of particulate matter (PM) [3]. For the Belgian northern region of Flanders it was estimated that PM is responsible for 300-600 premature deaths per year [4]. PM is not the only reason for concern, as despite a decrease of more than 50% in NO_x emissions in the EU since 1990, NO_x recorded values exceed the annual EU limits in several European countries and all 35 EU Member States (MS) record values exceeding WHO guidelines for NO_x [3,5].

Ocean Going Vessels (OGVs) emit a range of air pollutants such as SO_x, NO_x, and PM [6–9], contributing to 10-15% of global anthropogenic SO_2 emissions and 15-20% of NO_x emission [10,11]. At EU level, OGVs are estimated to be responsible for 24% of SO_2 and NO_x total emissions [12]. These emissions have severe health and environmental impacts [13–17]. While land-based sources of air pollution have been regulated for years thus leading to a reduction in their contribution to air pollution [5,18], shipping was left unregulated for much longer. In 2008 regulations were introduced under the

Marine Pollution Convention (MARPOL) of the International Maritime Organization (IMO) to decrease emissions from OGVs, in particular SO_x and NO_x [19,20]. MARPOL Annex VI introduced Emission Control Areas (ECAs) with stricter emission limits [21–25].

As part of MARPOL Annex VI, Regulation 14 sets limits on SO_x emissions from OGVs. In 2008, the North Sea and Baltic Sea were declared Sulfur Emission Control Areas (SECAs) [22,26,27] (Figure S1A). In the SECA OGVs are required to use compliant fuels or use an exhaust gas cleaning system (EGCS) [28–31]. Outside the SECA, sulfur limits have been tightened in 2020 by the so-called "Global Sulfur Cap" [32] (Figure S1B) and "Carriage Ban" [33]. SO_x emission regulations have been implemented in both EU and Belgian legislation [34–37]. The EU Sulfur Directive led to the implementation of mandatory inspection numbers and the creation of Thetis EU—the port inspection database managed by the European Maritime Safety Agency (EMSA) for the exchange of inspection and monitoring results [38].

Regulation 13 of MARPOL Annex VI introduces the NO_x emission limits [26,39,40]. In 2021, a NO_x Emission Control Area (NECAs) came into force in the North Sea and Baltic Sea [22,24] (Figure S1A). The NO_x emission limits are expressed as the weighted amount of NO_x emission (g) per Brake Horse Power (BHP) on the crankshaft (kWh). Based on the Keel Laying Date (KLD), the merchant fleet is divided in four tiers. The emission limit per tier is furthermore based on the Engine Rated Speed (ERS or n). Certification is done prior and post installation of the engines on board, based on test procedures described in the NO_x Technical Code [41]. These procedures are based on a weighted average of five different test cycles with four to five engine loads and corresponding weighting factors (Table S1) [41,42].

2. Methods

2.1. Belgian coastguard aircraft and sniffer sensor

The research was executed in the Southern North Sea, an area renowned for its high maritime traffic density [43,44]. The Scientific Service Management Unit of the Mathematical Model of the North Sea (MUMM) of the Royal Belgian Institute of Natural Sciences (RBINS) is one of the 17 Belgian coastguard partners [45]. MUMM is responsible for the monitoring and enforcement of MARPOL regulations in the Belgian North Sea area and neighboring waters, in the so-called Bonn Agreement (BA) Quadripartite Zone of Joint Responsibility (BAQPZJR) [45]. The Belgian coastguard aircraft, owned by RBINS, was used for this study. The aircraft is a Britten Norman Islander (BN2) equipped with modern avionics and a remote sensing system from Optimare (Bremerhaven, Germany). In 2015 the aircraft was equipped with a sniffer sensor system, developed by Chalmers University and built by FluxSense (Gothenburg, Sweden) [46].

2.1.1. Sniffer sensor

The sniffer sensor consists of a set of different sensors and equipment mounted in a standard 19-inch rack (Figure S2). The most important units are (i) a Thermo Trace Level Ultraviolet fluorescence sensor, used for the measurement of SO_2 in ppb; (ii) a Licor Bioscience nondispersive infrared (NDIR) sensor, used for the measurement of CO_2 in ppm (iii) an Ecotech Serinus 40 chemiluminescence sensor for the measurement of NO_x; (iv) a custom designed hydrocarbon kicker; (v) three powerful vacuum pumps (one for the SO_2 and CO_2 sensor, one for the hydrocarbon kicker and one for the NO_x sensor; (vi) pressure and flow regulators; (vii) a log computer; (viii) a combined Automatic Identification System (AIS) and Global Positioning System (GPS) receiver; (ix) an Aeronautical Radio INC. (ARINC) module and; (x) a particle filter (1 µm) installed at the air-inlet of the sniffer sensor and on the other side connected to a stainless-steel sampling tube (3/8") installed on the bottom of the aircraft [47].

2.1.2. FSC measurements

The Fuel Sulfur Content (FSC) can be calculated based on the ambient and the exhaust plume's SO_2 and CO_2 concentration [47–55]. To retrieve the amount of combusted fuel, the amount of Carbon (C) was multiplied with a Carbon fuel content of 87% [49,51].

$$\mathrm{FSC} = 0.232 \times \frac{\int [\mathrm{SO_2} - \mathrm{SO_{2,bkg}}]_{\mathrm{ppb}}\,\mathrm{dt}}{\int [\mathrm{CO_2} - \mathrm{CO_{2,bkg}}]_{\mathrm{ppm}}\,\mathrm{dt}} [\%\ \mathrm{Sulphur}] \quad (1)$$

When the NO_x sensor was installed in 2020, this formula was modified to correct for the NO cross sensitivity of the SO_2 sensor and was adapted by subtracting the measured SO_2 with the NO amount in the plume, multiplied by the cross sensitivity factor (CS_{NO}).

$$\mathrm{FSC_{NO}} = 0.232 \times \frac{\int [\mathrm{SO_2} - \mathrm{SO_{2,bkg}}]_{\mathrm{ppb}} - CS_{NO} \times [\mathrm{NO} - \mathrm{NO_{bkg}}]_{\mathrm{ppb}}\,\mathrm{dt}}{\int [\mathrm{CO_2} - \mathrm{CO_{2,bkg}}]_{\mathrm{ppm}}\,\mathrm{dt}} [\%\ \mathrm{Sulphur}] \quad (2)$$

The general modus of the NO_x sensor during surveillance operations was set to NO_x. To estimate the NO concentration from the measured NO_x concentrations a default NO/NO_x In Stack Ratio (ISR) of 80% was used [47,55].

$$\mathrm{FSC_{NO}} = 0.232 \times \frac{\int [\mathrm{SO_2} - \mathrm{SO_{2,bkg}}]_{\mathrm{ppb}} - CS_{NO} \times ISR \times [\mathrm{NO_x} - \mathrm{NO_{x,bkg}}]_{\mathrm{ppb}}\,\mathrm{dt}}{\int [\mathrm{CO_2} - \mathrm{CO_{2,bkg}}]_{\mathrm{ppm}}\,\mathrm{dt}} [\%\ \mathrm{Sulphur}] \quad (3)$$

The NO/NO_x ratio is however highly variable [56,57]. Therefore by default the NO_x mode was used, in case the initial FSC exceeded the operational threshold (T_{ops}), the sensor was set to NO mode and two new measurements were made.

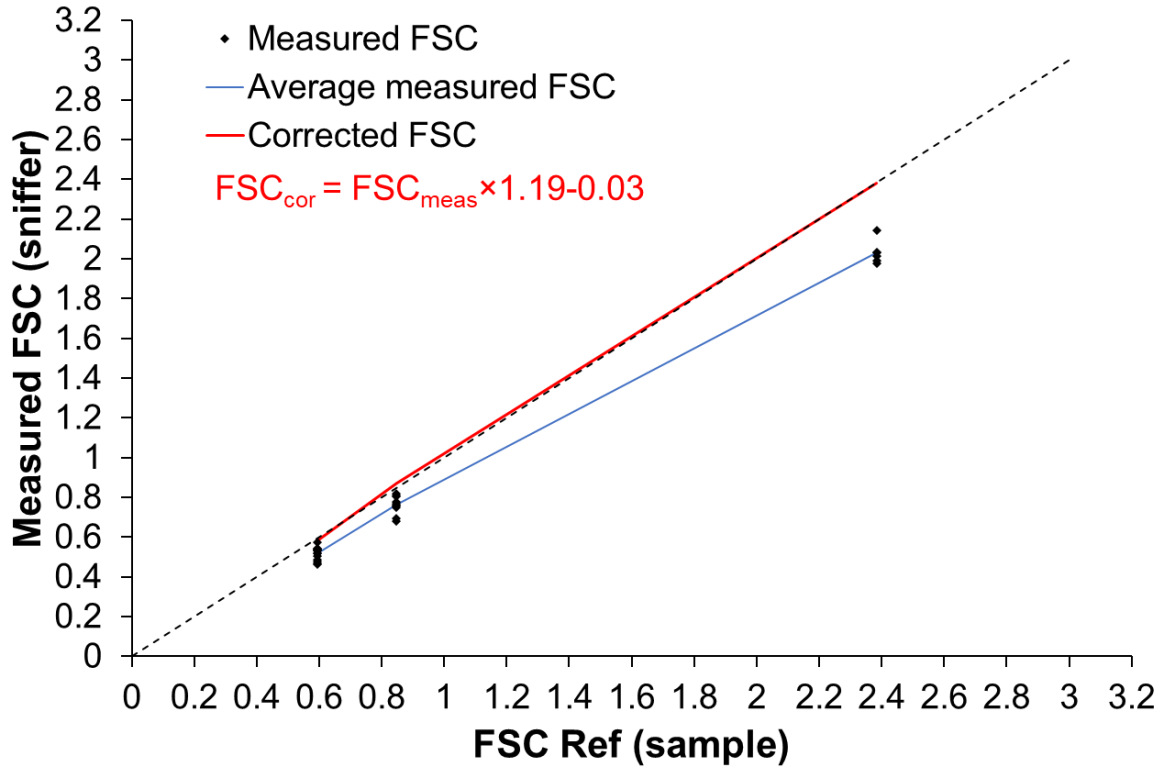


Figure 1. Correction using a linear regression (in red line) of FSC measurements of three special plume simulation mixtures (black ♦). The dashed line represents a perfect match (x = y).

The FSC measurement was found to have a negative bias that consisted of an absolute component or offset (b) and a relative component or slope (a) [50]. To determine these factors three special gas mixtures, containing SO_2 and CO_2 in different levels (Table S2) were used to imitate exhaust plume of different FSC levels (Figure 1).

$$\mathrm{FSC_{cor}} = \mathrm{FSC} \times a + b \tag{4}$$

2.1.3. NO_x measurements

The NO_x emission factor (EF_{NOx}) in g NO_x/kg fuel are calculated similarly to the FSC using the background and plume NO_x and CO_2 concentrations [51,53,56,58].

$$\mathrm{EF_{NO_x}} = \frac{M\,NO_2 \frac{g}{mol}}{\frac{M\,C \frac{g}{mol}}{0.87}} \times 1000 \times \frac{\int [NO_x - NO_{x,\mathrm{bkg}}]_{\mathrm{ppm}}\,dt}{\int [CO_2 - CO_{2,\mathrm{bkg}}]_{\mathrm{ppm}}\,dt} \left[\frac{g}{kg\ \mathrm{fuel}}\right] \tag{5}$$

$$\mathrm{EF_{NO_x}} = 3.33 \times \frac{\int [NO_x - NO_{x,\mathrm{bkg}}]_{\mathrm{ppb}}\,dt}{\int [CO_2 - CO_{2,\mathrm{bkg}}]_{\mathrm{ppm}}\,dt} \left[\frac{g}{kg\ \mathrm{fuel}}\right] \tag{6}$$

For the calculation of the NO_x emission in g NO_x/kWh, the NO_x emission factor (g NO_x/kg fuel) are then multiplied by the Specific Fuel Consumption (SFC), which is described by the amount of fuel consumed (in kg) per Break Horse Power (BHP) expressed in kilowatt hour (kWh).

$$\mathrm{SFC} = \frac{\mathrm{kg\ fuel}}{\mathrm{kWh\ BHP}} \tag{7}$$

$$\mathrm{EF_{P,NO_x}} = \mathrm{EF_{NO_x}} \times \left(\frac{\mathrm{kg\ fuel}}{\mathrm{kWh\ BHP}}\right) \tag{8}$$

Typically, the SFC ranges from 0.16 kg/kWh to 0.24 kg/kWh [11,48,59–67]. An average SFC of 0.2 kg/kWh is used by default. If the T_{OPS} is exceeded, radiocommunication with the OGV is established to obtain the fuel consumption and power data to improve the accuracy of the EF measurement.

2.1.4. Measurement Quality, Uncertainty and Reporting Thresholds

Only high quality measurements were retained, based on following requirements: (i) unquestionable linking of the plume to the OGV; (ii) comparable response times of the SO_2, NO_x and CO_2 gas sensors; (iii) sufficient plume sampling time; (iv) high Signal to Noise Ratio (SNR); and (v) absence of interference from other sources [50]. In addition, a Sniffer Quality Management System (SQMS) was composed describing the Standard Operational Procedures (SOPs) for the execution of the flights, the maintenance of the system and the management of the data [47,50,56].

The uncertainty (U) for the FSC measurements was assessed based on three levels of FSC [50]. Improvements were made in the SO_2 measurement uncertainty from 2020 onwards, the NO cross-sensitivity of the SO_2 sensor was eliminated. Furthermore, a custom-designed hydrocarbon kicker was introduced to remove the VOCs from the airflow and the measurement bias was eliminated by using custom SO_2/CO_2 gas concentration mixtures to simulate exhaust plumes (Table S2) [47]. The uncertainty of the NO_x measurement was calculated based on three levels of NO_x per tier level for both OGVs with an ERS $<$ 130 rpm and for OGVs with an ERS $>$ 500 rpm (Table S3) [56].

The calculated uncertainties were then used for establishing operation threshold levels (T_{ops}) for reporting non-compliant OGVs. Three colors were assigned as flags to categorize the alert level. The yellow flag indicates the lowest alert level with a confidence interval (CI) of 68% ($\sigma = 1$). The orange flag has a higher alert level with a CI of 95% ($\sigma = 1.96$). The red color flag is reserved for the most severe pollution alerts and are based on a 99% CI ($\sigma = 2.576$) (Table 1). If a first measurement suggested possible non-compliance, a second measurement was taken, except in cases where it was not feasible for operational reasons [47,50,51].

Table 1. Alert flag thresholds for FSC (%) as from 2015-2022 and for NO_x (g/kWh) from 2020-2022.

	Color flag	σ	U	CI	Sulfur limit	T	T_{ops}
2015-2019	Yellow	1	30%	68%	0.10%	0.145%	0.15%
	Orange	1.96	35%	95%	0.11%	0.174%	0.20%
	Red	2.576	43%	99%	0.15%	0.275%	0.40%
2020-2022	Yellow	1	25%	68%	0.10%	0.13%	0.13%
	Orange	1.96	38%	95%	0.11%	0.18%	0.20%
	Red	2.576	48%	99%	0.15%	0.29%	0.30%
2020-2022 (with n = 2)	Yellow	1	18%	68%	0.10%	0.12%	0.12%
	Orange	1.96	27%	95%	0.11%	0.15%	0.15%
	Red	2.576	34%	99%	0.15%	0.23%	0.25%

Tier	NO_x Limit	Color flag	NTE	σ	U	T	T_{ops-20}	T_{ops-22}
Tier I*	17	Yellow	15%	1	19.8%	21.2	25	25
		Orange	20%	1.96	44.5%	31.8	35	35
		Red	50%	2.576	58.5%	53.2	60	55
Tier II	14.4	Yellow	15%	1	19.8%	17.9	20	20
		Orange	20%	1.96	44.5%	26.9	30	30
		Red	50%	2.576	58.5%	45.0	50	45
Tier III	3.4	Yellow	50%	1	19.8%	5.4	7	6
		Orange	60%	1.96	44.5%	7.5	9	8
		Red	65%	2.576	58.5%	8.9	12	9

2.2. Thetis–EU

The EU Sulphur Directive led to the creation of Thetis–EU, an online database utilized for exchanging inspection results. The European Maritime Safety Agency (EMSA) manages and hosts the database. Thetis–EU is accessible to inspectors across all EU MS, including Norway and Iceland. However, due to Brexit, the UK no longer has access to the database [35,68].

2.2.1. Keel laying date

Information on the keel laying date (KLD) is crucial for determining the tier level in assessing NO_x compliance. This KLD data was acquired based on merging two database sources: (1) the Global Integrated Shipping Information System (GISIS) of the International Maritime Organization (IMO)[69] and; (2) Thetis–EU of the European Maritime Safety Agency (EMSA) [70]. The GISIS database was used to gather information on OGVs larger than 75 meters with built year and IMO number, while EMSA provided the accurate KLD and MMSI information of the OGVs that were constructed, but also about the planned vessels [56].

2.2.2. EGCS data

Thetis–EU also includes information on EGCS, a list of 6048 EGCS-OGVs was obtained from EMSA after a formal request from the Belgian National Competent Authority (NCA). The data is however based on the port inspections executed by the EU MS and is therefore non-exhaustive: there were several instances where OGVs have been observed to be equipped with EGCS that were not documented in the EMSA data [47,70]. In addition, EGCS information from the GISIS database from IMO was consulted [69], this contained 1516 additional EGCS-OGVs.

2.3. Inland air quality measurement data

2.3.1. Inland coastal data and non-coastal data

Air quality data from 41 inland measurement stations managed by the Flemish Environmental Agency (VMM) was collected to assess the impact of OGVS emissions on inland air quality [71]. The stations

were classified into two categories: (1) coastal or port stations and (2) non-coastal or non-port stations. Data was collected for the period of 2008-2022. The difference between the two categories stands in proportion to the air pollution contribution from the maritime transport sector. However, it should be noted that this difference also includes a significant contribution from industry and energy sources, as these facilities are largely located in port areas, which may be particularly true for SO_2.

2.3.2. Trend analysis by emission source

To conduct a trend analysis by emission source, data from VMM was used [71]. This data consists of emission data categorized by source for the period spanning from 2000 to 2020. In addition, a short-term linear regression trend was created for each SO_2 and NO_x source based on past years' data, omitting 2020 because it was affected by the global COVID pandemic. For most sources, the period used for the linear regression was either 2010-2019 or 2015-2019.

Regarding shipping, the future projections for SO_2 and NO_x were established by combining several trends: (1) the trend of the difference between coastal and non-coastal stations between 2016 and 2022 (slope = a, intercept = b), and (2) the projected increase in shipping (2.1% annually) [72]. An additional correction factor for FSC noncompliance (c) was added for the SO_2 future projects. This factor was based on the correlation between the increase in SO_2 emissions from shipping and the FSC non-compliance rate. This factor was calculated for the period 2021-2022 and was then between 1.06 and 1.08; therefore, a factor of 1.07 was used for the future projections (2023-2030).

$$NO_{x_i} = (a \times (2020 + i) + b) \times 1.021^i \tag{9}$$

$$SO_{2_i} = (a \times (2020 + i) + b) \times 1.021^i \times c \quad \text{with } i = \text{year} > 2020 \tag{10}$$

2.4. Statistical analysis

The normality of the emission measurement data was evaluated using a Kolmogorov-Smirnov test, which showed that the data did not follow a normal distribution ($P < 0.05$). Consequently, non-parametric tests were utilized. A two-tailed Kolmogorov-Smirnov test was used to compare the distributions of measurements obtained between different groups (temporal periods, Tier levels, EGCS, ...), statistical significance was determined at $P < 0.05$. To assess the difference in compliance rates between the two distributions, a two-sided chi-square test was used, with statistical significance defined as $P < 0.05$ [73,74]. When discussing Type I errors, they refer to false positives, while Type II errors refer to false negatives.

3. Results and Discussion

From 2015 onwards, the RBINS has been conducting airborne surveillance operations for the monitoring of Regulation 14 of MARPOL Annex VI concerning sulphur emissions from OGVs [47,50,75]. The RBINS expanded its monitoring efforts in 2020 to include Regulation 13 of MARPOL [47,56]. The collected dataset contains 6954 FSC measurements and 2353 NO_x measurements and therefore comprises the largest set of airborne OGV emission measurements to date.

3.1. Belgian airborne monitoring dataset

During the monitoring period from July 2015 to November 2022, the RBINS conducted 414 flights and 645 operational flight hours, making approximately 10446 low passes in the exhaust plumes of 7536 OGVs, measuring 6954 OGVs' FSC and 2353 OGVs' NO_x emission [47,50,56,75].

The predominant type of measured OGVs were container OGVs (31%), followed by tanker OGVs (29%), general cargo and bulk carrier OGVs (20%) and passenger and Roll On Roll Off (RORO) OGVs (15%;)

(Figure S3). Regarding NO_x monitoring, the majority of monitored OGVs were Tier I OGVs (52.6%); followed by Tier II OGVs (37.5%); Tier 0 OGVs (9.6%) and Tier III OGVs (0.3%).

The standard operating procedures (SOPs) specified a minimum ship length of 100 m, although smaller OGVs were occasionally included. The average length of the monitored OGVs was 214 m (Figure S4) and only OGVs that were on-route were measured, with an average speed of 12.7 knots (Figure S5). The majority of the monitored OGVs had a port of destination in Belgium (30%), Netherlands (24%), the UK (10%), and Germany (7%), with the main ports of Antwerp (22%), Rotterdam (17%), and Zeebrugge (5%) (Figure S6). The most frequently observed flag states were Liberia (11%), Panama (13%), and Marshal Island (10%) (Figure S7A & B), which corresponds to the global fleet distribution [76].

For the data collected between 2015 and 2019, no correction for the NO cross sensitivity was made. Therefore the data between 2015 and 2019 was first corrected to allow for a long-term analysis. For this purpose, the FSC values without NO correction (FSC uncorrected) and the FSC values with NO correction (FSC corrected) for the period 2020-2022 were used to conduct a linear regression (Figure 2). The regression values (a = 0.93; b = 0.02. and r = 0.98) were consequently used to correct the 2015-2019 FSC measurement data (FSC_{cor}) (Figure 2).

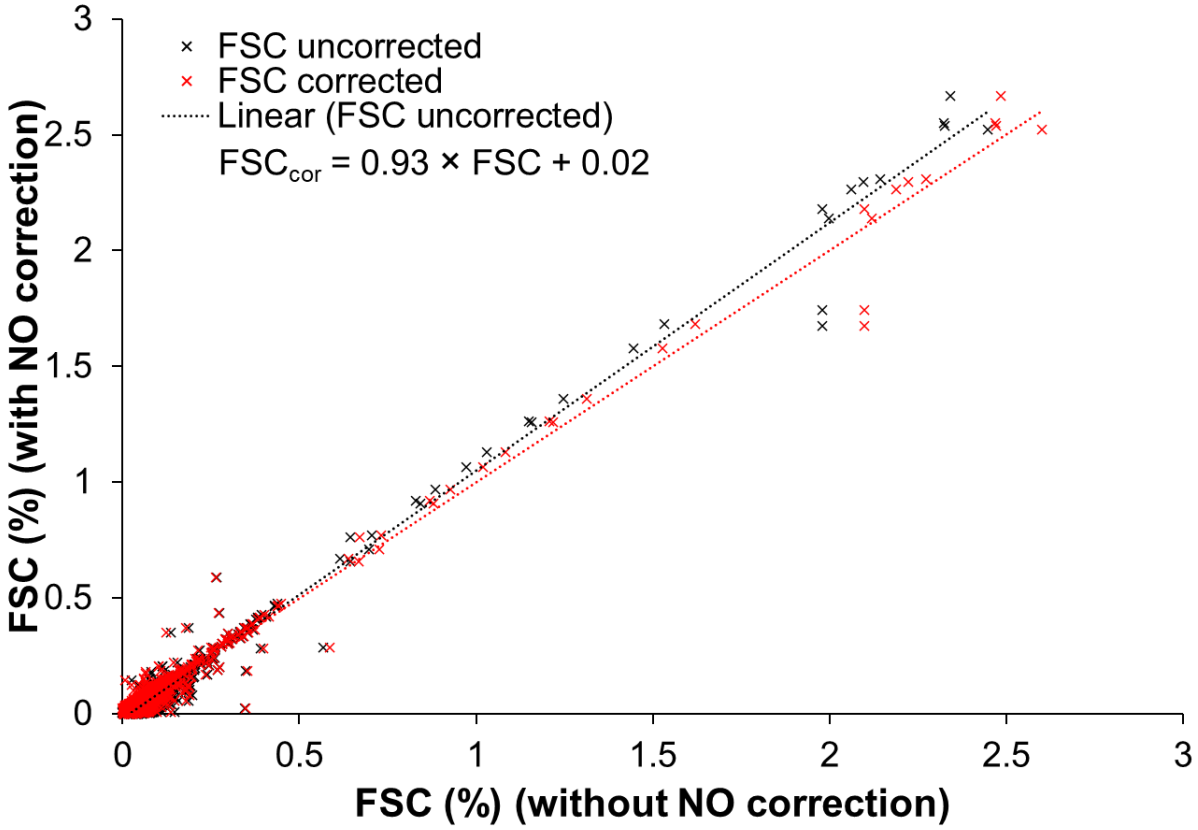


Figure 2. Linear regression between the FSC including the NO cross sensitivity and the FSC without NO cross sensitivity. The dashed line represents the perfect match (x = y).

3.2. Mean FSC and compliance trends

The improved measurement quality and reduced measurement uncertainty in 2020 allowed for more accurate measurements of the FSC [47]. To enable long-term trend analysis, the measurements for the 2015-2019 period were first corrected for their systematic bias. Based on the corrected FSC data, it was found that throughout the monitoring period 2015-2022, the mean FSC of the measured OGVs remained

relatively consistent (Figure 3A). However when examining temporal trends, it was discovered that after the implementation of the Global Cap in 2020 ($P < 0.01$) the mean FSC significantly decreased from 0.083% to 0.068%. The improved accuracy in 2020 reduced the OGV compliance threshold from 0.15% FSC to 0.13% FSC. Therefore, the FSC measurements from 2015 to 2019 were re-categorized according to the 2020 thresholds. While these thresholds are not suitable for individual OGV compliance re-assessments for 2015-2019, they can be used for long-term compliance analysis. The overall compliance rate spanning from 2015 to 2022 was 92.8%, increasing from 83.3% in 2015 to over 95.1% in 2019 (Figure 3B). After the introduction of the Global Cap in 2020, compliance rates continued to rise, reaching a maximum of 98.0% in 2021, but then decreased to 95.1% in 2022. Comparing the non-compliance rates of 2018-2019 (6.1%) with 2020-2022 (3.1%) showed a significant decrease ($P < 0.001$), indicating the effectiveness of the Global Cap.

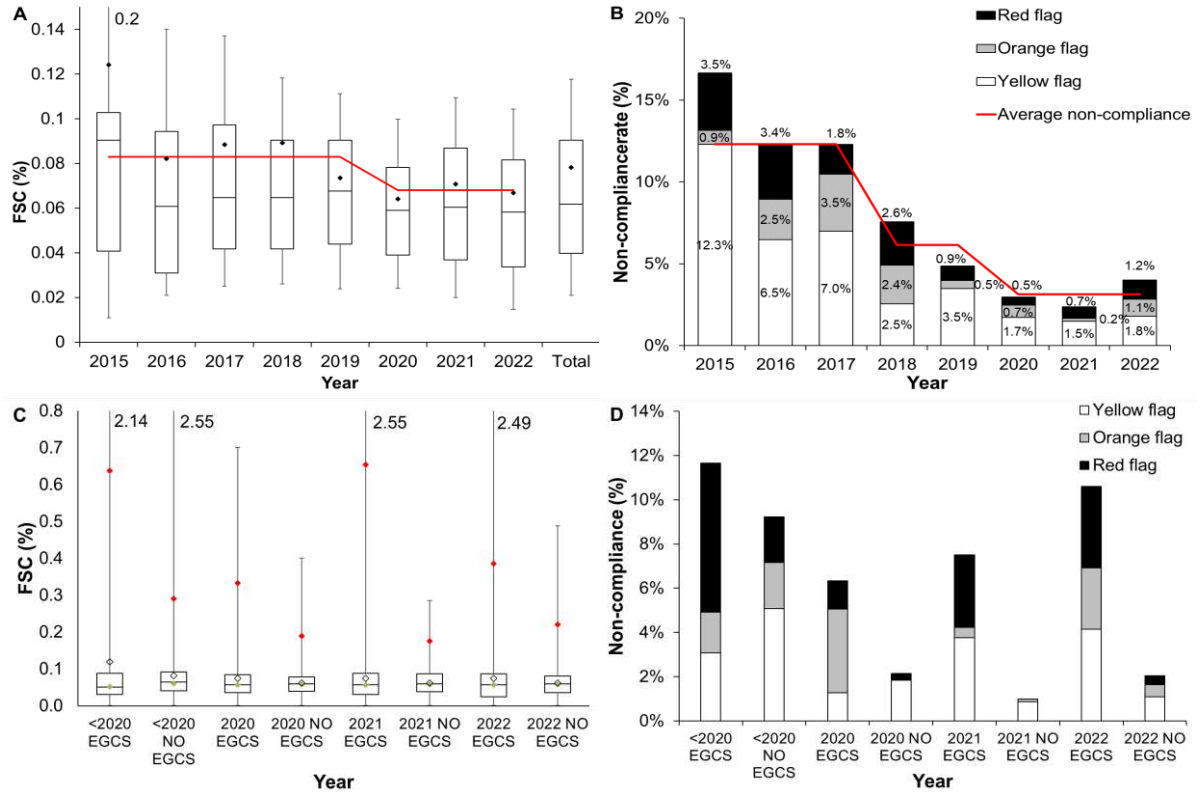


Figure 3. Evolution of the average corrected FSC concentration from 2015-2022 with median, 10, 25, 75 and 90% percentiles and average FSC per year (♦), with average FSC for the period before and after 2020 (red line) (A). Non-compliance evolution based on the corrected FSC data for 2015-2019 (B). Average, median, 25 and 75 percentile boxplots for monitored FSC for EGCS OGVs and non EGCS OGVs. The overall average is provided in white diamonds (◊) The average non-compliant FSC is provided in red diamonds (♦) the average compliant FSC is provided in green diamonds (♦) (C). Compliance rate of EGCS OGVs compared to OGVs without EGCS (D).

The non-compliance rates per flag state (OGV's nationality) were generally proportionate to the number of observations per flag state (Figure S7A). The "flags of convenience", i.e. flags of convenience are countries with favorable regulations and lower taxes, allowing OGV owners to avoid stricter regulations and labor standards in their home countries, were not found to create higher non-compliance levels. The flag states Germany (DE), Belgium (BE) and the UK had proportionate higher non-compliance rates. However, closer examination of the OGVs involved showed that they were very often linked to the same shipping companies. For DE ten out of 11 possible non-compliant OGVs were from one company (seven different OGVs). For BE, nine out of ten possible non-compliant OGVs were from one company (three different OGVs) and all observations were in 2016. For the UK, nine out of 21 OGVs concerned one

OGV that was equipped with an EGCS and was repeatedly observed non-compliant during the commencing phase of its EGCS in 2016-2017. Six other observations concerned one OGV, this OGV belonged to the same company of the nine non-compliant BE observations. This shows that some shipping companies have a higher risk profile for violations than others. However, since no general information related to ship owners was available, this could not be widely verified.

During the monitoring period from 2015 to 2022, there was a significant increase in the number of OGVs equipped with Exhaust Gas Cleaning Systems (EGCS). At the start of the monitoring in 2015, less than 1% of OGVs had an EGCS. However, as a result of the implementation of the Global Cap, by the end of 2022, approximately 30% of the global fleet was equipped with an EGCS [77]. The effect of this trend was examined by comparing the mean FSC and non-compliance rates for EGCS and non-EGCS OGVs. It was found that EGCS OGVs had significantly higher FSC levels (0.100% FSC) compared to non-EGCS OGVs (0.075% FSC) ($P < 0.001$) (Figure 3C). Also the non-compliance rate was found to be significantly higher for EGCS OGVS (9.5%) compared to non-EGCS OGVs (6.9%) ($P = 0.0101$) (Figure 3D).

Furthermore, the analysis revealed both a very high relative contribution and very high absolute emission values for non-compliant EGCS OGVs. In the period 2015-2019, 14 out of 102 red flags were related to EGCS OGVs (14%), whereas from 2020 onward, out of the 20 observed red flags, 16 were related to EGCS OGVs (80%). This indicates that EGCS OGVs not only result in higher amounts of non-compliance, but of equal concern, they were found to emit substantially higher levels of SO_2 once identified as non-compliant. The issues with EGCS OGVs can be attributed to certain international regulations, with MARPOL Annex VI Regulation 13 that allowed the use of EGCS systems in the first place. Furthermore, the introduction of the Global Cap resulted in a decrease of mean FSC and non-compliance rates. However, the lower global limits have also led to wider use of EGCS OGVs, especially outside ECAs. Based on this analysis, however, this has resulted in higher SO_2 emissions and non-compliance rates. Finally the EGCS guidelines do not provide for an effective monitoring mechanism for the port inspection authorities to verify the proper functioning of the Continuous Emission Monitoring System (CEMS) used by the EGCS [29]. It should be noted that this adverse effect on air quality is in addition to other environmental concerns arising from the discharge of washwater from EGCS [28,78–80].

3.3. Real world NO_x emissions and compliance trends

The airborne monitoring of NO_x emissions from OGVs began a year before the implementation of the NECA in 2021, this allowed to assess the impact of the new regulations on real-world NO_x emissions and compliance to regulation 13 of MARPOL Annex VI. It was found that neither the mean NO_x emission level nor the non-compliance rate were reduced after the NECA was introduced. On the contrary, there was an observed significant increase in the mean NO_x emissions from OGVs from 12.6 to 13.5 g NO_x/kWh ($P < 0.001$) (Figure 4A). The non-compliance rate also increased from 3.7% to 3.9%, though this difference was not found to be significant ($P = 0.8$).

The previously discovered trend that Tier II OGVs have a higher mean NO_x emission and non-compliance rate compared to Tier I [56] was re-confirmed by including the data from 2022 (Figure 4B&C). This is a result of the validation method for engine certification in the NO_x Technical Code which defines two engine cycles for main engines based on four different engine states for the calculation of the weighted average (Table S1). This means that an engine is considered compliant as long as the weighted average is below the limit, even if emissions at certain engine states exceed the limit. Tier II engines were found to have higher NO_x emissions in the lower engine states due to fuel optimization, while Tier I engines have more constant emission levels with engine load [56]. As lower engine states are

often used in coastal shipping lanes with heavy traffic density, this results in Tier II OGVs emitting more NO_x in areas most vulnerable from an environmental and health perspective. Furthermore, currently for main engine states below 25% there are no emission limits in place and 23% of the observed non-compliant OGVs had an engine load below 25% and were therefore not regulated (Figure 5).

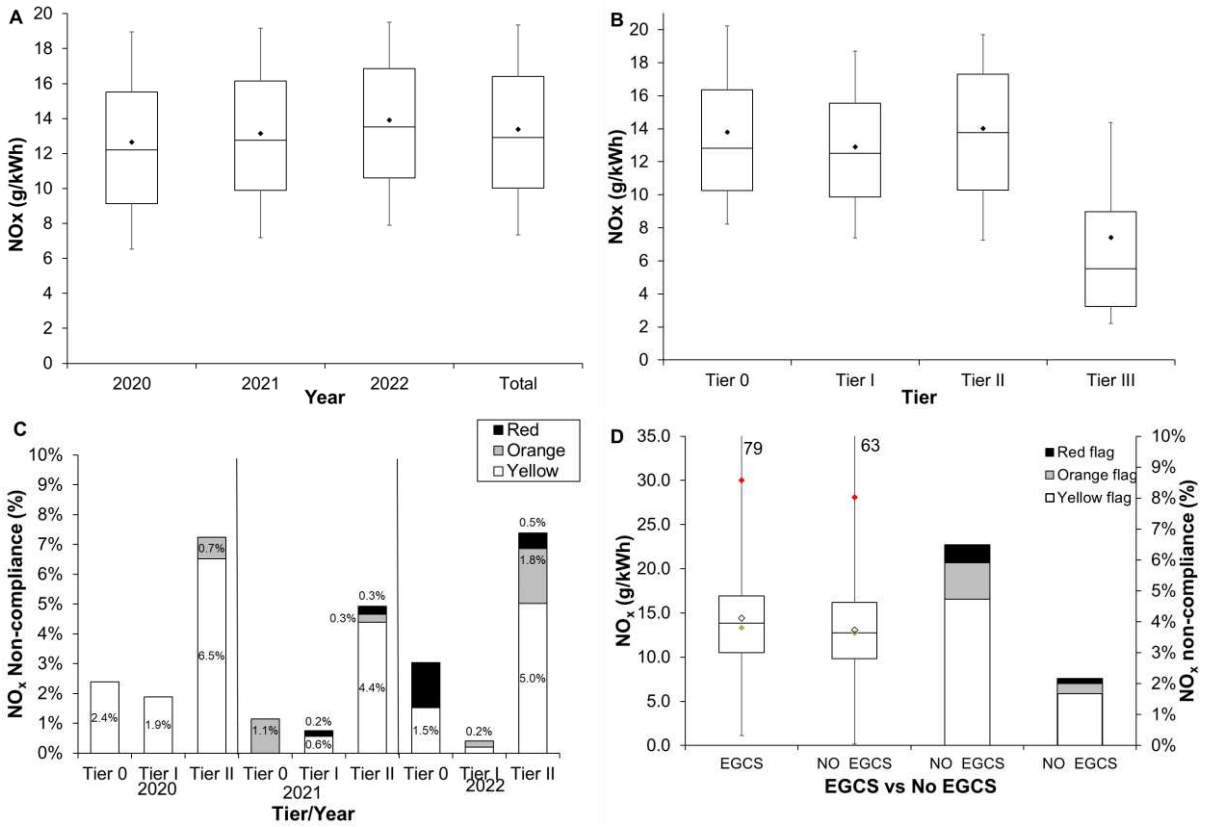


Figure 4. Boxplot with median 10, 25, 75, 90% percentiles, and mean NOx emissions per year (A) and per tier level (B). NOx non-compliance per tier and per year (Tier III is not represented due to the absence of Tier III data between 2020 and 2021) (C). Boxplot with median 10, 25, 75, 90% percentiles, and mean NOx emissions between EGCS and non-EGCS OGVS. The overall mean is provided in white diamonds (◊). The mean non-compliant FSC is provided in red diamonds (♦); the mean compliant FSC is provided in green diamonds (♦). On the right side of this graph the NOx non-compliance difference between EGCS and non-EGCS OGVs is provided. (D)

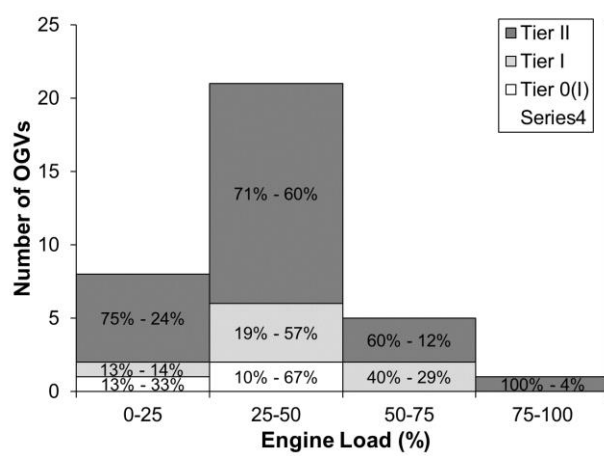


Figure 5. Distribution of the engine load of the observed non-compliant OGVs for NOx.

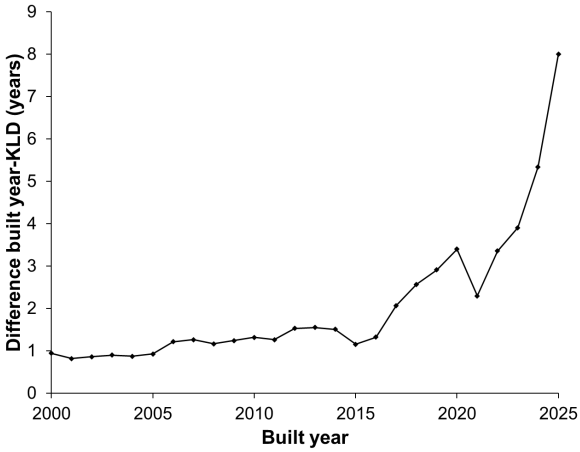


Figure 6. Difference between Built Year and Keel Laying Date over time.

Tier III engines have a not-to-exceed (NTE) limit for all engine states, set at 150% of the emission limit, making it easier to assess compliance as it doesn't require an assessment of the weighted average. However, only seven Tier III OGVs (0.3%) have been monitored so far. This is concerning as the majority of the OGVs that were built after 2021, when the Tier III limits came into force, still have a KLD before 2021. This means that they can still follow the Tier II limits. Based on the collected KLD information, it was discovered that only 21% of the merchant OGVs larger than 5000GT, built in 2021 and 2022 had a KLD in or after 2021 and were certified as Tier III, the implementation of the NECA in the US in 2016 and Europe in 2021 can be clearly identified in the difference between the built year and KLD (Figure 6).

It cannot be overstated that this delay will have a substantial impact on the environment and public health [13,56]. Another remarkable discovery was that 43% of the limited number of observed Tier III OGVs were found to be non-compliant, this is in line with the observations made during the EU-funded Horizon 2020 project "Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations" (SCIPPER) [81]. The analysis provided clear evidence of the inefficacy and even counterproductive nature of the international maritime NO_x emission regulations in reducing actual NO_x emissions from OGVs in the ECA.

Looking at non-compliance by flag state, levels of non-compliance generally do not vary much by flag state (Figure S7B). However, it was observed that the Hong-Kong (HK) and Danish (DK) flagged OGVs had a higher risk profile for non-compliance. For the DK flags ten out of 13 belonged to one company (nine different OGVs), for the Hong-Kong flagged OGVs, ten out of 12 possible non-compliant OGVs belonged to the same shipping company (eight different OGVs), the two other observed OGVs belonged to another company (2 different OGVs).

To evaluate how EGCS affects NO_x emissions, an analysis was conducted on the mean NO_x emission levels and compliance rate to NO_x emission standards between EGCS OGVs and non-EGCS OGVs. The findings revealed that EGCS-equipped OGVs had an mean NO_x emission level of 14.4 g NO_x/kWh, which was significantly higher than the 13.1 g NO_x/kWh for non-EGCS OGVs ($P < 0.001$). Furthermore, the non-compliance rate for EGCS OGVs was significantly higher at 7%, compared to 2% for non-EGCS OGVs ($P < 0.001$) (Figure 4D). These results were consistent across all monitoring years and for both Tier I and Tier II (Figure S8). These results confirm previous research that indicated the (minor) effect of EGCS on NO_x emission levels [78].

3.4. Impact emissions from OGVs on Belgian inland air quality

By analyzing the annual mean SO_2 and NO_x concentrations conducted in air quality monitoring stations located in coastal or port areas compared to those not situated in such areas the relative importance of air pollution from OGVs was elaborated. It was of no surprise that both SO_2 and NO_x concentrations were substantially higher in coastal/port areas, although declining concentrations were generally observed for both SO_2 and NO_x at all stations (Figure 7).

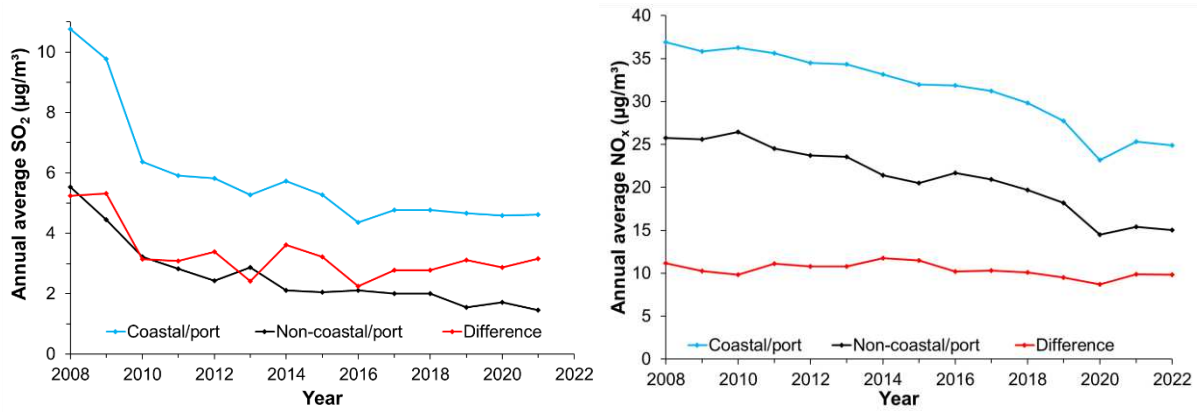


Figure 7. Evolution of measured SO_2 (left) and NO_x (right) concentrations for inland coastal and non-coastal air quality measurements stations in Flanders (data obtained from VMM) [71]

The difference in SO_2 concentration between coastal/port and non-coastal/port stations was found to slightly decrease between 2008 and 2016, but later started to re-increase slightly (Figure 7, left). Clear reductions were observed in 2010, 2013, 2015, and 2016, which can be attributed to the implementation of international SO_2 emission limits for OGVs. However, the reduction in 2013 can be neglected as it was linked to a short-term increase in pollution for non-coastal stations due to inland pollution sources [71]. Regarding the difference in NO_x concentration between coastal/port and non-coastal/port stations, a very stable trend was observed over the last decade (Figure 7, right). This indicates that emissions from OGVs have not decreased over time and were not substantially impacted by the introduction of the NECA in 2021. Consequently, emissions from OGVs are increasingly contributing to the total inland NO_x pollution.

The SO_2 analysis categorized by emission source, clearly indicates the impact of the introduction of the SECA and subsequent reductions in maximum allowed FSC in 2010 and 2015 (Figure 8A). However, the future trend analysis also suggests that the contribution of SO_2 emissions from OGVs to the total SO_2 emissions in the Flemish region is expected to increase to approximately 7% by 2030.

Regarding NO_x emission sources, the impact of international shipping regulations was found to be less profound. The contribution of NO_x emissions from OGVs to inland NO_x in the Flemish region shows an upward trend. The establishment of the NECA in 2021 has had no significant impact on this trend, it is even projected that by 2025 the NO_x emission contribution from OGVs will surpass any other source and contribute to 40% of all NO_x emissions for the Flemish region by 2030 (Figure 8B). These results largely corroborate the findings of previous large-scale studies that modelled the shipping contribution to inland pollution [30,31,82–86].

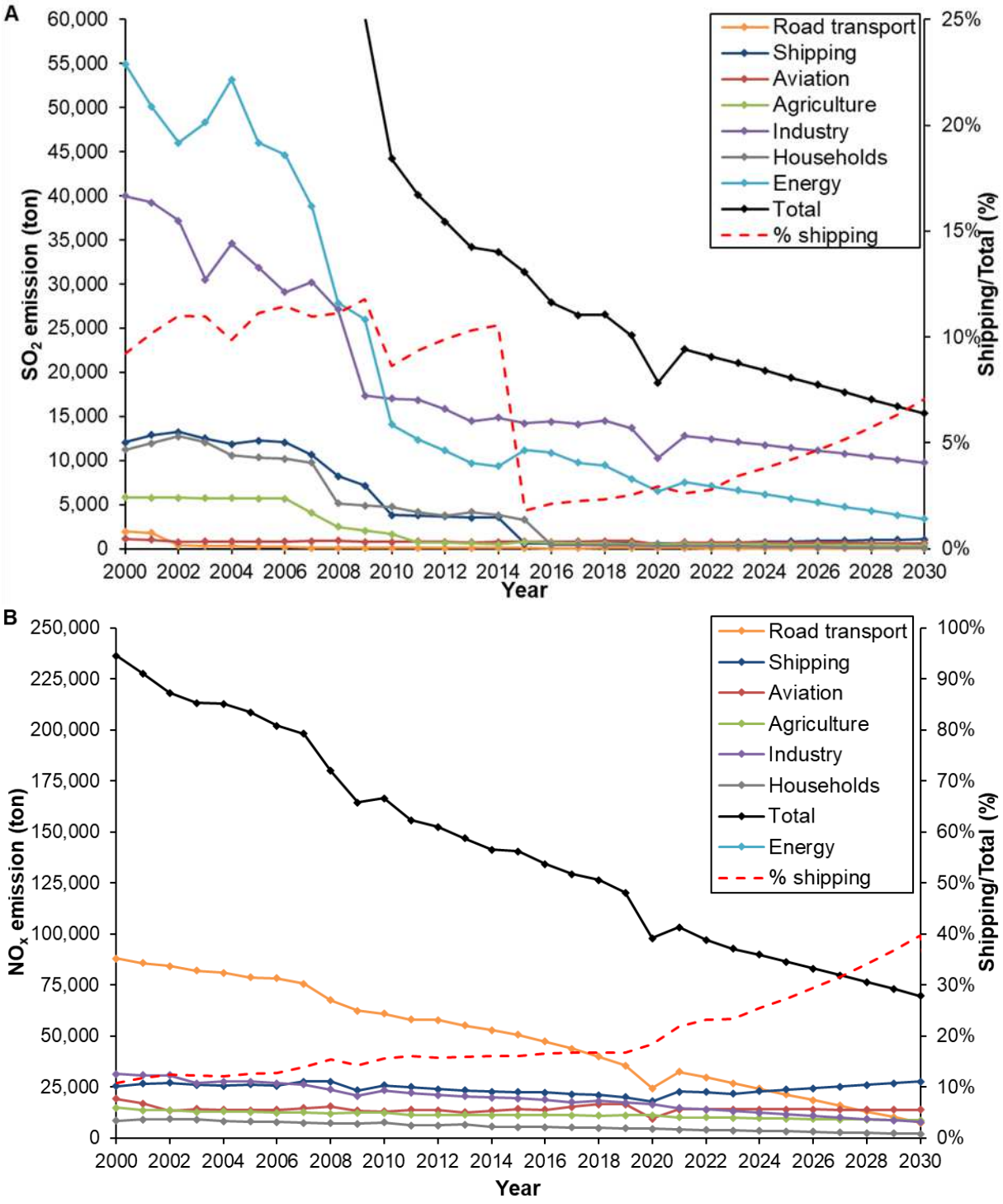


Figure 8. Evolution of SO_2 (A) and NO_x (B) emissions from different sources for the region of Flanders with future trend unitll 2030 and contribution of shipping (data from 2000-2020 obtained from VMM)[71]

4. Conclusions

This study showed that the implementation of Regulation 14 of MARPOL Annex VI and the assignment of the North Sea Emission Control Area, have had a significant impact on the reduction of SO_2 emissions from OGVs. It also revealed that the introduction of the Global Sulphur Cap has further reduced SO_2 emissions, diminishing the contribution of shipping to domestic SO_2 pollution in Belgium from over 10% in the early 2000s to 3% in 2015. The implementation of the Global Sulphur Cap also coincided with

an improvement in compliance levels, which can be partly attributed to the increased implementation of remote monitoring by North Sea coastal states. The effective implementation of clear regulations, monitoring and enforcement practices at various policy levels (IMO, EU, Belgium) has proven to be successful in addressing SO_2 emissions from OGVs.

Yet, the study shows that SO_2 emissions from OGVs are expected to rise to 7% by 2030. The Global Sulphur Cap has led to an increased use of EGCS and SO_2 emissions from EGCS equipped OGVs were found to be considerably higher than those OGVs without EGCS. Moreover, non-compliance is significantly more prevalent in EGCS-equipped OGVs and FSC values appear to be particularly high when non-compliance is found in EGCS equipped OGVs.

The study found that Regulation 13 of MARPOL Annex VI had no beneficial effect on the average reduction of NO_x emissions from OGVs. On the contrary, due to the way regulations are structured, the study demonstrated that real-world average NO_x emissions from OGVs are increasing. This trend, in combination with the expected growth in maritime transport, will make OGVs the largest contributor to NO_x emissions by 2025. By 2030, OGVs are estimated to be responsible for 40% of total domestic NO_x emissions in Belgium. Finally, this study showed that EGCS not only increased SO_2 emissions, but also resulted in higher mean NO_x emissions and increased non-compliance with NO_x regulations. These findings highlight that several aspects of the international NO_x regulations should be revised. In addition, this study shows that there are operational issues with EGCS OGVs that require attention.

Data availability: The Belgian airborne monitoring dataset is available on: https://doi.org/10.24417/bmdc.be:dataset:2687

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6. Supplementary figures and tables

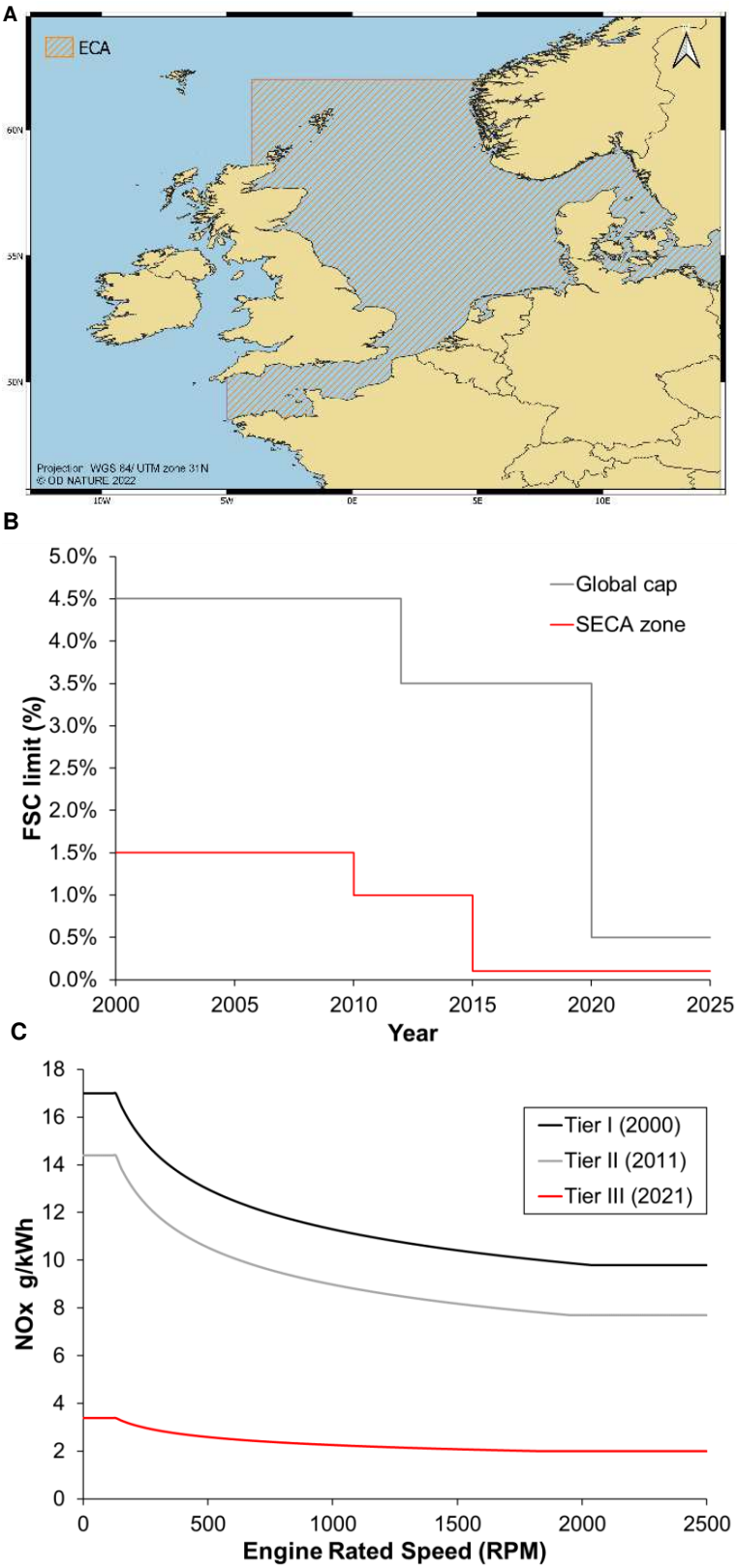


Figure S.1. Emission Control Area (ECA) as defined by MARPOL Annex VI, focusing on the North Sea (A). Limits on the Fuel Sulfur Content of marine fuels according to the MARPOL Annex VI regulation 14 (B). NO_x emission limits according to MARPOL Annex VI Regulation 13 (C).

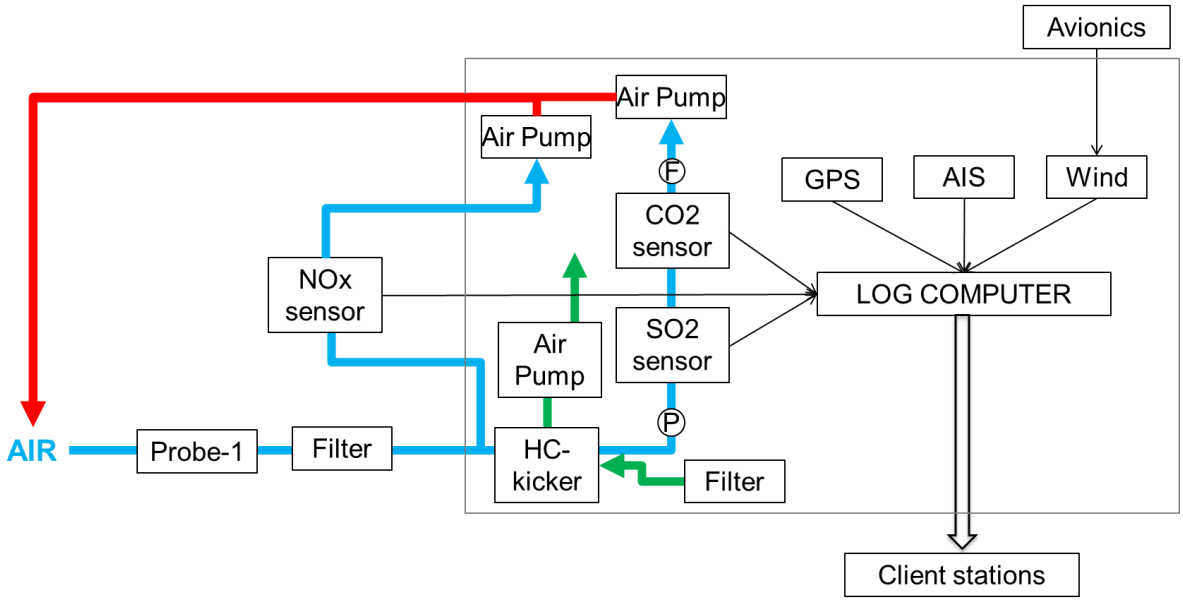


Figure S.2. Schematic overview of the updated sniffer sensor system, with NO_x sensor and HC kicker.

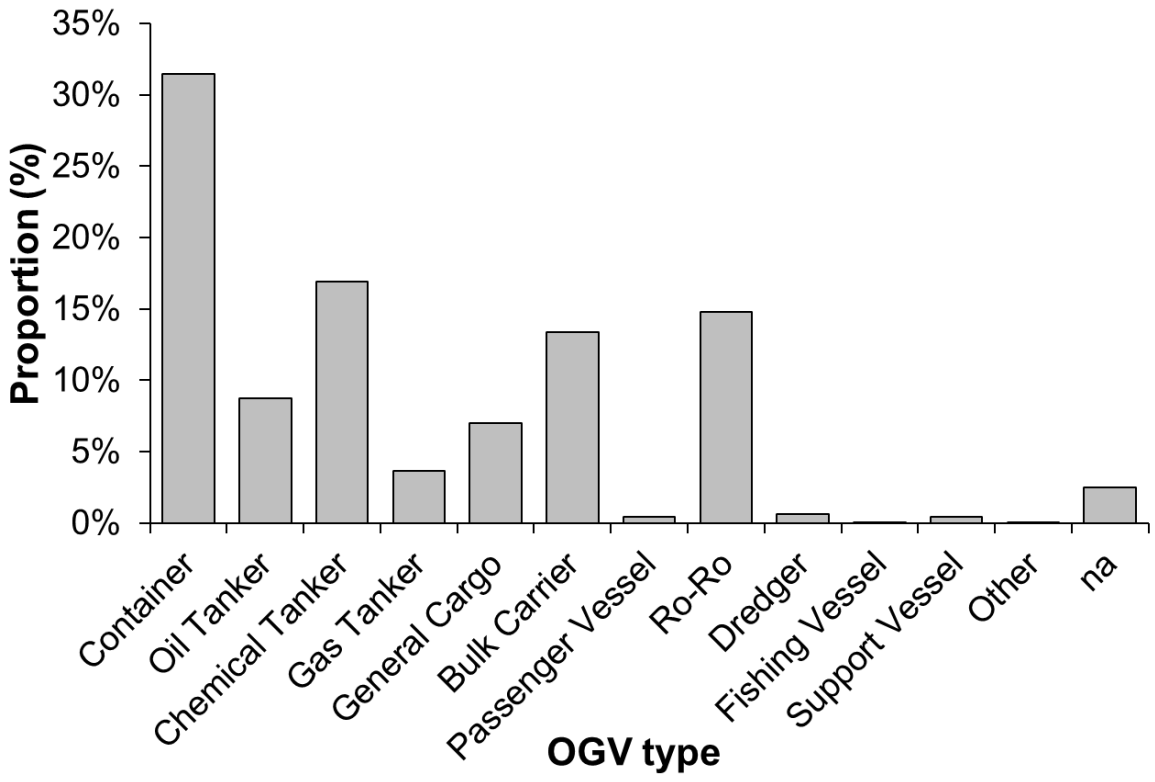


Figure S.3. Distribution of the observed OGVs according to OGV type.

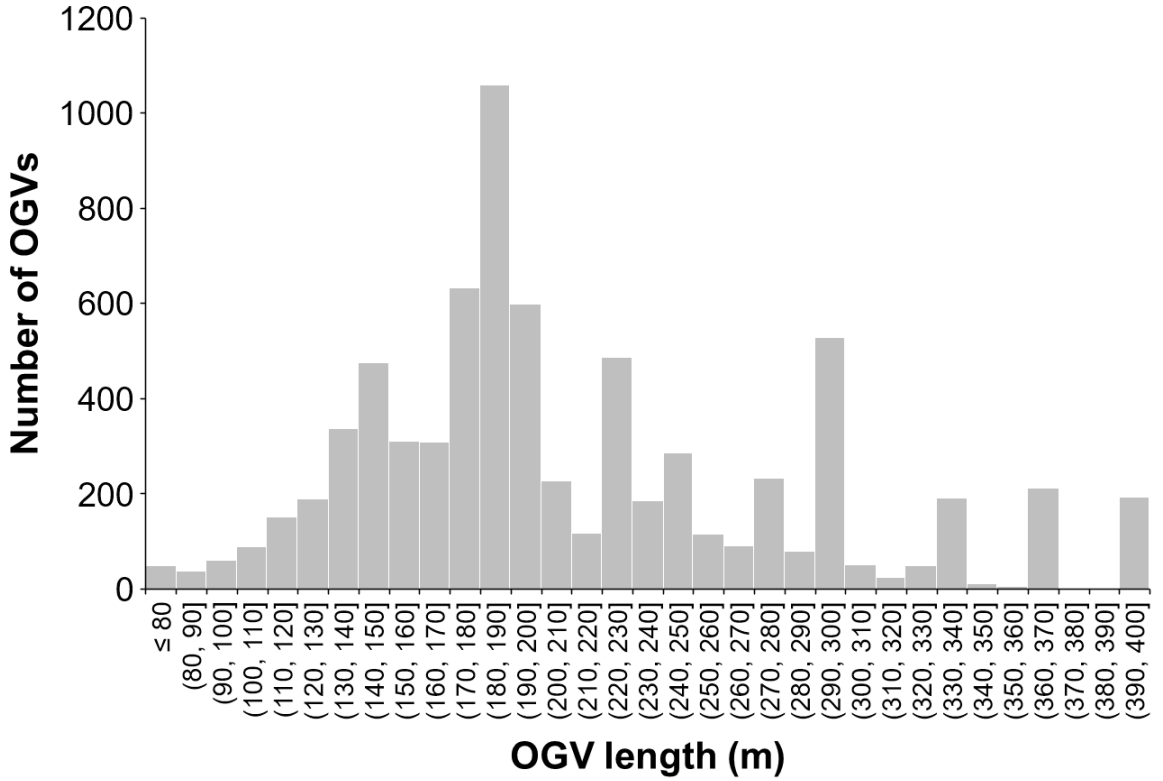


Figure S.4. Distribution of the observed OGVs according to OGV length (m).

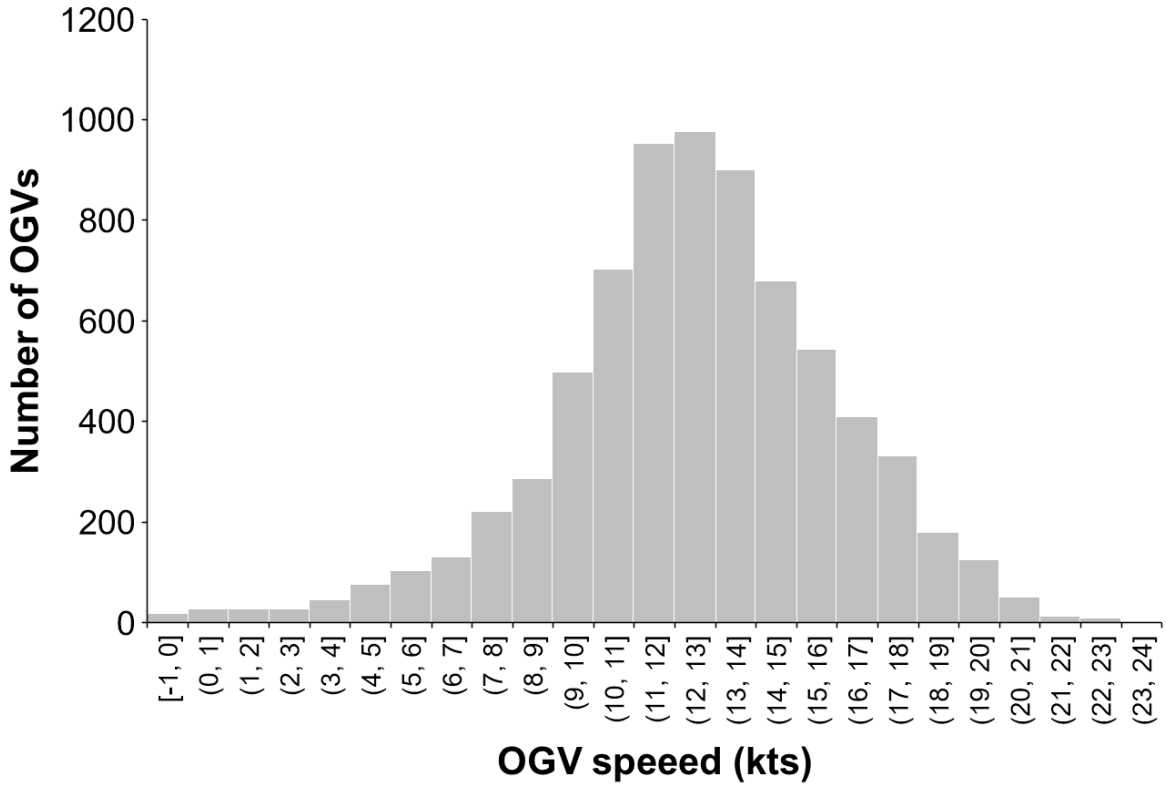


Figure S.5. Distribution of the speed of the observed OGVs.

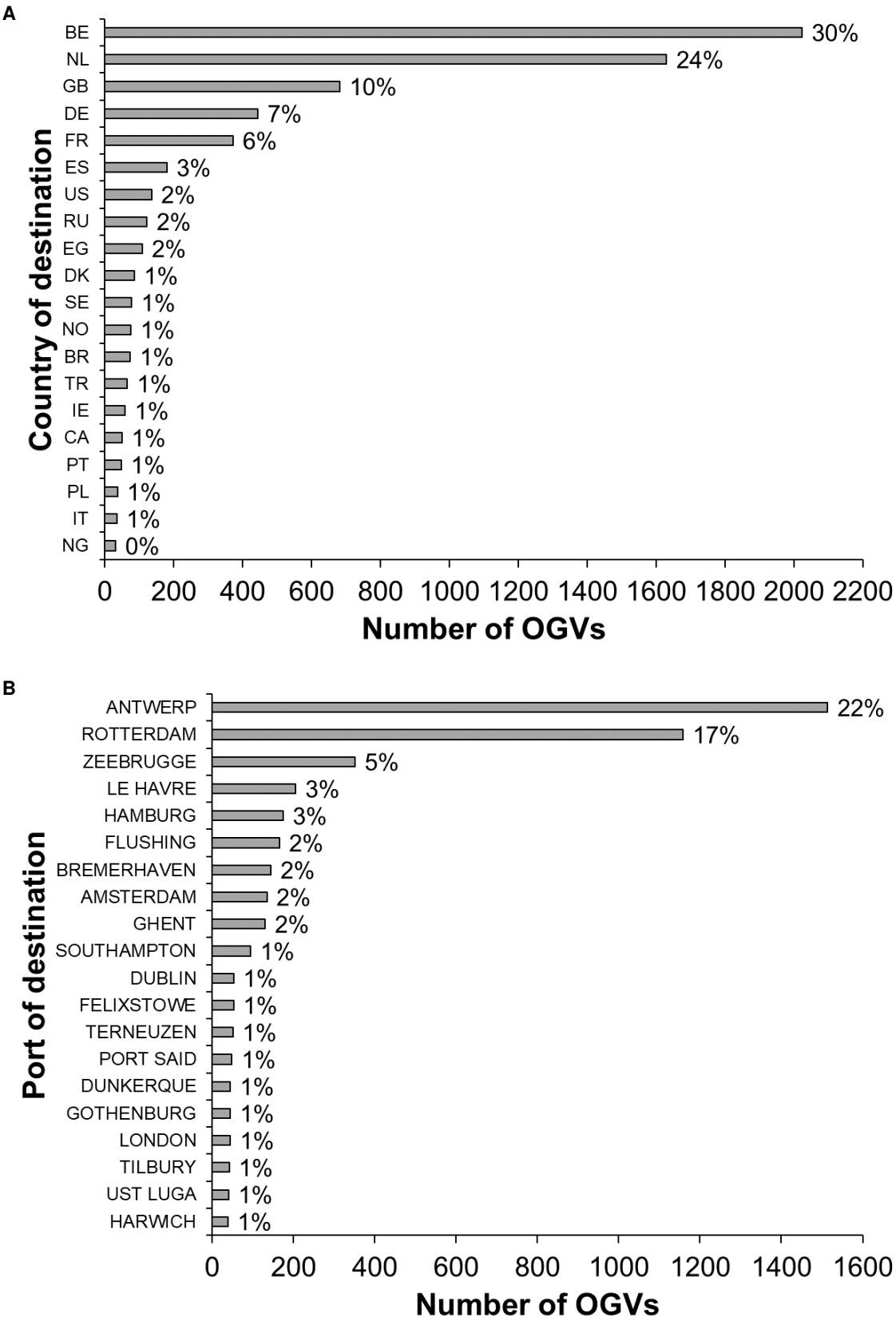


Figure S.6. Distribution of 20 most observed countries (A) and ports of destination, based on the AIS information transmitted by the OGVs (B).

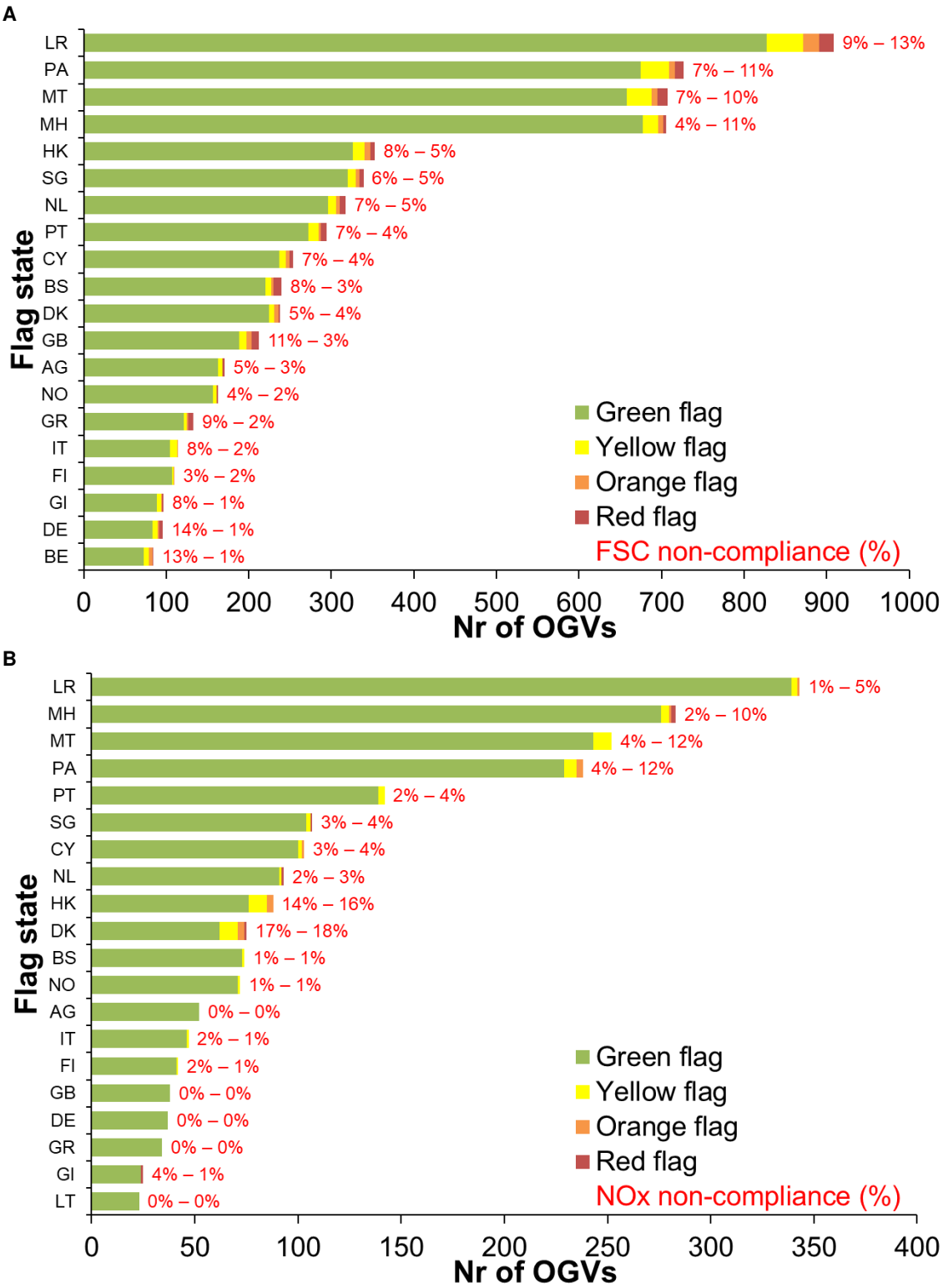


Figure S.7. Non-compliance for FSC (A) and NO_x (B) according to flag state. The left non-compliance rate (%) is based on the non-compliance rate per flag state, the right percentage is the proportion of the number of non-compliant OGVs per flag state compared to the overall number of observed non-compliant OGVs.

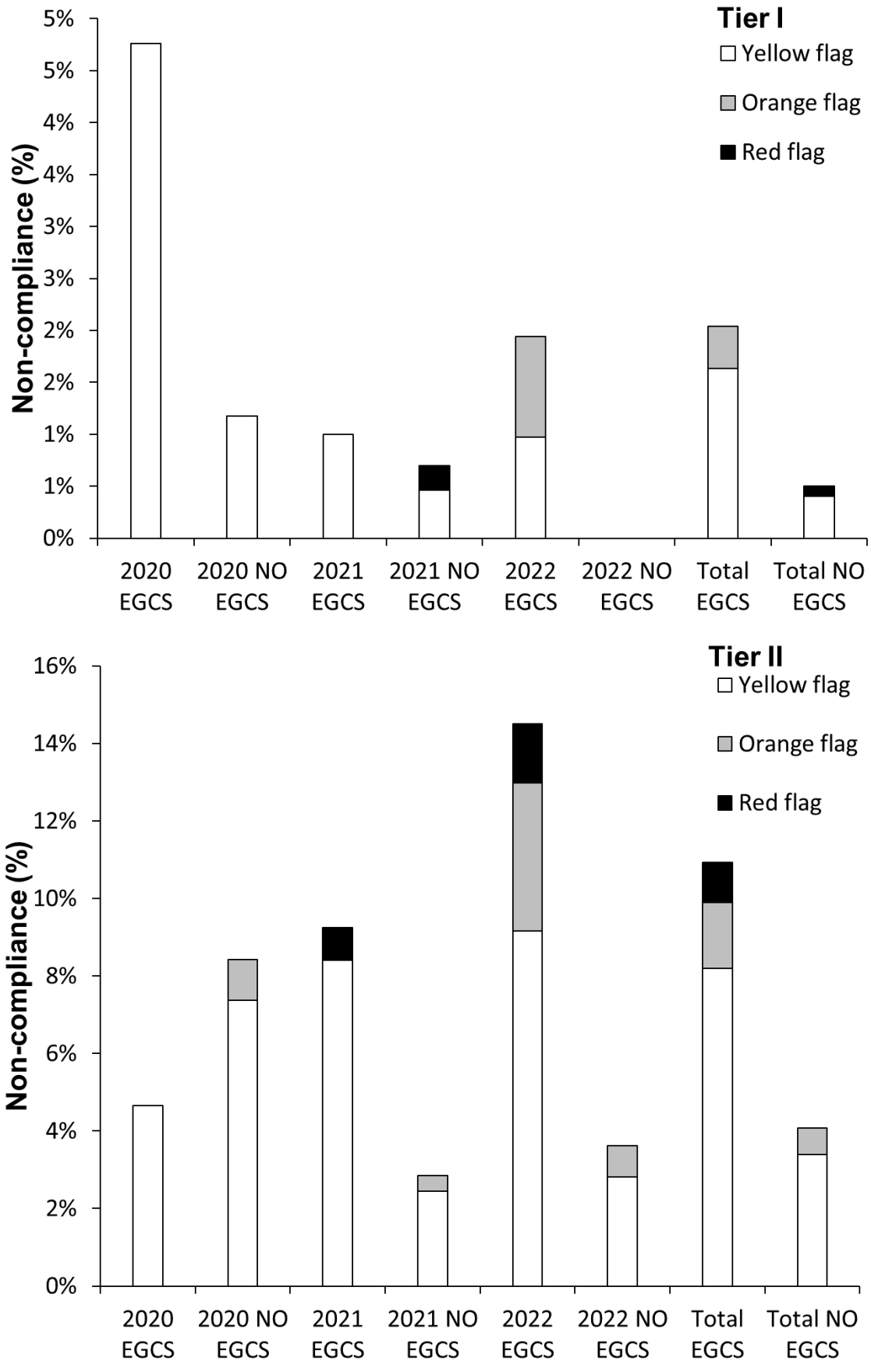


Figure S.8. Difference in compliance levels for EGCS OGVs versus non-EGCS OGVs for Tier I (upper) and Tier II (lower) OGVs.

Table S.1. Test cycles and weighting factors according to the NOx Technical code.

E2	Speed	100%	100%	100%	100%
	Power	100%	75%	50%	25%
	WF	0.2	0.5	0.15	0.15
E3	Speed	100%	91%	80%	63%
	Power	100%	75%	50%	25%
	WF	0.2	0.5	0.15	0.15

Table S.2. SO_2 and CO_2 concentrations of the ordered plume simulation mixtures and effective FSC value.

Mixture	FSC	SO_2 (ppm)	CO_2 (%)
Low	0.59	25ppm	1%
Medium	0.85	5ppm	0.1%
High	2.38	100ppm	1%

Table S.3. Intra-Assay Coefficient of Variability, freedom of degrees and total uncertainty for FSC and NO_x.

	2020 FSC range (%)			>2020 FSC range (%)			NO_x range (g/kWh)		
	<0.2%	0.2-0.4	>0.4	0.13-0.2	0.2-0.3	>0.3	0-10	10-20	>20
CV_{RW}	18.3%	11.6%	13.7%	18.0%	8.04%	4.82%	16.1%	14.9%	18.6%
n	109	49	29	20	12	14	24	79	45
u_{tot}	19%	13%	15%	25%	20%	18%	21.9%	21.1%	23.9%
$\|b\|$	4%	1.33%	0.66%	15%	14%	12%	13.4%	13.4%	13.4%
U ($\sigma = 1.96$)	42%	27%	30%	64%	52%	48%	29.6%	28.0%	33.4%

Chapter 6: Assessment of the international maritime regulations' impact in the North & Baltic Sea.



Personal picture taken at Wedel (DE) (22/03/23)

Assessment of the international maritime regulations' impact in the North & Baltic Sea.

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Abstract

For over 15 years, international regulations have been established to address SO_2 and NO_x emissions from shipping. In Europe, the tightest restrictions on SO_2 and NO_x came into effect only recently. For regions outside designated emission control areas, stricter SO_2 limits were introduced in 2020. Although research indicated that these regulations would provide significant health and environmental benefits, there remained a gap in understanding their effectiveness in reducing real-world ship emissions following implementation. This study addresses this gap through an analysis of more than 110,000 measured ship plumes, ship inspection results and satellite data. The study revealed that sulfur compliance rates are higher near ports than in open waters. Moreover, the study revealed the regulations had no effect on NO_x emission regulations, on the contrary the study reveals NO_x pollution has risen in the past three years. These findings highlight the need for more effective regulations to address ship emissions.

1. Introduction

With a death toll of up to 8.8 million premature deaths per year, anthropogenic air pollution has been identified as the global leading cause of death [1,2]. Air pollution from ocean going vessels (OGVs) is one of the main sources of air pollution. Sofiev et al. have calculated that OGVs are responsible for up to 800,000 of these premature deaths [3], which are mainly caused by fine particles ($PM_{2.5}$), but other pollutants, like ozone, SO_2 and NO_x contribute to a substantial degree [3–7]. In 2014, OGVs were responsible for 13% and 14% of the global anthropogenic emissions of respective SO_2 and NO_x [8–13]. According to the International Maritime Organization (IMO), thanks to the establishment of Emission Control Areas (ECAs) and the stricter SO_2 emission limits in 2015, SO_2 emissions fell by 28.6% between 2014 and 2017, while NO_x reported a 1.2% increase over the same period [12]. Sofiev et al. have estimated that before the strengthening of the global sulfur emission regulations for OGVs in 2020, SO_2 and sulfur related particles in OGVs emissions were responsible for up to 403,300 premature deaths a year and 14 million cases of childhood asthma [3]. With the introduction of global emission regulations for OGVs, it was estimated that 263,300 premature deaths (-33%) and 7.6 million cases of childhood asthma (-54%) could be avoided [3,4]. When concerning NO_x, the health benefits of introducing NO_x emission regulations are not immediately observed as new emission abatement technology needs to be introduced to be compliant to the defined emission limits of the regulations. The compliance rate is therefore linked to the scrapping rate, i.e. the rate at which old OGVs are scrapped and replaced by new OGVs as well as the engine overhaul rate, i.e. the rate at which old engines are replaced by new engines with lower emission limits [9]. Zhang et al. have estimated that the application of the latest introduced Tier III NO_x emission standards, is the most advantageous approach to further reduce the detrimental impact of shipping on human health, as it would reduce up to 36,400 premature deaths per year [4]. The recently

completed EU funded Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations (SCIPPER) project also recommended the establishment of further NO_x Emission Control Areas (NECAs) [14]. It must be highlighted that to attain the afore-mentioned health benefits a high compliance rate of international emission standards for OGVs needs to be reached.

The regulations put in place to reduce emissions from OGVs fall under the MARPOL Convention of the IMO [15]. Annex VI of the revised MARPOL Convention aims for a gradual decrease of the global air pollution by SO_x and NO_x from OGVs [16] (supplementary material, MARPOL Annex VI). In addition, MARPOL Annex VI introduced ECAs with tighter emissions standards (figure S.1A-C). and is ratified by 105 countries representing 96.81% of the gross tonnage (GT) of the world merchant fleet [17–21].

Despite the fact that the above-mentioned publications projected significant health benefits from the implementation of international maritime emission regulations and that emissions models predict a decrease of air pollution from shipping [22,23], there still remains a research gap regarding the effectiveness of the established international regulations in reducing real-world emissions from OGVs in the wider ECAs. At the national level, Van Roy et al. showed varying results of the success of international regulations to improve air quality in Belgium [24].

The main objective of this article is therefore to examine the effects of the implementation of the European ECAs and other international maritime regulations in the wider North Sea and the Baltic Sea on OGVs' emissions. This is accomplished in a three-step approach. The first step examines the effects of international emissions regulations in the Bonn Agreement (BA) area (North Sea and North-East Atlantic area) (figure S.2). This was done by analyzing compliance rates based on more than 100,000 remote OGV emission measurements collected by the BA Contracting Parties (CPs) (table S.2). In the second step, data on emission violations and penalties for the BA area were examined. In addition, the overall port inspection results for the entire EU were examined. In the third, step satellite data is used to assess any changes in the atmospheric concentrations of SO_2 and NO_2 in the European ECAs. The presented work reveals that international regulations on fuel sulfur content (FSC) are well enforced by the BA Parties and by extension by the entire EU. Compliance rates are well under control and the results of this study show that SO_2 non-compliance has reduced significantly since the introduction of the global sulfur cap. The number of recorded infringements in BA and EU ports follows a similar trend. Based on satellite data it was found that atmospheric SO_2 concentrations inside the ECA have decreased since the introduction of the global sulfur cap. In contrast, this article demonstrates that NO_x emission regulations are less successful, NO_x emissions from OGVs are even increasing.

2. Results

2.1. Regionwide analysis of the remote monitoring data

Non-compliance data from all remote measurement stations and deployments was collected based on three different cut-off levels. This allows the assessment of the severity of the non-compliance behavior in addition to a temporal and spatial non-compliance trend analysis. For the main results, the 0.15% FSC cut-off level was used.

2.1.1. Temporal sulfur compliance trends

A decreasing trend in FSC non-compliance rates was observed across all measurement locations within the European Sulfur Emission Control Area (SECA) regions. The non-compliance rate decreased from 7.1% to 0.7%, with an average non-compliance rate of 1.5% when a 0.15% FSC cut-off level is used (Figure 1). The pattern is similar for the other cut-off levels (figure S.3A&B). Following the implementation of the global sulfur cap in 2020, the non-compliance rates reached their lowest point, with an average non-compliance rate of 0.6%. It is important to acknowledge that the implementation

of the sulfur cap in 2020 coincided with the global COVID-19 pandemic, which led to reduced fuel prices [25,26]. Additionally, several monitoring operations observed a slight increase in non-compliance, starting from 2022. This increase can be attributed to the rise in marine fuel prices resulting from the Russian invasion in Ukraine and the subsequent global price inflation [27].

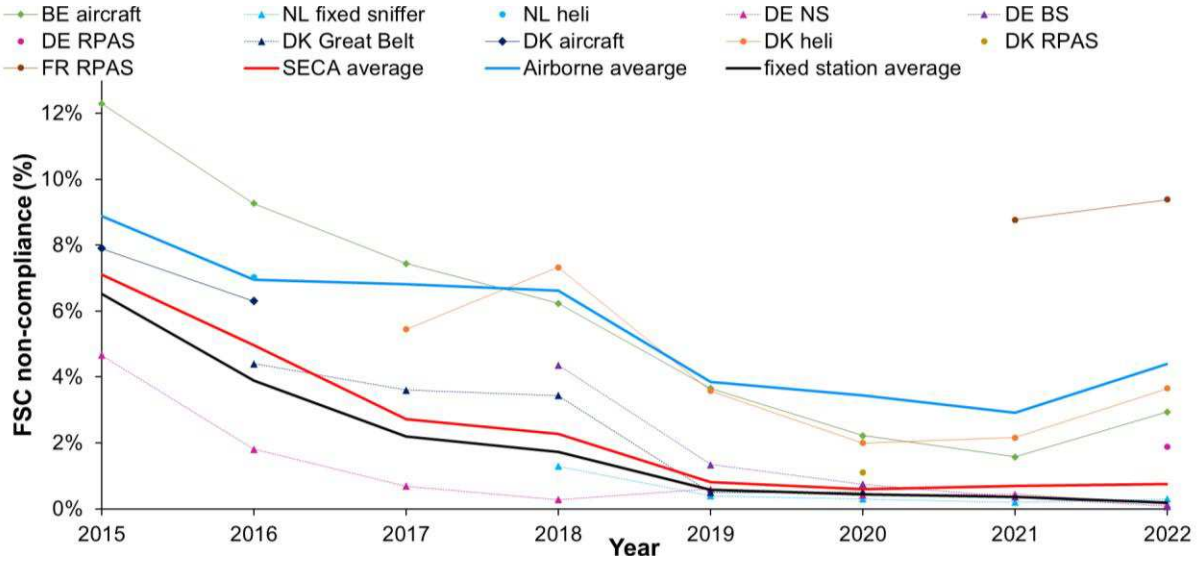


Figure 1. FSC non-compliance for remote monitoring locations in the SECA for a 0.15% FSC cut-off level. Measurements with fixed wing aircraft are displayed with full lines and diamond markers (♦), measurements using RPAS and helicopters have full lines and circle markers (●), fixed sniffer measurements are displayed with dotted line and triangular markers (▲).

Among the different remote measurement operations applied by the SECA countries, the French measurements with the remote piloted airborne systems (RPAS) exhibited the highest non-compliance rates. The average non-compliance rate was 9.4% and therefore substantially higher than the non-compliance observed by the other remote measurement operations, which varied between 0.1% and 3.7% for the same period. When considering the remote monitoring locations that conducted measurements throughout the entire 2015-2022 period, the Belgian airborne measurements recorded the highest non-compliance rate for the 0.15% FSC cut-off level (5.2%). However, the Danish helicopter measurements displayed the highest non-compliance rate for the 0.13% FSC cut-off level (8.5%). This distinction is noteworthy as it illustrates that while the OGVs in Danish water exhibited higher absolute non-compliance rates, the level of the FSC exceedances was higher for the OGVs in Belgian waters.

2.1.2. Spatial sulfur compliance trends

The temporal analyses reveal notable disparities in non-compliance rates between fixed stations (1.0%), typically situated near ports, and airborne measurements (5.3%) (Figure 1). Similar patterns were observed for the other cut-off levels (figure S.3A&B). These differences in non-compliance rates between airborne measurements and fixed stations were statistically significant for all cut-off levels ($P < 0.001$).

Although based on the same methodology (supplementary material, Measurement techniques), fixed and airborne measurements use different operational methods, which can partly explain the differing non-compliance rates. Airborne platforms try to avoid redundant measurements of the same OGVs, while fixed stations take a non-selective approach and measure all passing OGVs. This may therefore lead to a slight underestimation of the determined non-compliance rate by fixed stations if compliant OGVs like compliant ro-ro ferries are overrepresented in these datasets. Furthermore, aerial remote measurements may tend to focus on OGVs with a higher risk profile, and, to some extent, avoid OGVs operating only in the SECA, or smaller coasters, i.e. small to medium-sized cargo OGVs designed for transportation along coastlines or in relatively calm waters. This may overestimate the overall non-

compliance rate by airborne measurements. Nevertheless, these findings indicate a clear pattern of adaptive non-compliant behavior among OGVs.

Comparison of non-compliance trends between the various measurement campaigns revealed a high consistency (table S.3&4). It was observed that locations in closer proximity to the SECA border have higher non-compliance rates. Measurements taken at the border by the MUMM and Chalmers University [28] demonstrated an average non-compliance rate of approximately 30%. When plotting the non-compliance data against the distance from the border, it followed an exponential decreasing curve, with a high goodness of fit (Figure 2A). In order to mitigate the influence of the high compliance rate in ports, the combined airborne data from RPAS, helicopter, and aircraft was utilized (Figure 2B). In this case, an excellent goodness of fit was also observed. Given the significant disparity between non-compliance rates observed in ports compared to those at sea, the relationship between compliance and the distance from port was determined (Figure 2C). Similar patterns were observed for the other FSC cut-off levels (figure S.4A-C). The fitting constants and correlation factors (R^2) of the curve fittings for all cut-off levels are provided in table S.5&6.

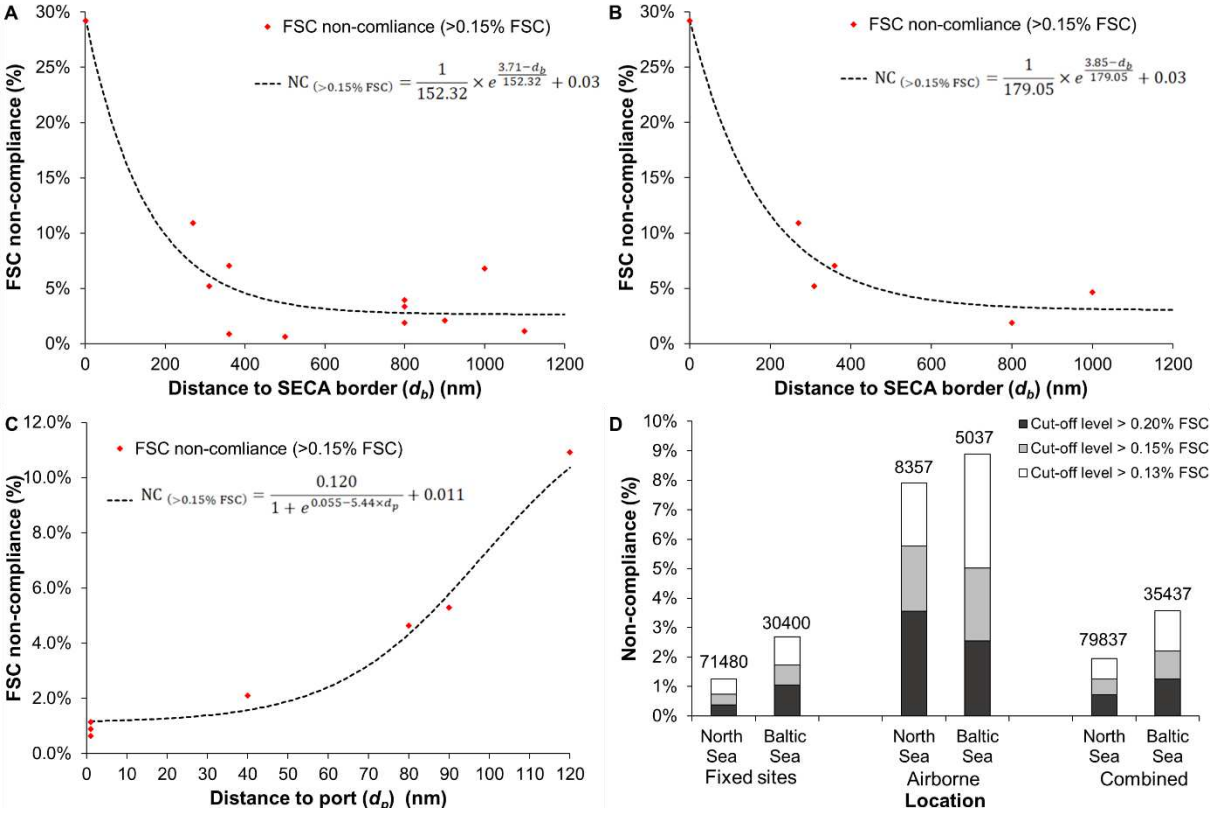


Figure 2. Non-compliance fitting based on the mean non-compliance of the different remote measurement locations in function of the distance to the SECA border, for all remote measurements (A) and for when only the airborne measurements are considered (B). Non-Compliance fitting in function of the distance to port (C). Difference in compliance rates between Baltic Sea and North Sea SECA, with the number of measurements per SECA (D).

This spatial analysis provided valuable insights into the distribution of non-compliance risks along the SECA border. Notably, the analysis revealed that the highest risk for non-compliance was observed within the first 500 nm from the SECA border. The results indicate that compliance rates at sea, beyond a distance of 500 nm, varied between 2-3% for the 0.15% FSC cut-off level. Furthermore, these findings indicate that non-compliance begins to notably increase at approximately 50-70 nm from port. At a distance of 100 nm from the port, the proximity to the port stops influencing non-compliance behavior. It must be acknowledged that the number of points for these fittings were, in particular for the non-

compliance in function of the distance from port, very low. To obtain a better understanding of these relationships it is recommended that a dedicated more in-depth analysis based on the raw measurement data is conducted.

Upon comparing the Baltic Sea and the North Sea, noticeable differences in non-compliance rates were observed. In general, the Baltic Sea exhibited higher non-compliance rates, with an overall non-compliance rate of 1.3%, compared to 2.2% for the North Sea for the 0.15% FSC cut-off level (Figure 2D). Similarly for the other cut-off levels the Baltic Sea demonstrated higher non-compliance rates. Importantly, for all cut-off levels, the differences were determined to be statistically significant ($P < 0.001$). When comparing the airborne results, for the North Sea a higher non-compliance rate is observed for the 0.15% FSC and the 0.20% FSC cut-off levels. However, the Baltic Sea showed a higher non-compliance rate for the 0.13% cut-off level. This indicates that non-compliant OGVs at sea in the North Sea tend to have higher absolute FSC levels compared to those in the Baltic Sea, whereas in the Baltic sea, low FSC exceedances appear to occur more often.

2.1.3. NO_x Emission Control Area

For this study it was not feasible to compare the Belgian NO_x non-compliance data with other locations since there are no other NECA countries reporting on NO_x non-compliance in an operational setup. However, it is worth noting that numerous other agencies conduct measurements of NO_x levels in addition to monitoring SO_2 concentrations in OGV exhaust plumes. While a direct comparison of NO_x non-compliance data may not be possible yet, these additional measurements provide valuable insights on the overall emissions profile and environmental impact of OGVs.

The examination of the Belgian data reveals that the mean NO_x emissions are not decreasing as anticipated with the implementation of stricter emission limits. On the contrary, the data indicates that NO_x emissions are increasing [24,29]. Furthermore, non-compliance levels for NO_x emissions are also rising [24,29]. This trend can be attributed to the higher emission levels reported for Tier II OGVs compared to Tier I OGVs. Based on the Belgian data, a strong correlation ($R^2 = 0.9993$) was found between the annual mean NO_x emissions and the proportion of Tier II OGVs (Figure 3). Nevertheless, the weakness of this 3-point correlation aligns with the previous findings demonstrating substantially higher NO_x emissions for Tier II OGVs [24,29,30]. These findings have significant implications for the parameterization of emission models, such as the Steam Model [31,32], which are fundamental sources for global emission inventories for shipping. By incorporating the correct NO_x emission factors based on the real-world emission factors per IMO tier, more accurate global assessments of NO_x emissions from OGVs can be achieved, thereby improving the understanding of their environmental impact.

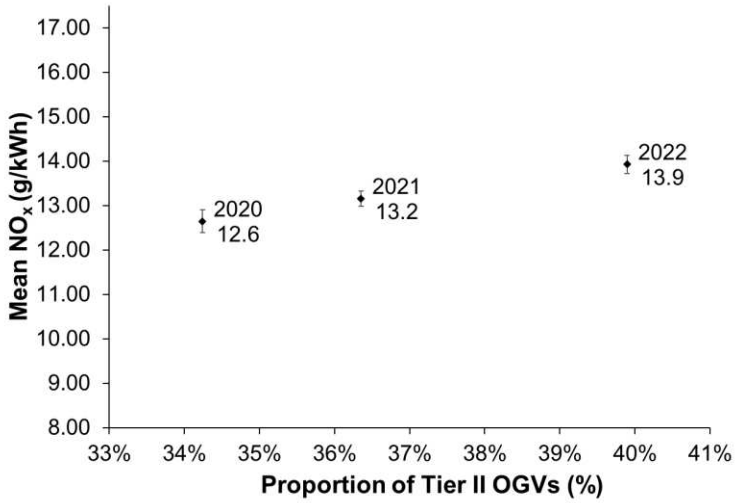


Figure 3. Annual average measured NO_x emission (in g/kWh) and standard error in function of the proportion (%) of Tier II OGVs (based on the Belgian airborne dataset collected between 2020-2022) [24]. The Y-axis shows the minimum and maximum emission limits for respectively Tier II and Tier I.

The Danish company Explicit took a different approach to the Belgian one by using modelling. They estimated main engine power and fuel consumption as input for the calculation of NO_x emission factors in grams of NO_x per kilowatt-hour (g NO_x/kWh) [30]. Explicit used this approach for reassessing the Danish historic NO_x measurement data. The findings of this study align with the results of the empirical approach of Belgium, revealing higher emission factors and a greater non-compliance rate for Tier II OGVs compared to Tier I OGVs. The Danish study also confirmed that OGVs emit more NO_x when operating at lower engine loads. Additionally, the results demonstrated that larger engines generate higher emission factors, which is in line with the Belgian measurements, albeit with a weak correlation. An increasing trend was observed across all Tier levels, excluding Tier III due to limited measurements (figure S.5).

Non-compliance with NO_x standards has also recently been investigated within the SCIPPER project. A particular emphasis was placed on Tier III OGVs. The advantage for the enforcement of Tier III OGVs is that a not-to-exceed limit (NTE) is defined for all four engine load points, set at 50% of the applicable emission limit (Appendix II, MARPOL Annex VI) [16]. However, because the keel laying date (KLD) is defined in the MARPOL Annex VI regulations to determine Tier III classification, a significant majority (73%) of the recently constructed OGVs are registered with a KLD prior to 2021. Consequently, they are subjected to the Tier II emission limits instead of the stricter Tier III emission limits [24].

In total 65 Tier III OGVs were monitored by the SCIPPER partners. The findings indicated that approximately half of the observed Tier III OGVs did not comply with the maximum NO_x emission limits for Tier III; ca 20% of the observed tier III OGVs did not even meet Tier II emission limits [33]. This observation aligns with the limited Tier III non-compliance results reported by Belgium, where a non-compliance rate of 43% was observed. Various other studies have also highlighted concerns regarding elevated levels of NO_x emissions from Tier III OGVs [34,35].

2.2. Port inspections on sulfur and NO_x infringements

2.2.1. Results within the Bonn Agreement

The results of the sulfur infringements from most BA CPs follow an increasing trend between 2015 and 2020 (figure S.6A). The primary reason for this is that not all CPs immediately implemented inspection protocols; needed to gain experience; and had initially only limited information available to single out suspicious OGVs for inspection. As a result, not all CPs have inspection results for 2015. From 2016, all BA CPs were actively conducting inspections within their ports. During this time, remote monitoring operations and the exchange of alerts via Thetis-EU began to gain momentum, leading to the discovery of a higher number of infringements and deficiencies.

Due to a high number of observed sulfur infringements by one BA CP, the total observed number of infringements in the years 2015 and 2016 still provided the highest number of observed infringements (243 and 223) (Figure 4A). The year 2018 provided the third highest number of recorded infringements (178). However, following that year, the number of identified infringements began to decline. It is important to note that the EU Sulphur Directive mandates Member States (MS) to provide port inspection data by June, as a result, at the time of publication, not all CPs were able to submit data for the year 2022.

The EU-Commission Implementing Decision played a significant role in maintaining a consistent number of inspections conducted on OGVs throughout the entire time period. Although there was a decrease in inspections in 2020 due to the global pandemic, the majority of CPs were still able to fulfill the mandatory inspection requirements. It is worth noting that in this context, numerous CPs utilized the exemption outlined in the Implementing Decision to reduce the number of inspections by implementing remote monitoring (Art 3.3(a)) [36].

Regarding the reported penalties on sulfur, an upward trend was observed between the years 2015 and 2017, reaching a peak of 126 cases in 2017 (figure S.6B). Subsequently, the number of penalties declined. It should be noted that there is a time lag in the reporting of penalties, as often the reported penalties correspond to infringements observed in the previous year. Therefore, the peak in penalties in 2019 aligns with the peak of infringements in 2018. To address this time lag, it is necessary to analyze the data from the original cases and assign them to the year of observation. However, this analysis was not feasible due to the sensitive nature of the legal cases involved.

When looking at the mean number of sulfur deficiencies and infringements observed by the BA CPs' port inspection authorities, a substantial decrease was observed after the global sulfur cap came into effect (Figure 4A). Over the total period 2015-2022, 996 infringements were observed of which 544 were penalized. In the period 2015-2020, before the global sulfur cap came into effect, 885 infringements were observed by the port inspection authorities with a mean of 21.6 cases per year, 442 penalties were executed in the same period or on average 10.8 penalties per year, corresponding to 56% of the infringements. In the period 2020-2022, after the global sulfur cap came into force, in total 111 infringements were observed. The mean annual number of observed deficiencies per BA CP decreased therefore significantly to 4.8 cases per year ($P < 0.001$). In total, 102 penalties were handed out after the global sulfur cap came into effect (91%). The mean number of penalties per BA CP per year therefore decreased significantly to 4.3 penalties ($P < 0.05$), which is just below the mean number of observed infringements, indicating that as of today there is a good legal follow up of possible infringements within the BA.

There is a notable disparity between sulfur and NO_x. The result of the inquiry with the BA CP on sulfur provided an abundance of data regarding sulfur infringements and demonstrated the successful enforcement and legal follow up with penalties for sulfur infringements. In contrast, the results of the inquiry on NO_x enforcement within the BA CPs on reported NO_x violations and penalties was disappointing (Figure 4B). Only two BA CPs have reported NO_x infringements and penalties. Most of the other BA CPs are currently not enforcing NO_x regulations nor collecting data on the results of the NO_x inspections at the time of publication. Currently, only one BA CP has imposed a penalty for a NO_x violation. This demonstrates that enforcement of NO_x regulations by BA CPs is currently lacking. Upon examining the limited available NO_x inspection data, it becomes evident there has not been a decrease in violations since the NECA was implemented, but rather, an increase. However, the scarcity of data does not allow statistical analysis or strong conclusions to be drawn about compliance rates within the BA.

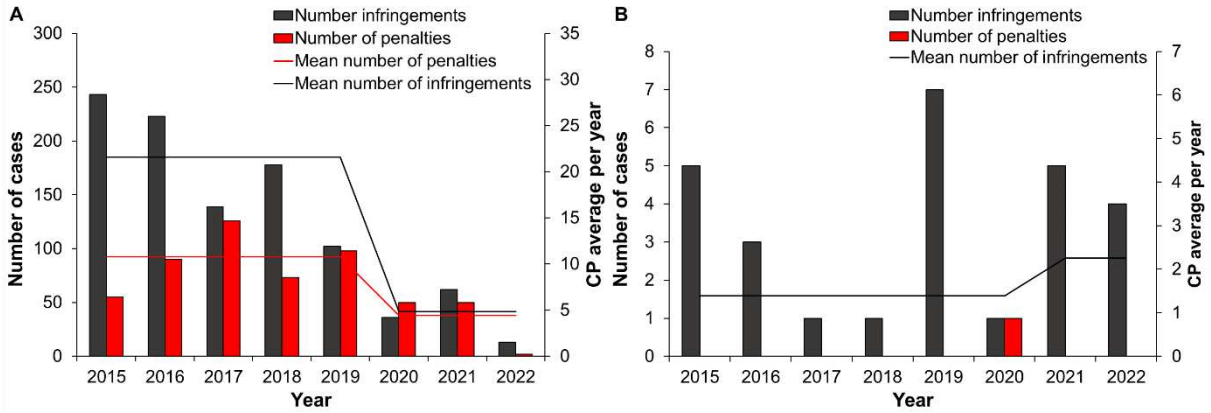


Figure 4. Number of observed infringements and penalties in the BA area by port inspection authorities for SO_2 (A) and NO_x (B). Note that for 2022 not all CPs were yet able to provide data.

2.2.2. Results within the EU

Upon examining the data on sulfur inspections and non-compliance rates within the EU, similar patterns were observed within the Baltic Sea and North Sea ECA as within the BA (Figure 5A). In the wider SECA, in total 110,657 documentary inspections were conducted. The annual amount showed a slight increase since entering into force in 2015, with a relatively stable trend over the entire period, except for a small decline in 2020. This increase was mainly a result of the increased number of inspections by the North Sea ECA countries, while the Baltic Sea countries had a more stable number of conducted inspection throughout the entire period. The non-compliance rate based on documentary inspections followed a similar trend as the number of infringements in the BA. However, it is important to note that this pattern is largely influenced by a significant reduction in non-compliance in the North Sea, while the reduction in the Baltic Sea is less pronounced. Also, when looking at the compliance results outside the SECA, the reduction was less pronounced. The overall non-compliance rate in the North Sea (7%) was found to be significantly higher compared to the Baltic Sea (3%) ($P < 0.001$). The non-compliance rate within the SECA (5%) was significantly higher compared to the non-compliance rate outside the SECA (2%) ($P < 0.001$).

In addition to the documentary inspections, in accordance to the EU regulations [36,37] fuel samples were collected by the EU MS (Figure 5B). Besides a small reduction in the number of fuels samples collected in 2020 due to the global COVID-19 pandemic, the number of fuel samples remained fairly consistent, with most EU MS providing a number above the mandatory required fuel sampling. When analyzing the inspection results from the fuel samples within the SECA, a significant increase in non-compliance was observed in 2016 and 2017, followed by a drastic reduction towards 2020, which then stabilized. This trend was observed for both the North Sea and the Baltic Sea. However, there was a slight increase in non-compliance observed in the North Sea in 2022, aligning with the findings from the remote monitoring operations in the BA. The North Sea non-compliance results of the fuel analysis (5%) were notably higher than the Baltic Sea (2%) ($P < 0.001$). The non-compliance trend of the fuel analysis outside the SECA also showed a substantial decrease by 2020, while the overall non-compliance rate (4%) was not found to be significantly different from the overall non-compliance rate of the fuel analysis within the SECA (4%) ($P = 0.9488$).

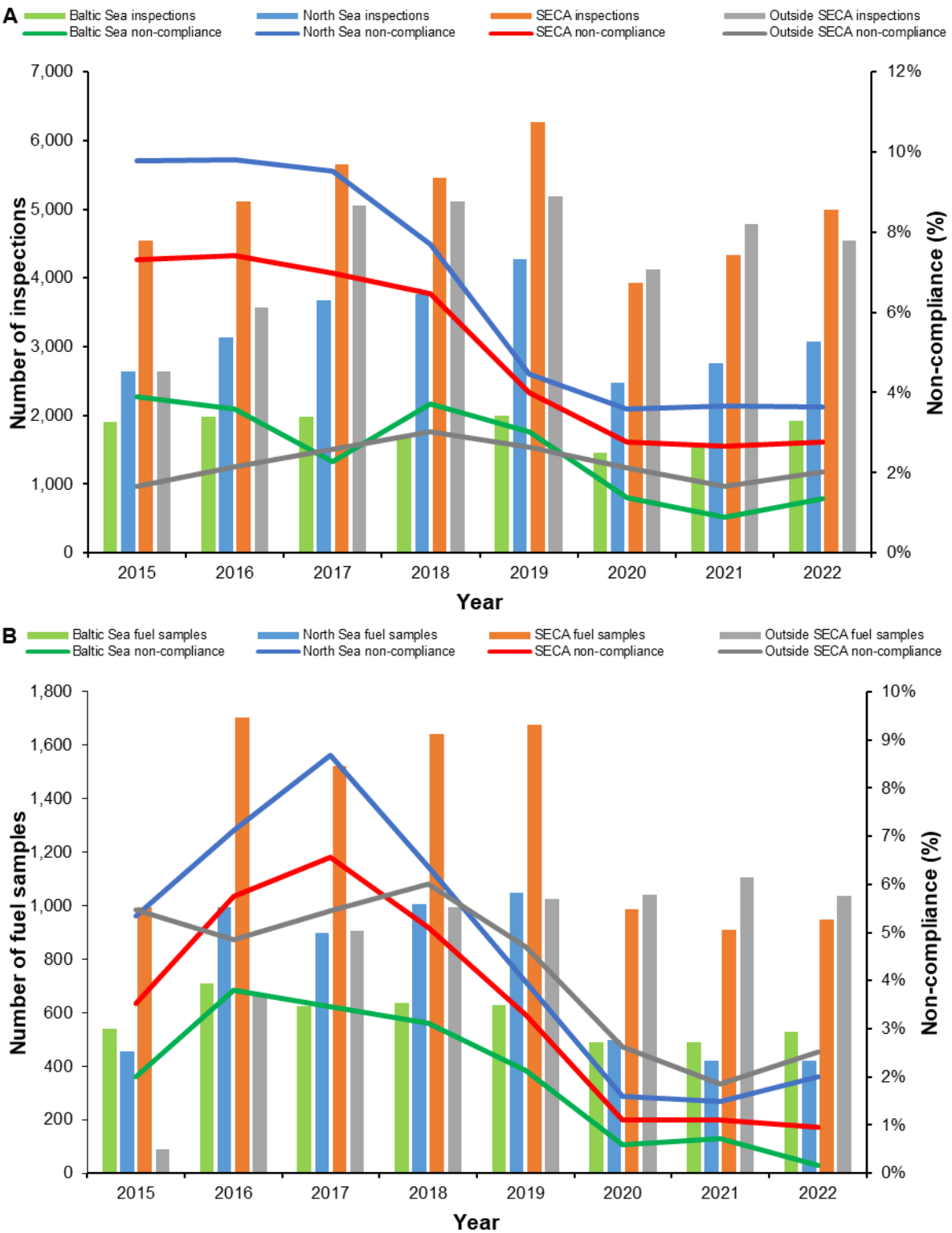


Figure 5. Inspection results in the EU based on Thetis-EU data, based on documentary inspections (A) and fuel sample analysis (B).

2.3. Spatiotemporal analysis of satellite data

2.3.1. Spatial analysis of atmospheric SO_2 data

Upon comparing the SO_2 vertical column density (VCD) across the various regions (Figure 6) for 2019 and 2021, notable findings emerged. Specifically, the BAQPZJR exhibited the highest concentrations of SO_2 pollution within the ECA. Meanwhile, the Bay of Biscay, displayed a much lower pollution pressure of SO_2 (table S.7). The implementation of the global sulfur cap is shown to have created a comparable

reduction of SO_2 pollution levels across the SECA. The region outside the SECA did not seem to be impacted. When looking at the period 2018-2022, for some areas an increase was observed (figure S.7). However due to absence of certain months in 2018 and 2022, this was attributed to seasonal effects.

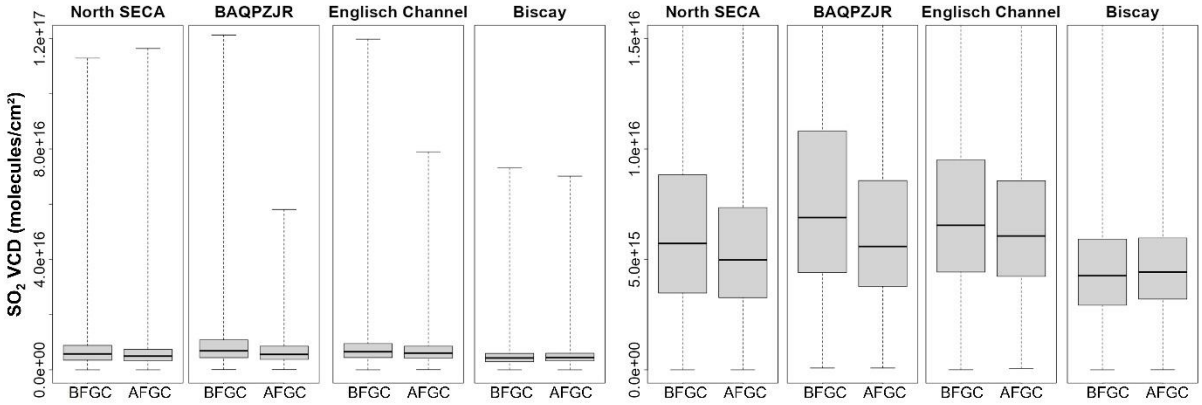


Figure 6. Box plot of SO_2 (VCD) between different areas before (BFGC) and after (AFGC) the global sulfur cap, with minimum, 25% percentile, median, 75% percentile and maximum. The left plots include the maximum values, while the right plots give the 25-75% percentile range.

2.3.2. Temporal analysis of atmospheric SO_2 data

From the start point of the satellite data in 2018, the overall emission levels of SO_2 at sea were already relatively low, in particular in the SECA due to the implementation of the 0.1% FSC limit in 2015. Consequently, the SO_2 VCD maps for 2019 and 2021, the respective years before and after the global sulfur cap came into effect, visualize widely dispersed concentration levels, although areas with high shipping activities can be, to some extent, identified. (figure S.8). Accordingly, the proportional difference of SO_2 pollution levels before and after the implementation of the global sulfur cap do not exhibit a distinct pattern (Figure 7).

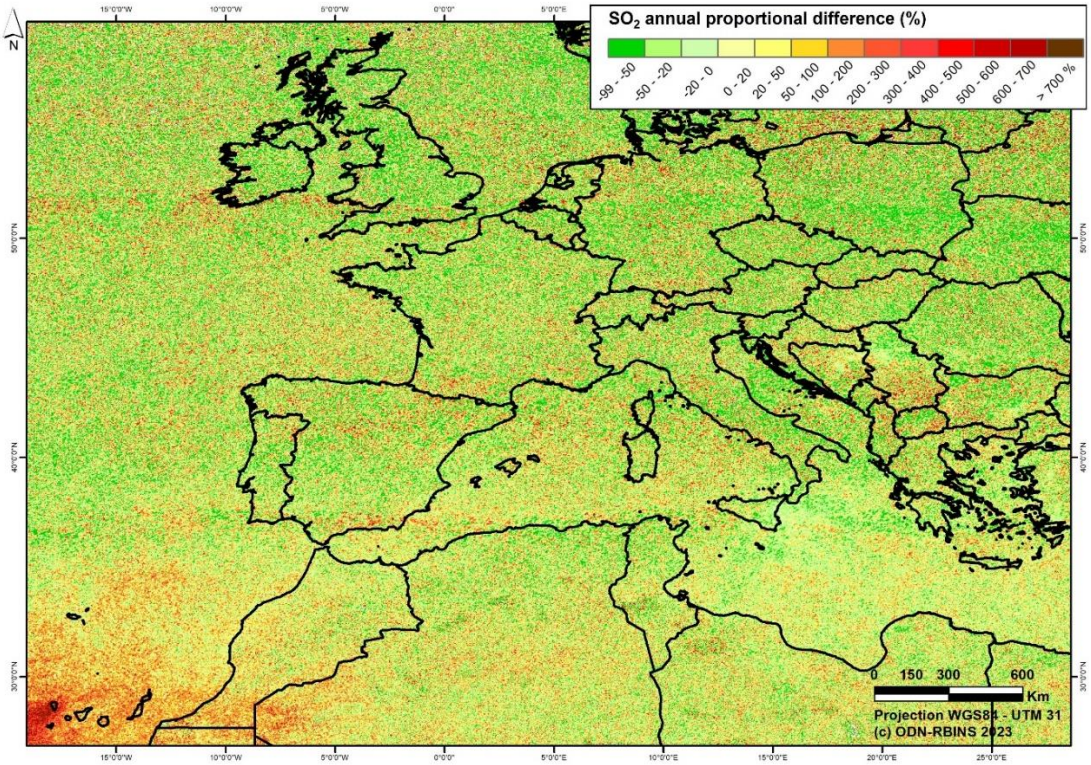


Figure 7. Annual proportional difference of SO_2 VCD levels between 2019 and 2021

When comparing the proportional difference in SO_2 VCD after the implementation of the global sulfur cap amongst the different areas, the most substantial decrease was observed for the BA Quadripartite Zone of Joint Responsibility (BAQPZJR) (-22.5%), the northern part of the SECA (-15.9%) and the English Channel (-9.5%), it should be noted that the yearly mean SO_2 in these areas were most impacted by the global COVID-19 pandemic (figure S.9). The Bay of Biscay was less impacted by the pandemic or the global sulfur cap and even showed a negligent increase (+3.0%), most probably because this area already had a lower SO_2 pollution pressure compared to the densely navigated waters of the SECA. However, there is also an indication that the sensitivity of the TROPOMI SO_2 data might be insufficient to conduct a thorough analysis of SO_2 pollution trends in areas with lower SO_2 pollution levels.

To conclude, the conducted spatiotemporal analysis indicated a positive influence of the global sulfur cap and other international and EU regulations on ambient SO_2 concentrations in the European SECAs. The findings are in line with the results obtained from the remote measurements and inspections conducted within the BA and the EU, therefore strengthening the validity and reliability of the findings. However, it must be noted that when utilizing satellite images to assess air quality improvement for SO_2 outside the ECAs, the analysis heavily relies on the shipping density and ambient SO_2 pollution levels.

2.3.3. Spatial analysis of atmospheric SO_2 data

When comparing absolute NO_2 VCD levels across different areas (Figure 8), it was demonstrated that the NO_2 VCD within the North Sea NECA is on overall considerably higher compared to the areas outside the NECA. Particularly in the BAQPZJR and the English Channel, NO_2 VCD levels are notably elevated, although there are some seasonal differences (figure S.10-12). However, it is important to acknowledge that the elevated NO_2 VCD levels in these areas are likely to be influenced, to some degree, by industrial activities and other densely populated areas in the southern parts of the UK, northern parts of France, Flanders, and the Netherlands. On the other hand, Riess et al. provided evidence that the TROPOMI data primarily captures emissions within the first 200 meters above sea [38]. In addition, despite possible other contributing factors, the monthly NO_2 VCD satellite data clearly reveals visible shipping patterns (figure S.13). Consequently, it can be stated that emissions from OGVs provide the dominant factor in the observed NO_2 VCD data.

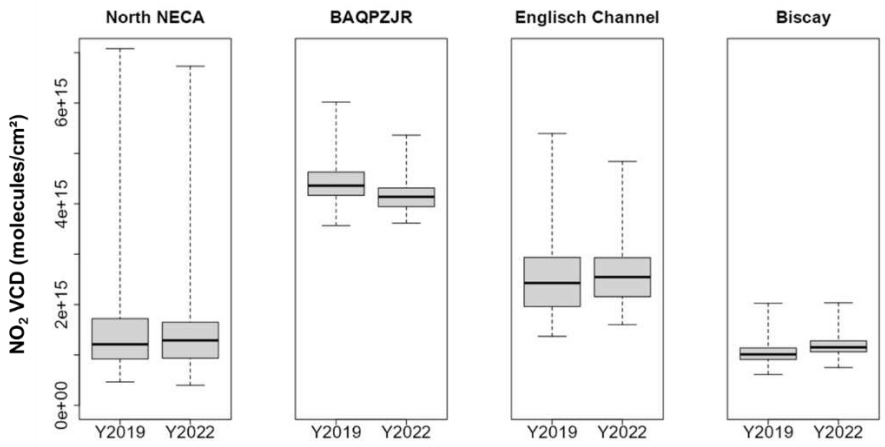


Figure 8. Box plot of NO_2 (VCD) levels between different areas for 2019 and AFNC representing the impact of the implementation of the NECA on the annual NO_2 VCD.

When looking at the average NO_2 levels before and after the implementation of the NECA for the different areas, it was demonstrated that NO_2 levels after the introduction of the NECA were impacted in different ways. The BAQPZJR area remained the most polluted area, with the English Channel following closely behind. However, since the implementation of the NECA, the Bay of Biscay became the third most polluted area, before the Northern NECA.

2.3.4. Temporal analysis of atmospheric NO_2 data

For the temporal analysis of NO_2, an annual approach and a monthly approach were used. For the annual approach, the proportional difference between 2019 and 2022 was determined (Figure 9). This map shows varying results on the proportional difference in NO_2 VCD levels throughout the North Sea NECA, with an annual proportional increase of +14.4% in the Bay of Biscay; +4.1% in the English Channel; and +1.0% in the Northern part and of the NECA. A decrease of -5.8% was observed in the highest polluted BAQPZJR area. This analysis does however not include seasonal differences, which could result in an over- or underestimation of the NO_2 pollution trends.

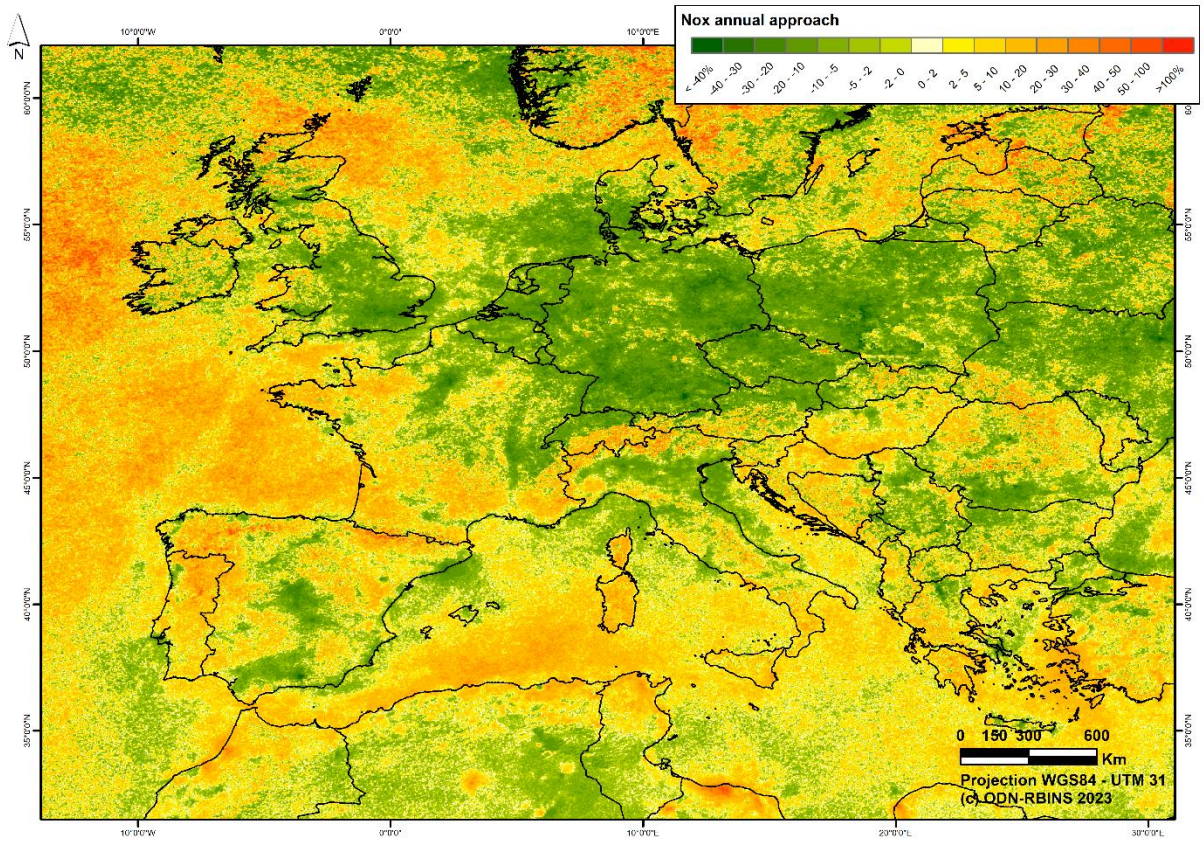


Figure 9. Annual proportional difference of NO_2 (VCD) between 2019 and 2022.

The comparison of the monthly NO_2 VCD levels did indeed reveal a seasonal effect in certain areas, particularly in the BAQPZJR. Consequently, to mitigate the potential for a seasonal bias and to get a better understanding of the ambient NO_2 VCD trends throughout the year, a monthly proportional difference analysis was conducted. For this monthly analysis, the proportional difference between the period before and after the implementation of the NECA was calculated for each month (figure S.14). This analysis yielded variable results. In the months of January, February, May, July, August, September, October, and December, there was a limited impact with localized variations with either an increase or decrease. On the other hand, March and June showed an overall increase, while April and November demonstrated an overall decrease in NO_2 VCD levels. Subsequently, the proportional difference maps per month were combined to create an average monthly proportional NO_2 difference map (Figure 10A). This map demonstrates a slightly different picture compared to the annual proportional difference. Also here a NO_2 increase, albeit slightly lower, is observed for the Bay of Biscay (+10.3%) and the English Channel (+4.0%). However, a small decrease was observed for the Northern NECA (-1.4%). For the BAQPZJR, the monthly analyses demonstrates a similar reduction (-5.0%) as for the annual analysis. The differences with the annual analysis can be attributed to the influence of seasonal variability and the inclusion of the years 2020 and 2021, which were affected by the global COVID-19 pandemic. The evolution of the overage NO_2 VCD over 2018-2022 clearly demonstrate the

effect of the global COVID-19 pandemic. The impact was most substantial in the Northern NECA zone (-44%), the BAQPZJR (-19%), and the English Channel (-9%). The Bay of Biscay (+18%) was not impacted by the COVID-19 pandemic (figure S.15A).

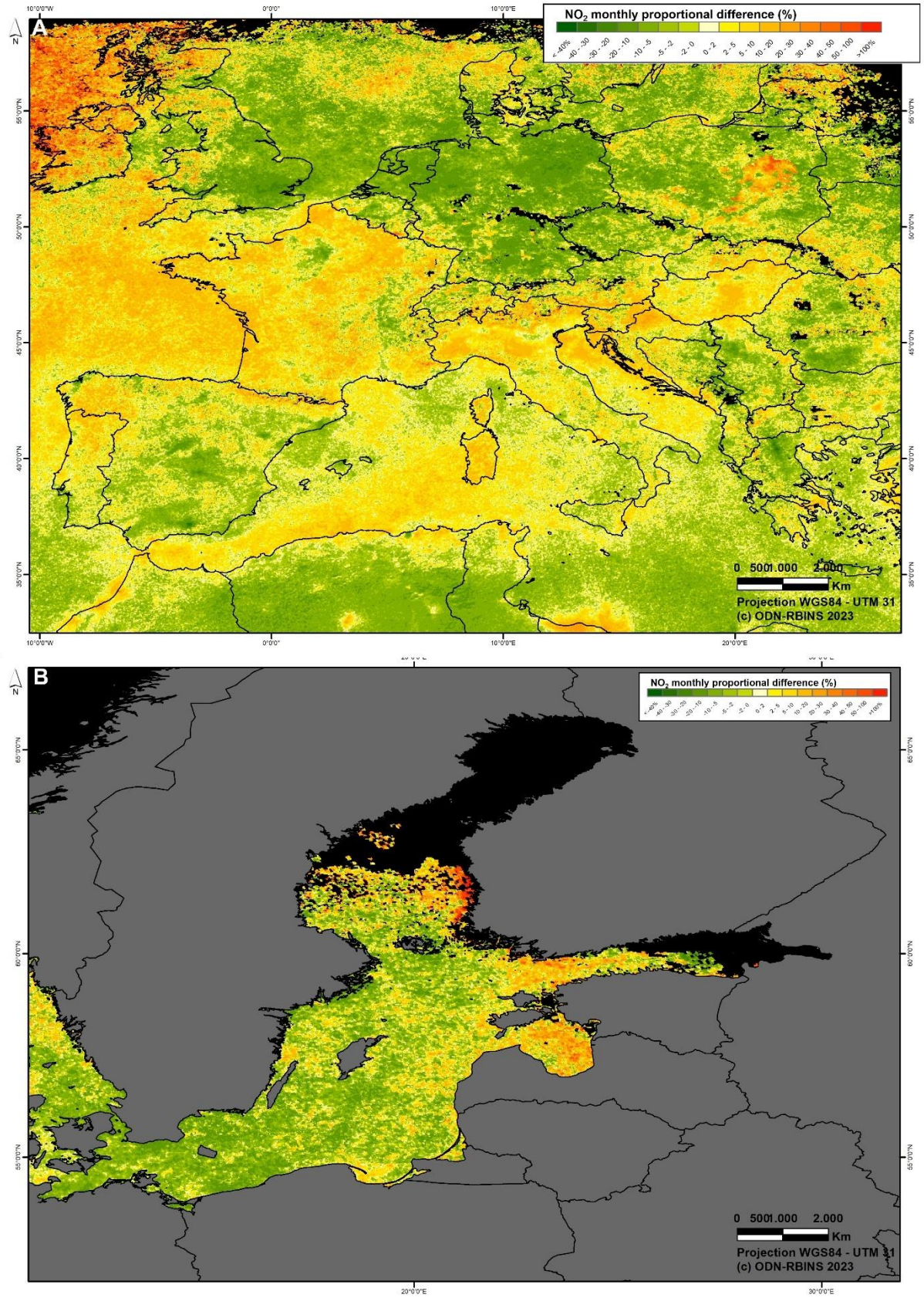


Figure 10. Average monthly proportional difference of NO_2 (VCD) between the period before (2018-2020) and after (2021-2022) the NECA implementation for the North Sea SECA (A) and the Baltic Sea SECA (without December) (B).

Additionally, significant increases were observed in the Mediterranean Sea, and Atlantic Ocean, with increases in the average monthly NO_2 VCD levels of up to 20%. Due to lack of data for the winter months in the north of the Baltic Sea, a full-year assessment could not be made. Nevertheless, the data that is available for the months January-December indicates a slight reduction (Figure 10B). In conclusion, these analyses confirm that the ambient NO_2 levels throughout the year either increased after the NECA implementation or where they decreased, the decrease was less substantial at sea compared to inland.

3. Discussion

Through the analysis of over 110,000 remote measurements of OGV emissions spanning a duration of seven years, valuable insights were obtained regarding the FSC compliance behavior of OGVs in the European ECAs. The results indicate a consistent decline in FSC non-compliance rates across the SECAs. However, it is important to maintain vigilant as remote measurements suggest a potential rise in non-compliance in recent years. Despite certain differences in measurement uncertainty and methodology, a strong correlation was observed between the results obtained from fixed sniffers, sniffer sensors utilized on fixed wing aircraft and mini-sniffers employed on RPAS and rotary wing aircraft. This indicates a significant level of agreement between the different measurement methods and sensors, further supporting the reliability of the findings and suggesting a consistent pattern of compliance trends.

A spatiotemporal analysis conducted on the remote measurements revealed relatively high compliance within the SECA region, while also highlighting specific spatial compliance patterns in relation to the distance from ports, distance to the SECA border, and differences between the Baltic Sea and North Sea areas. It should be noted that this spatial analysis provides only an initial broad-scaled assessment. To obtain a more comprehensive understanding of the spatial distribution of non-compliance an average FSC levels, a thorough analysis of the raw measurement data is necessary. Conducting such an analysis would enable a deeper understanding of the specific factors influencing non-compliance risks within the SECA region. To compare average FSC levels, an intercomparison study first needs to be conducted. In light of this intercomparison, it should be noted that the Belgian monitoring data was adjusted for its measurement bias by utilizing plume simulation gas mixtures with specific concentrations of CO_2 and SO_2 [27]. These plume simulation mixtures could be employed as a "round robin" mechanism to rectify measurement discrepancies between different sensors, enabling a comprehensive comparison of average FSC levels. This in turn would enable a more refined spatial analysis of compliance patterns, providing a higher resolution assessment. The insights gained from such an analysis can be utilized to identify areas with a high risk of non-compliance, guiding the strategic deployment of remote monitoring operations. By focusing on these high-risk areas, enforcement efforts can be optimized to effectively address non-compliance and ensure better enforcement of international emission regulations.

In contrast, to the relatively good FSC compliance proceeding the global sulfur cap implementation, the introduction of the NECA in 2021 did not create any substantial impact on the remotely measured NO_x concentrations in European waters, nor did it result in an effective enforcement and sanctioning mechanism. On the contrary, it was found that NO_x emission factors and potential NO_x non-compliance are increasing. This outcome was somewhat expected, considering that the stricter emission regulations within the ECA primarily apply to Tier III vessels. Given the limited number of Tier III vessels currently in operation, the NECA implementation has not yet made a significant impact in reducing average NO_x emission factors. Furthermore, previous studies already indicated increased NO_x emission factors for Tier II vessels compared to Tier I vessels [14,24,29,33,39,40]. Consequently, the outcomes of this study align closely with the conclusions drawn from other research studies.

The Parties of the BA, and by extension the EU MS, have successfully implemented a comprehensive and efficient system for conducting on-board port inspections of OGVs with regard to sulfur content of marine fuels. Based on the results of more than 110,000 documentary inspections and more than 26,000 fuel samplings, the study indicates that non-compliance with FSC regulations in port in both European SECAs exhibit a similar declining pattern. Nevertheless, by implementing remote monitoring to identify non-compliant OGVs and establishing an enforcement mechanism that considers the highest measured emission levels, the enforcement capacity can potentially be further improved. Conversely, the study revealed that the enforcement of the international NO_x emission regulations for OGVs in port is currently highly ineffective due to insufficient inspection and sanctioning procedures outlined in international regulations. The absence of a comprehensive EU regulatory framework specifically addressing NO_x emissions from shipping with inspection rules can be considered a critical factor in this context. In light of this, Canada recently submitted a document for the July 2023 meeting of the Marine Environment Protection Committee (MEPC80), subsidiary body of the IMO, to address some of these Tier III-related issues [41]. It is worth noting that as early as 2007, the US already had submitted a document to the IMO Sub-committee on Bulk Liquid and Gases (BLG), foreseeing and addressing some of the very challenges that are currently being observed in the certification and testing processes of Tier III OGVs [42].

In order to evaluate the influence of international regulations on air quality within the European SECA, this study analyzed TROPOMI Sentinel 5 data from 2018 to 2022. The analysis of the spatiotemporal patterns in SO_2 satellite data demonstrate a limited decrease in SO_2 pollution levels in the North Sea SECA and a status quo or even a slight enhancement outside the SECA. The subsequent international and EU regulations on SO_2 have therefore had a substantial, positive impact on public health and the environment in the European SECAs. It is important to acknowledge that data for 2021 may have been affected by the global COVID-19 pandemic. Unfortunately, a complete annual dataset for 2022 could not be obtained. Future analysis will need to determine if the recent increase in FSC non-compliance, observed by the remote monitoring operations, and the recovery of economic activity after the global COVID-19 pandemic, will impact the overall SO_2 pollution levels. Additionally, it should be noted that as shipping activities increase, an overall rise in SO_2 emissions is anticipated [24]. However, it should be acknowledged that the sensitivity of the TROPOMI data for SO_2 does not seem to be optimal for detailed analysis outside densely navigated areas.

In contrast, the TROPOMI NO_2 products proved significantly more useful for performing a meaningful analysis. The spatiotemporal analysis of the NO_2 satellite data reaffirmed the findings from the remote measurements and port inspections, indicating that the implementation of the NECA has not resulted in a substantial reduction of the NO_x pollution pressure from the shipping sector. On the contrary, it appears that NO_2 pollution levels only decreased substantially in the most polluted area (BAQPZJR), in other areas of the NECA, signs of an increase were observed. Strong decreases were observed over land, in particular above the cities of Paris, Brussels, Londen, etc. This also inevitably impacted the temporal analysis, particularly within the BAQPZJR region, explaining the observed NO_2 reduction in that area. Although this reduced drive from land based pollution was not accounted for in this study, it is safe to assume that when this land based pollution would be incorporated, an overall increase across all areas would be observed.

The findings derived from this study provide substantial evidence regarding the effectiveness of international regulations and the enforcement measures taken to address FSC non-compliance in the shipping sector. Notably, the implementation of inspections regimes in EU ports and the deployment of remote monitoring operations at sea have functioned as a considerable deterrent effect. These measures have proven instrumental in discouraging FSC non-compliant behavior within the shipping industry, emphasizing the pivotal role of well-defined and stringent regulations and effective enforcement

measures. However, the results indicate that compliance is lower at sea compared to the port areas. In addition, the comprehensive analyses of the remote NO_x measurements and NO_2 pollution levels at sea solidify the conclusion that the international regulations on NO_x emissions from ships were ineffective in reducing NO_x pollution from the shipping sector. Therefore, this study strongly recommends the revision of current NO_x regulations, the implementation of additional NO_x emission regulations and decisive and effective enforcement measures in the North Sea and Baltic Sea.

Furthermore, the increased NO_2 VCD in the Bay of Biscay, the Mediterranean Sea and Iberian coast are highly notable. These findings strongly emphasize the importance of establishing a Mediterranean NECA in conjunction with the Mediterranean SECA, which is entering into force on 1 May 2024 [43]. The introduction of a North Atlantic NECA encompassing the waters of France, Spain, and Portugal is also recommended. Based on the analysis conducted on the existing European NECAs, it should be emphasized that the introduction of additional NECAs without enhanced emission regulations would not result in the anticipated improvements in air quality.

4. Methods

4.1. Research area

4.1.1. Bonn Agreement

The BA is a regional co-operation established in 1969 to prevent marine pollution from OGVs in the North Sea. Initially this focused on oil pollution. The BA consists of 11 CPs including all North Sea coastal States, Spain, Ireland and the EU (represented by EMSA) [44]. Among others, through intensive cooperation, the BA recorded a significantly reduced amount of oil pollution over the last two decades [45–47]. Over the years, the BA was expanded to include other harmful substances besides oil. From 2015, several BA CPs petitioned the BA to extend the scope of the BA to include air pollution from shipping. In October 2019, the Ministerial Meeting of the BA formally approved the extension of the scope of the BA to include MARPOL Annex VI, recognizing the BA as the appropriate intergovernmental forum to roll out OGV emission monitoring activities [44,48].

4.1.2. North Sea and Baltic Sea Emission control area

The establishment of the ECAs was included in the adoption of the MARPOL Annex VI regulations in 2008 [16]. After several years of negotiations, the North and Baltic Sea SECAs were established in 2011, in addition to ECAs in North America and the Caribbean Sea [18]. The SECA covers the North Sea, the English Channel, and the Baltic Sea. The European NECAs were established in 2021 [19]. The North and Baltic Sea NECAs cover the same area as the SECAs and are therefore both referred as ECAs. The North and Baltic Sea ECAs cover a vast sea area, spanning from the English Channel to the Russian border, impacting air quality for over 280 million European citizens.

4.2. Remote measurement data in the Bonn Agreement

4.2.1. Remote monitoring locations

To obtain a comprehensive assessment of the impact of maritime SO_2 emission regulations in the European SECAs, annual compliance monitoring data from five fixed monitoring sites and nine airborne monitoring operations from six BA CPs in the SECA were analyzed (table S.2), encompassing a total of 115,274 OGV measurements. Some deployments have been terminated, others are still ongoing, data from operations that are still ongoing were obtained from: 1) MUMM operates the Belgian coastguard aircraft equipped with a sniffer sensor from 2015; 2) BSH (Hamburg, Germany) is in charge of the German network of fixed sniffer stations from 2015, with stations in Hamburg, Kiel and Bremerhaven; 3) TNO (Delft, The Netherlands) operates a fixed sniffer station at the port of Rotterdam in The Netherlands on behalf of the Human Environment and Transport Inspectorate (ILT) from 2015; 4) Explicit executes RPAS measurements with dual mini-sniffers on behalf of EMSA in Denmark, France,

Germany, Lithuania and the Spain [30,49–58] from 2019. Data from following terminated operations was used: 1) Chalmers University (Goteborg Sweden) operated an airborne sniffer and a fixed sniffer station at the Great Belt bridge in Denmark on behalf of the Danish Environmental Protection Agency (EPA) from 2015-2020; 2) Explicit (Virus, Denmark) conducted airborne measurements using helicopters equipped with dual mini-sniffers, and uses single mini-sniffers on RPAS, in Denmark on behalf of the Danish EPA from 2017-2022; 3) Explicit, conducted dual-sniffers measurement with a helicopter in the Netherlands in cooperation with ILT in 2016.

Out of the total measurements taken, the majority (101,464) were conducted using fixed stations along frequently navigated shipping lanes. This was followed by airborne measurements carried out by aircraft (8,210), and subsequently by RPAS and helicopter measurements using mini-sniffers (4,732). The Belgian airborne dataset contributed to more than half of the total number of airborne measurements (6,961). However, the number of measurements conducted by any of the fixed sniffer sites greatly surpasses the number of measurements conducted by the airborne monitoring platforms. For determining average non-compliance rates within the SECA, a weighted average was calculated based on the number of measurements per station or deployment.

4.2.2. Compliance cut-off levels

Three different cut-off levels were used to assess possible violations: 0.20% FSC, 0.15% and 0.13% FSC. These three cut-off levels were used to facilitate the evaluation of variations in non-compliance levels across different scales, as a direct comparison of average FSC levels was not feasible due to the unavailability of raw measurement data. In addition, although remote monitoring stations and platforms employ similar techniques, slight differences in measurement methodologies and uncertainties exist among the different stations. Nonetheless, the data used in this study remains suitable for conducting a comparative analysis of general temporal and spatial compliance trends.

4.2.3. Selection of data for temporal analysis

Several stations or platforms only measured a low number of vessels for certain years. A minimum of 100 operational measured OGVs per year was applied for the temporal compliance analysis. As a result, in total seven annual compliance results were omitted from four different locations.

4.2.4. Spatial trend analysis

For the selection of the measurement sites for the spatial analysis, a minimum continued measurement period of two years and a total of 200 measured OGVs was applied. Locations that did not meet this requirement were either omitted or added to the location of the nearest other remote measurement location. The RPAS data from Lithuania (142 measurements in 2021) was therefore omitted. The data from the different airborne assets in Denmark were merged to one location. Furthermore, the airborne mini-sniffer measurements of the Netherlands in 2016 were added to the Belgian airborne measurements.

For the spatial analysis, in addition to the SECA measurements, measurements conducted at the southern ECA border were used. These measurements were conducted by Chalmers University (114 in 2016) and the Belgian coastguard aircraft (23 in 2022). As sufficient data was not available for a temporal analysis and as these measurements were conducted with the same sensor technology, the data at the SECA border was combined for the spatial analysis.

For the fitting of the emission data in function of the distance to the SECA border (d_b) the following formula was used.

$$\text{Non\_compliance (\%)} = \frac{1}{b} \times e^{\frac{a - d_b(\text{nm})}{b}} + c \quad (7)$$

The least square method was applied for the determination of the factors *a, b* and *c*. In addition the non-compliance was also expressed in function of the distance to the closest main port (d_p). This data was fitted on the following curve.

$$\text{Non\_compliance (\%)} = \frac{k}{1+e^{n-o\times d_p(\text{nm})}} + p \quad (8)$$

The least square method was also applied here for the determination of the factors *k, n, o* and *p*.

4.3. Inspection results of port inspection authorities in the Bonn Agreement

In accordance with the EU Sulphur directive and the Commission Implementing Decision, the port state authorities of the EU MS conduct sulfur inspections [36,37]. These are done by either documentary inspection or by analyzing the fuel in accordance with the fuel inspection guidelines from IMO [59]. Within the scope of this research and the work conducted under the BA, inspection and sanctioning results from port State authorities from 9 out of 10 BA CPs were obtained. This data is part of the annual inspections results that are reported to the EC. The most CPs apply a 0.15% threshold for reporting infringements to the EC. Of all BA CPs, two are located outside the ECA (Spain and Ireland) and two are currently not reporting to the EC (Norway and United Kingdom). In addition to the sulfur inspection results, NO_x inspection results were also collected. As NO_x is currently not regulated through a EU directive, inspection results are currently not being shared with the EC.

4.4. EU inspection results and Thetis-EU

The EU Sulphur Directive led to the creation of Thetis-EU, an online database used for exchanging inspection results. EMSA manages and hosts the database. Thetis-EU is accessible to inspectors across all EU MS, including Norway and Iceland. However, due to Brexit, the UK no longer has access to the database [37,60].

4.4.1. Keel laying date

Information on the KLD is required for the determination of the tier level when assessing NO_x compliance. For the Belgian NO_x remote monitoring assessment, this KLD data was acquired based on merging two database sources: (1) the Global Integrated Shipping Information System (GISIS) of the IMO [61] and; (2) Thetis-EU of EMSA. The GISIS database was first used to gather information on OGVs larger than 75 meters with construction year. In a second step, EMSA provided the accurate KLD [29]. For the Danish analysis, a ship database was acquired from IHS Markit.

4.4.2. Inspection results

Under the EU Member States' obligations to report inspection outcomes to the EC as stipulated by the EU Sulphur Directive and Commission Implementing Decision [36,37], data on sulfur inspections conducted by the EU MS were obtained from EMSA [60]. As most, but not all, BA CPs are part of the EU, there is a certain overlap with the BA data. The EU data contains more States and includes all EU MS outside the SECAs. The EMSA data therefore gives a broader overview of the inspection results throughout the EU. However, the EU data does not contain results on penalties. Moreover, due to the lack of EU regulation regarding NO_x emissions from OGVs, the EMSA data does not contain NO_x inspection results.

The EMSA website publicly displays the amount of port inspections and compliance levels resulting from documentary inspections conducted by EU MS [60]. Its purpose is to enable EMSA to deliver thorough reports to the EC to assess the implementation of the EU Sulphur Directive by the EU MS [36,37]. Additionally, the EMSA website includes records of non-compliance detected through fuel sample analysis. However, the actual number of fuel samples themselves are not available on the website.

A request for this information was made to EMSA to facilitate the analysis of temporal trends in fuel sample results.

4.5. Statistical analysis of remote monitoring data and port inspection results

Previous studies using the Belgian airborne data have already shown that emission measurements deviate from a normal distribution [24,27,29]. When the distribution of remote measurement data is compiled, they initially appear to follow a normal pattern, with the emission limit as the central point. However, although small negative values are occasionally observed, there are no highly negative values, while very high FSC values are possible. As a result, this inevitability renders the distribution non-normal. Pearson chi-square tests were used to assess the difference in compliance rate between two locations/deployments, with statistical significance defined as $P < 0.05$ [62].

4.6. Satellite analysis

A spatiotemporal analysis was conducted using satellite data from the Tropospheric Monitoring Instrument (TROPOMI) Sentinel 5 to investigate the distribution and changes in SO_2 and NO_2 levels over European waters. The temporal analysis of SO_2 focused on the evaluation of the impact of the global sulfur cap, which entered into force on 2020 [63], while the temporal analysis of NO_2 focused on the implementation of the European NECAs in 2021 [64]. Additionally, a spatial analysis compared SO_2 and NO_2 pollution levels between different areas within the ECAs and differences between the ECAs and regions outside the ECA.

4.6.1. TROPOMI data

Data was gathered from TROPOMI on board of the Copernicus Sentinel-5 Precursor satellite, which is operated by the European Space Agency (ESA). The satellite data contains measurements of the VCD, expressed in molecules per square centimeter, of SO_2 and NO_2 in the lower atmospheric layer (up to 80km). For SO_2, the retrievals from the scientific COBRA V01 scheme processed by BIRA-IASB were used [65] for the period May 2018 until September 2022. For NO_2, the satellite operational data product (Level 2 data) was collected from the Copernicus Open Access Hub [66] for the period May 2018 until December 2022, using the PAL v2.3.1 retrieval algorithm. with the NO emissions are converted to NO_2, factors such as ambient meteorological condition, ozone (O_3), and solar radiation influence the conversion speed. However, conversion is considered to be in the time span of seconds to tens of minutes during daytime [67,68]. Therefore, the NO_2 satellite analysis gives a good representation of NO_x pollution levels.

TROPOMI retrievals for SO_2 and NO_2 have been filtered based on their quality assurance (QA) value. Only pixels with a QA value equal to or larger than 0.75 were selected, removing cloudy pixels (cloud radiance fraction > 0.5) and erroneous retrievals [66]. Subsequently they were averaged to generate monthly VCD products. The monthly average VCD products were further compiled using ArcGIS and Qgis to generate VCD maps for spatial and temporal analysis.

4.6.2. Spatial analysis

For the spatial analysis, average SO_2 and NO_2 levels were compared between different areas. The North Sea ECA was divided into three zones: 1) the Northern part of the ECA; 2) the BAQPZJR and; 3) the English Channel. In addition, a fourth zone was added outside the SECA in the Bay of Biscay (Figure 11). The Baltic Sea was not included for the spatial satellite data analysis due to substantial influence of land-based sources and the lack of satellite coverage for the winter months in the northern Baltic Sea.

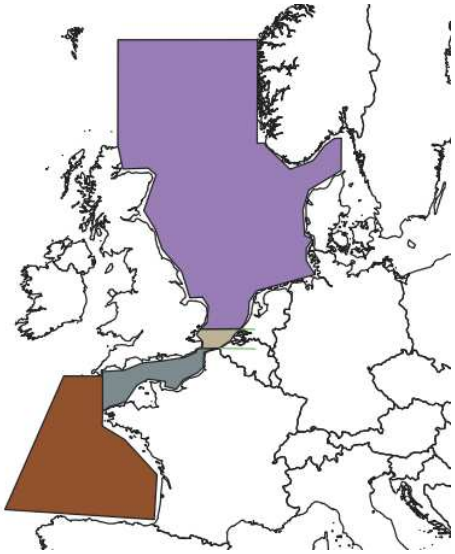


Figure 11. Definition of the areas used for the spatial analysis of emission levels for SO_2 and NO_2. The purple area is the Northern ECA; the light gray area is the BAQPZJR; below in dark gray is the English Channel; the brown area is the Bay of Biscay used as reference outside the ECA.

4.6.3. Temporal analysis SO_2

Several studies provided scientific evidence of the impact of the global COVID-19 pandemic on ambient SO_2 levels, although this mainly concerned inland SO_2 pollution, pollution levels over sea were less impacted [65,69]. Additionally, the implementation of the global sulfur cap in 2020 marked a significant turning point for SO_2. Consequently, the temporal data analysis for SO_2 excluded the year 2020 to ensure unbiased comparability.

For the temporal analysis of SO_2, first the SO_2 VCD maps per month (i) for the period before (2018-2019) and after (2021-2022) the global sulfur cap came into effect were combined in a monthly mean SO_2 VCD map. As the year 2020 was omitted, the period before and the period after the global sulfur cap implementation composed the same amount of months (21).

$$\overline{SO_2}_{\text{Period}}(\text{VCD}) = \frac{\sum_i^{21} SO_{2_i}}{21}\ (\text{VCD}) \tag{1}$$

This data demonstrated a substantial seasonal impact on pollution levels (figure S.7). The years 2018 and 2022 could not be used as they did not contain data for the full year. Therefore, the annual SO_2 VCD maps of 2019 and 2021 were calculated. In the second step the proportional difference between these two maps was calculated to create the proportional difference between the annual SO_2 VCD.

$$\text{Diff}_{SO_2}(\%) = \frac{\overline{SO_2}_{2021} - \overline{SO_2}_{2019}}{\overline{SO_2}_{2019}} \tag{2}$$

4.6.4. Temporal analysis NO_2

In 2022, Ward Van Roy et al. used TROPOMI data to evaluate the impact of the implementation of the NECA [29]. For that analysis, the absolute difference in NO_2 VCD between 2020 and 2021 was determined. By looking at the absolute difference, areas with high pollution levels are more prone to be emphasized This indicated a potential decrease of NO_2 in the northern part of the North Sea SECA, but an increase in the southern part. However, by looking at the absolute difference, areas with high pollution levels are more prone to be highlighted. In addition, the analysis was limited to the years 2020 and 2021, which were impacted by the global COVID-19 pandemic [29,69,70]. Riess et al. reported a reduction of observed NO_2 concentrations in shipping lanes, between 10% and 20% as a result of the global COVID-19 pandemic [71]. For these reasons, a wider analysis was required that incorporated the

relative impact of the NO_x regulations on the overall NO_2 pollution levels. The NO_x temporal analysis in this study focused on two analysis, an annual proportional difference and a monthly proportional difference. It must be acknowledged that, due to limited satellite coverage throughout the year the Baltic Sea ECA could not be fully assessed.

For the annual proportional difference, a similar analysis was conducted as what was performed for SO_2, while for NO_2, data for the complete 2022 was obtained. With 2021 being the turning point year, with the introduction of the NECA, the years 2019 and 2022 were compared.

$$\text{Diff}_{NO_2}(\%) = \frac{\overline{NO_2}_{2022} - \overline{NO_2}_{2019}}{\overline{NO_2}_{2019}} \tag{3}$$

As initially a potential seasonal effect was observed (figure S.10-11), an average monthly proportional difference was also calculated. First, monthly mean VCD maps were created for the period before (BFNC) and after (AFNC) the NECA came into effect. The BFNC period was composed of the months May 2018 until December 2020 (32 months), the AFNC period was composed of the months from January 2021 until December 2022 (24 months). Thus, for every month (i) two or three years (j) were available.

$$\overline{NO_2}_{\text{i\_period}}(\text{VCD}) = \frac{\sum_{\text{j}}^{\text{years}} NO_{2_{\text{j}}}}{\text{years}} \ (\text{VCD}) \tag{4}$$

This provided 12 NO_2 maps before (BFNC) and 12 NO_2 maps after (AFNC) the NECA came into force. In the second step, the proportional difference between these maps was calculated per month.

$$\text{Diff}_{NO_{2_i}}(\%) = \frac{\overline{NO_2}_{\text{i\_AFNC}} - \overline{NO_2}_{\text{i\_BFNC}}}{\overline{NO_2}_{\text{i\_BFNC}}} \tag{5}$$

In the final step, the average monthly proportional difference was calculated

$$\text{Diff}_{NO_2}(\%) = \frac{\sum_i^{12} \text{Diff}_{NO_i}}{12} \ (\%) \tag{6}$$

To provide an analysis throughout the entire 2018-2022 period, the years 2020 and 2021 were not omitted. As NO_2 levels in 2021 were lower compared to 2020 (figure S.15), this almost certainly creates a negative bias for the period after the NECA came into force.

It must also be acknowledged that local concentrations of NO_2 are affected by the lifetime through background levels of NO_2 itself, O_3, and available sunlight [72]. As these vary in time, this will influence uncertainty in temporal comparisons. This dynamic is investigated in detail by Riess et al., showing that this will influence the calculated changes in emissions [71], not VCD levels used for this study. Meteorological conditions, driving dispersion, will also show temporal variability influencing the extent to which the study areas will be impacted by land based sources or inversely drive ship emissions outside of the study areas. Such effects are not accounted for in this study but are expected to be minor given the year-to-year comparison.

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6. Supplementary material

6.1. Marpol Annex VI

6.1.1. SO_x regulation

Regulation 14 of MARPOL Annex VI introduced limits on SO_x emissions from OGVs and designated the Baltic Sea, the North Sea and English Channel as a SECA (supplementary Figure S.1A) [16,64]. From 2008 OGVs operating in the SECA are obliged to use compliant fuels or an Exhaust Gas Cleaning System to achieve the same amount of sulfur emission reduction as for using compliant fuel [73,74]. Since 2015 the maximum allowed FSC inside SECAs is 0.10 %S m/m. In 2020, the FSC limits outside ECAs were also sharpened to 0.50 %S m/m by the so-called "global sulfur cap" [63] (supplementary Figure S.1B) and the "carriage ban" [75]. In addition, SO_x emission regulations have been implemented at the level of the EU by the EU Sulphur Directive ((EU) 2016/802) [37]. Assessment of compliance by port inspection authorities is based on analysis of fuel samples or documentary checks in accordance with the Commission Implementing Decision ((EU) 2015/253) [36]. Inspection data is shared through Thetis-EU — the port inspection database managed by (EMSA) and reported on an annual basis to the European Commission (EC) [60].

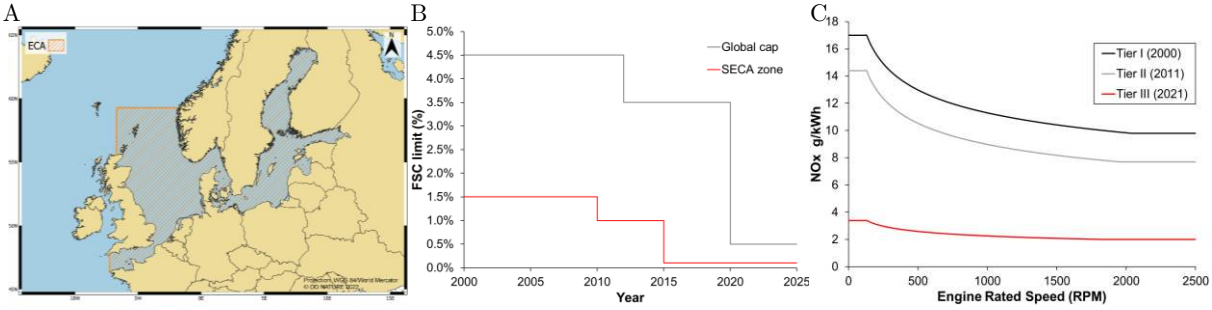


Figure S.1. Emission Control Area (ECA) as defined by MARPOL Annex VI (A). Limits on the Fuel Sulfur Content of marine fuels according to the MARPOL Annex VI regulation 14 (B). NO_x emission limits according to MARPOL Annex VI Regulation 13 (C).

6.1.2. NO_x regulation

Regulation 13 of MARPOL Annex VI introduced NO_x emission limits [16,76,77] and dedicated NECAs. In 2016, the first NECAs entered into force on the East and West coasts of North America and the Caribbean Sea. The Baltic and North Sea SECA was designated as NECA in 2021 and is referred to as

an ECA from that moment [18,21] (supplementary Figure S.1A). The establishment of the ECAs required cooperation and agreement from many countries. The aim of the ECAs was not only to reduce the emissions of NO_x and SO_x in Europe's most densely populated areas, but more importantly it was hoped that SO_x and NO_x emission restrictions would also lead to a reduction of the particulate matter (PM).

The NO_x emission standards are determined by the amount of NO_x emissions (in g) per brake horse power (BHP) on the crankshaft (in kWh) and are categorized into four tiers based on the KLD of the OGV. The limit for each tier decreases with the Engine Rated Speed (ERS or n) expressed in rotations per minute (rpm), although the limits per tier are uniform for OGVs with an ERS of less than 130 rpm, which in reality applies to the vast majority of the section of medium to large sized merchant vessels ($>$ 5000 GT) (supplementary Figure S.1C). The engines are certified before and after installation on board, utilizing testing methods outlined in the NO_x Technical Code [78]. For the two test cycles of the MEs, the verification procedures take into account a weighted average of four engine loads with corresponding weighting factors (supplementary Table S.1) [16,78]. As a result of legal restrictions and operational constraints, the port inspection authorities can rely solely on examining the mandatory onboard documentation to verify compliance to the NO_x regulations. The use of emission measurements as legal evidence is currently not implemented nor is its use as an enforcement mechanism described in the regulations. Moreover, conducting an analysis in port would not necessarily yield meaningful results, as to verify compliance, the ME need to operate at an engine load of minimum 25%. In the case of Tier III OGVs, the port inspection authorities have the added option to verify the effective operation of abatement technology like selective catalytic reduction (SCR) and exhaust gas recirculation (EGR). However, there is a lack of explicit guidelines in the NO_x technical code regarding the recording of onboard measured emission data and the tracking of abatement system operations. Moreover, it is important to highlight that malfunctioning SCR systems can generate N_2O emissions [79]. This is currently not regulated by MARPOL Annex VI. This is a matter of great significance considering the impact of climate change, as N_2O has a global warming potential (GWP) of approximately 300 times that of carbon dioxide (CO_2) [79,80].

Table S.1. Test cycles and weighting factors according to the NO_x Technical code [78].

E2	Speed	100%	100%	100%	100%
	Power	100%	75%	50%	25%
	WF	0.2	0.5	0.15	0.15
E3	Speed	100%	91%	80%	63%
	Power	100%	75%	50%	25%
	WF	0.2	0.5	0.15	0.15

Unlike SO_2, NO_x emissions from ships are not regulated by an additional EU directive, which means there are no common EU monitoring rules and enforcement procedures. As a result, the NO_x inspection data of EU MSs are not shared through Thetis-EU, nor are inspection results reported to the EC. On board inspections executed by the port inspection authorities are currently limited to documentary checks.

6.2. Measurement techniques

6.2.1. Remote FSC measurements

All of the measurements were conducted using a similar methodology based on comparable sensors [27,81–83]. However, it is worth noting that the airborne measurements conducted with mini-sniffers use a similar sniffer measurement technique, but are based on more compact and less costly electrochemical sensors for SO_2. As a result the measurement precisions is lower and the time response longer. Nevertheless, due to the longer duration RPAS and helicopters spent in the plume (hovering), their accuracy is higher, hence, the measurement uncertainty is comparable to the heavier sniffer sensors [81,82].

The FSC can be calculated based on the ambient and exhaust plume SO_2 and CO_2 concentrations [27,81,83–89]. As 97.8% of the sulfur (S) in the fuel will be transformed to SO_2 [8,12,90], the SO_2 values are used to retrieve the S-content, the CO_2 is used to derive the carbon (C) content. To retrieve the amount of combusted fuel the C-content is multiplied by 87%, which is the average C-content for marine fuels [83,86].

$$\text{FSC} = 0.232 \times \frac{\int[\text{SO}_2 - \text{SO}_{2,\text{bkg}}]_{\text{ppb}}\,\text{dt}}{\int[\text{CO}_2 - \text{CO}_{2,\text{bkg}}]_{\text{ppm}}\,\text{dt}}\,[\%\ \text{Sulphur}] \quad (1)$$

Fixed stations and airborne sniffers have a NO cross sensitivity for the SO_2 sensor, therefore this formula is adapted by subtracting the measured SO_2 with the NO amount in the plume, multiplied by the NO cross sensitivity factor (CS_{NO}).

$$\text{FSC}_{\text{NO}} = 0.232 \times \frac{\int[\text{SO}_2 - \text{SO}_{2,\text{bkg}}]_{\text{ppb}} - CS_{NO} \times [\text{NO} - \text{NO}_{\text{bkg}}]_{\text{ppb}}\,\text{dt}}{\int[\text{CO}_2 - \text{CO}_{2,\text{bkg}}]_{\text{ppm}}\,\text{dt}}\,[\%\ \text{Sulphur}] \quad (2)$$

6.2.2. Remote NO_x measurements

A challenge in utilizing remote NO_x measurements for assessing NO_x non-compliance arises from the technical emission standards of the NO_x Technical Code which express emission limits as weighted average NO_x (in g) over brake horsepower (in kWh). The NO_x emission factor (Fe_{no}) in g NO_x/kg fuel is calculated similarly to the FSC using the background and plume NO_x and CO_2 concentrations [29,86,88].

$$\text{EF}_{\text{NO}_x} = \frac{\text{M NO}_2 \frac{\text{g}}{\text{mol}}}{\frac{\text{M C} \frac{\text{g}}{\text{mol}}}{0.87}} \times 1000 \times \frac{\int[\text{NO}_x - \text{NO}_{x,\text{bkg}}]_{\text{ppm}}\,\text{dt}}{\int[\text{CO}_2 - \text{CO}_{2,\text{bkg}}]_{\text{ppm}}\,\text{dt}} \left[\frac{\text{g}}{\text{kg fuel}}\right] \quad (3)$$

$$\text{EF}_{\text{NO}_x} = 3.33 \times \frac{\int[\text{NO}_x - \text{NO}_{x,\text{bkg}}]_{\text{ppb}}\,\text{dt}}{\int[\text{CO}_2 - \text{CO}_{2,\text{bkg}}]_{\text{ppm}}\,\text{dt}} \left[\frac{\text{g}}{\text{kg fuel}}\right] \quad (4)$$

For the calculation of the NO_x emission in g NO_x/kWh, the NO_x emission factor (g NO_x/kg fuel) is then multiplied by the Specific Fuel Consumption (SFC).

$$\text{SFC} = \frac{\text{kg fuel}}{\text{kWh BHP}} \quad (5)$$

$$\text{EF}_{\text{P,NO}_x} = \text{EF}_{\text{NO}_x} \times \left(\frac{\text{kg fuel}}{\text{kWh BHP}}\right) \quad (6)$$

Typically, the SFC ranges from 0.16 kg/kWh to 0.24 kg/kWh [12,29,84,91–95]. The exact SFC can be obtained through radio communication (as done by the MUMM) or by applying a modeled approach based on voyage and OGV characteristics (as done by Explicit).

While Belgium has the ability to request information on engine parameters from the monitored OGVs, other remote monitoring agencies lack this option. As a result, these agencies face difficulties in directly assessing NO_x emission levels expressed in g NO_x/kWh based on remote measurements alone, highlighting the need for alternative approaches or additional data sources to accurately evaluate NO_x emissions. In addition, as the emission limits for main engines are expressed as the weighted average over four engine loads, it is challenging to define non-compliance on remote measurements in particular for low exceedances of the emission limits and when OGVs operate at a low engine load ($<$ 25-50%), due to the low weighting factor of these lower loads. Furthermore, it is worth noting that the RPAS of the European Maritime Safety Agency (EMSA) have the capacity to measure NO_x emissions. However, since there is currently no specific EU Directive addressing NO_x emissions from OGVs, EMSA has no legal mandate to monitor NO_x emissions. As a result, the focus of EMSA's monitoring efforts remains primarily on SO_2 and other maritime surveillance tasks, which have established EU regulatory frameworks in place.

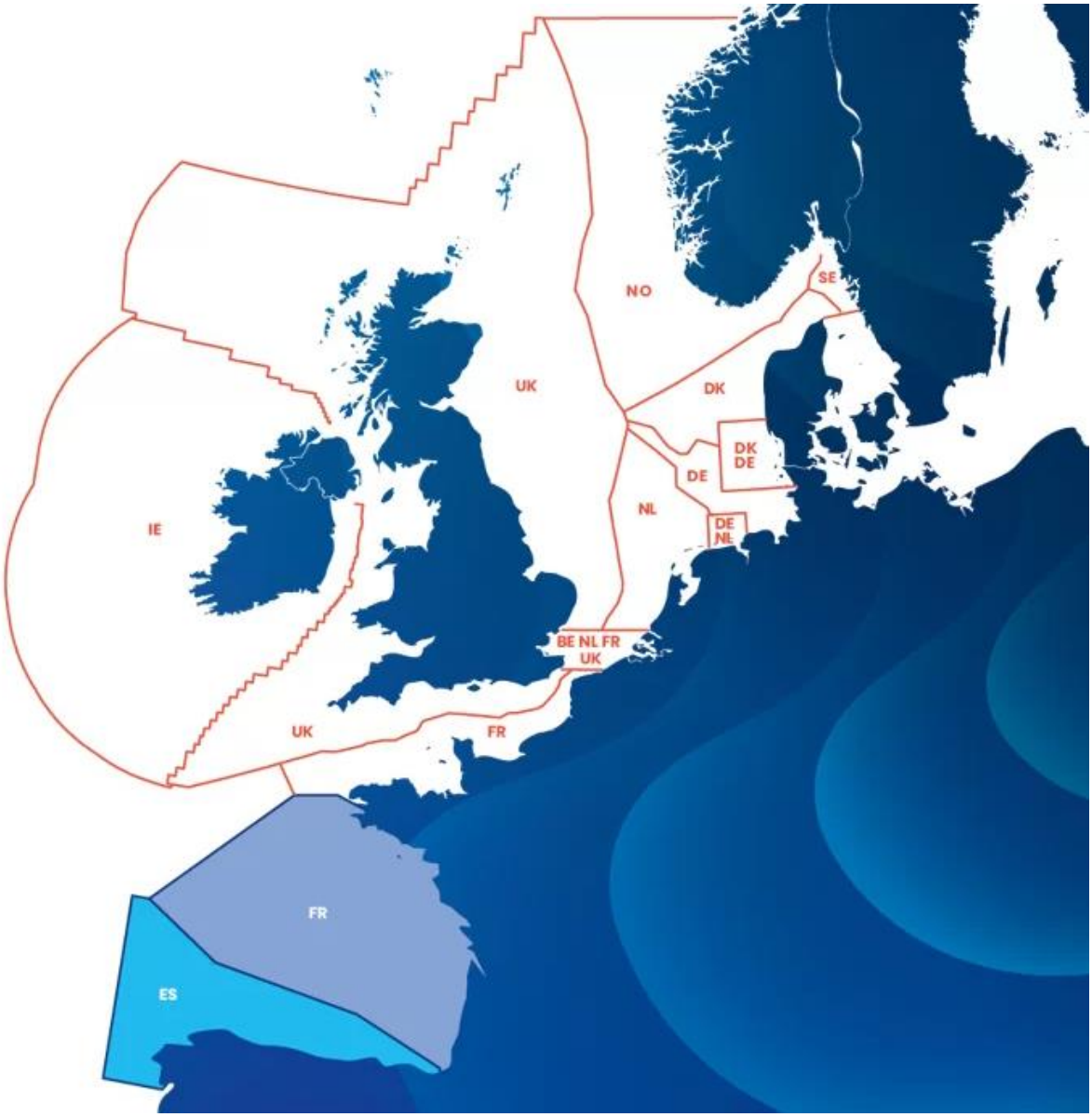


Figure S.2. The Bonn Agreement area [96].

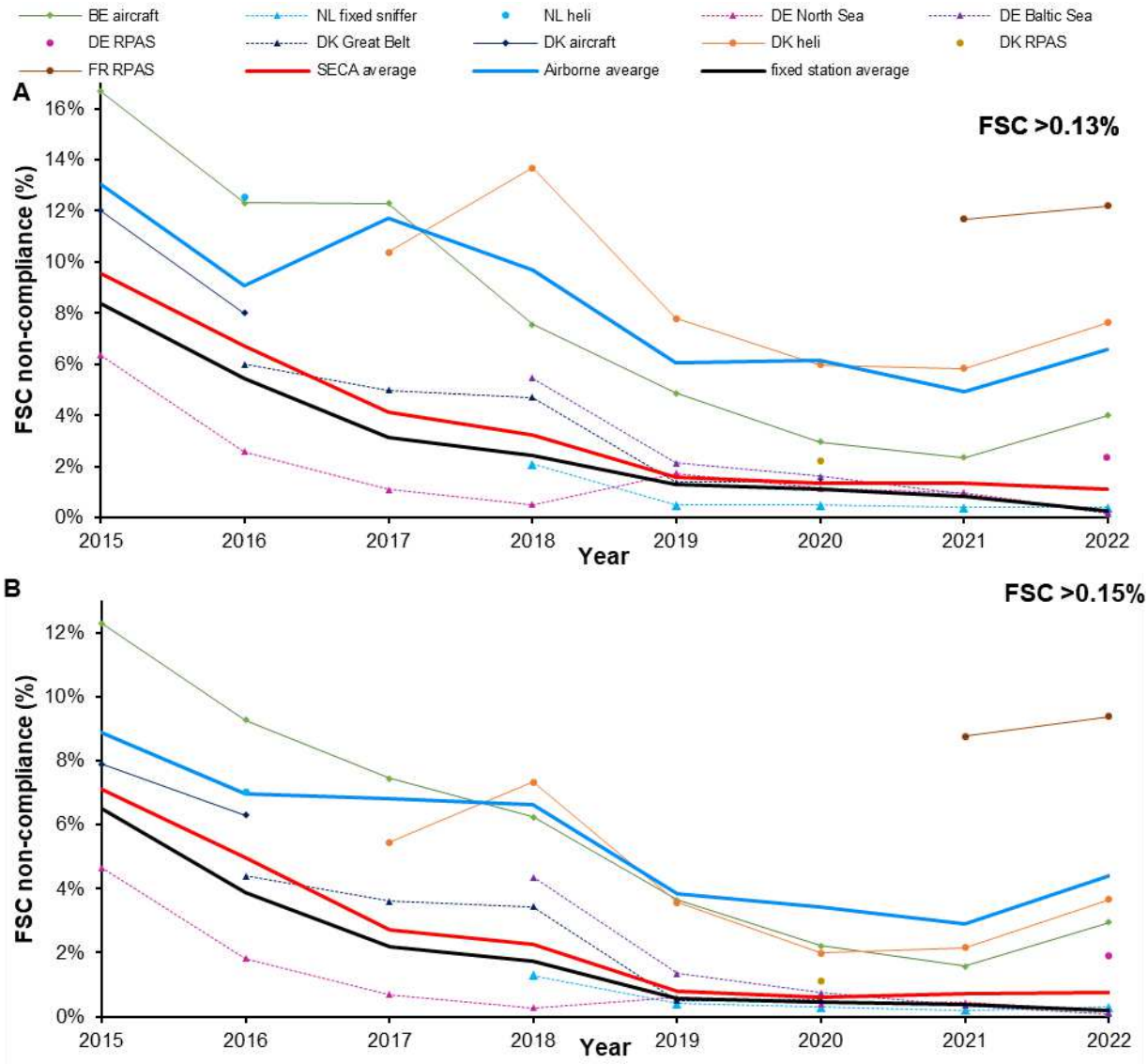


Figure S.3. FSC non-compliance for remote monitoring locations in the SECA for cut-off levels: 0.13% FSC (A) and 0.20% FSC (B). Measurements with fixed wing aircraft are displayed with full lines and diamond markers (♦), measurements using RPAS and helicopters are have full lines and circle markers (•), fixed sniffer measurements are displayed with dotted line and triangular markers (▲).

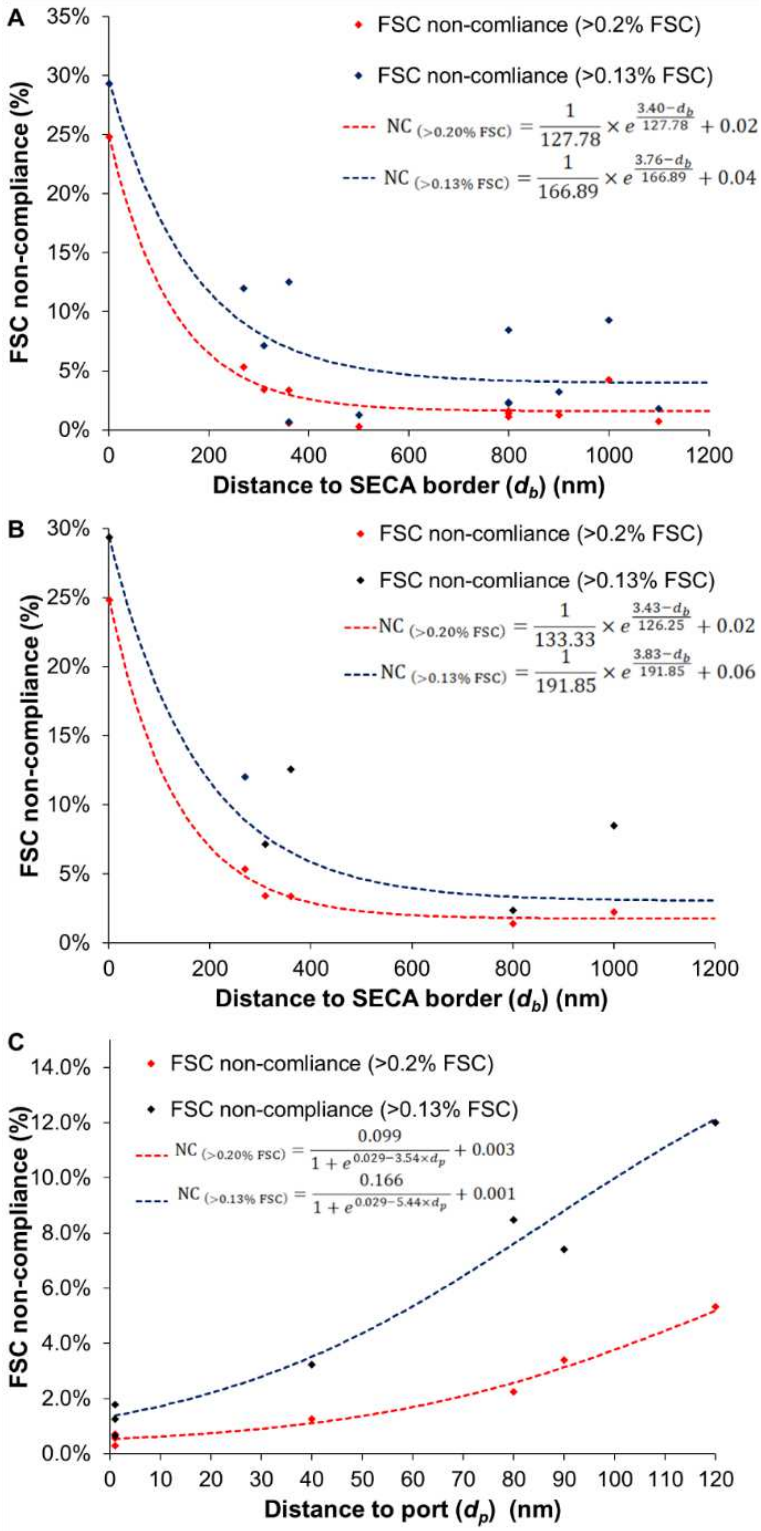


Figure S.4. Non-compliance fitting based on the mean non-compliance of the different remote measurement locations in function of the distance to the SECA border (d_b) for the 0.13 and 0.20% FSC cut-off levels, for the all remote measurements (A) and for when only the airborne measurements are considered (B). Non-Compliance fit in function of the distance to port (d_p) (C).

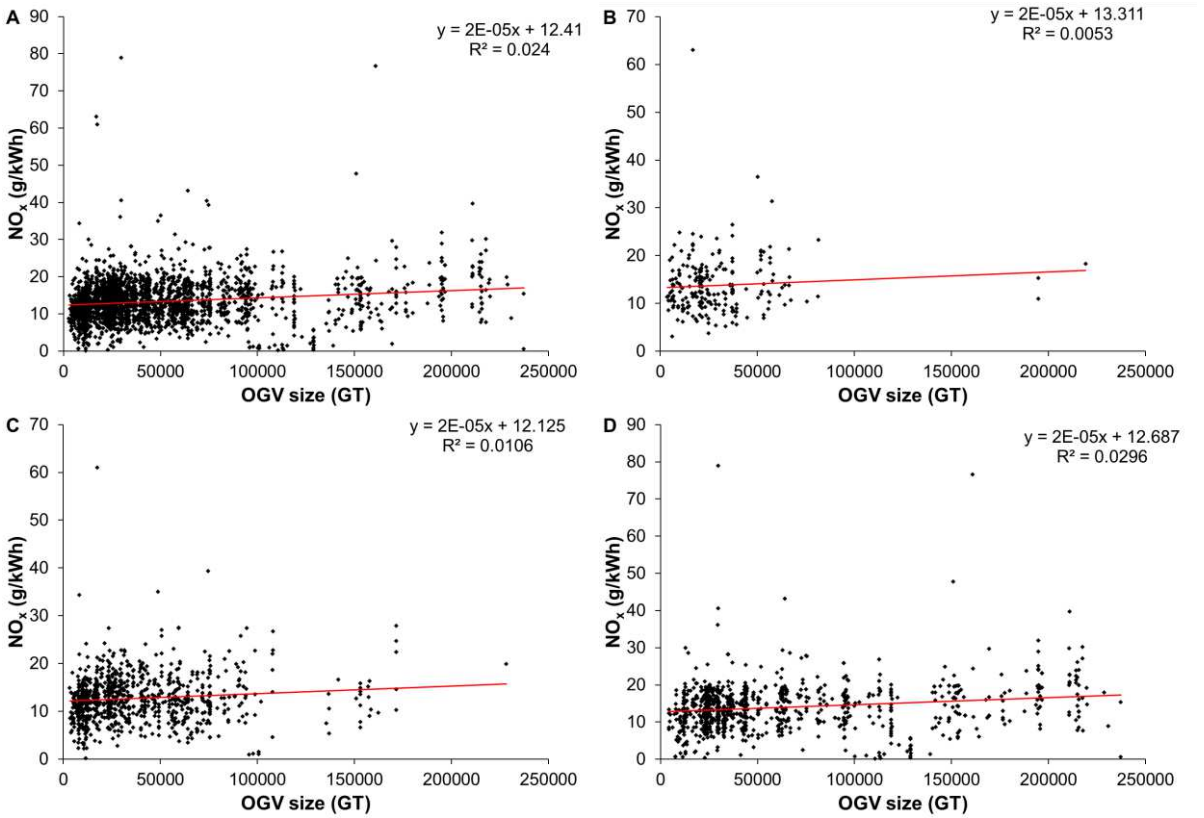


Figure S.5. Results of the Belgium remote NO_x emission expressed in function of the OGV size (in GT), for all measured OGVs (A), for only the Tier 0 OGVs (B), Tier I OGVs (C) and Tier II (OGVs).

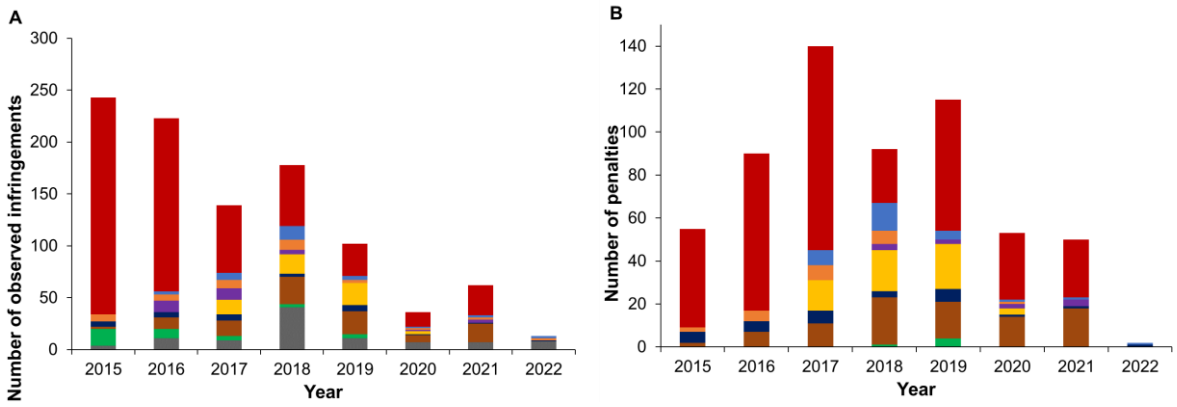


Figure S.6. Number of reported sulfur infringements (A) and penalties (B) for the BA CPs. The nationality of the BA CPs is not released on request of certain BA CPs.

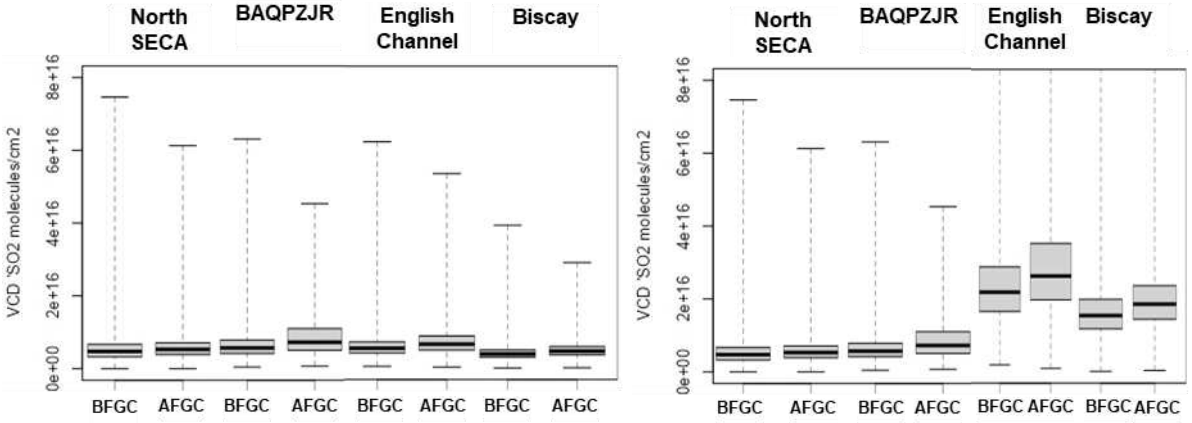
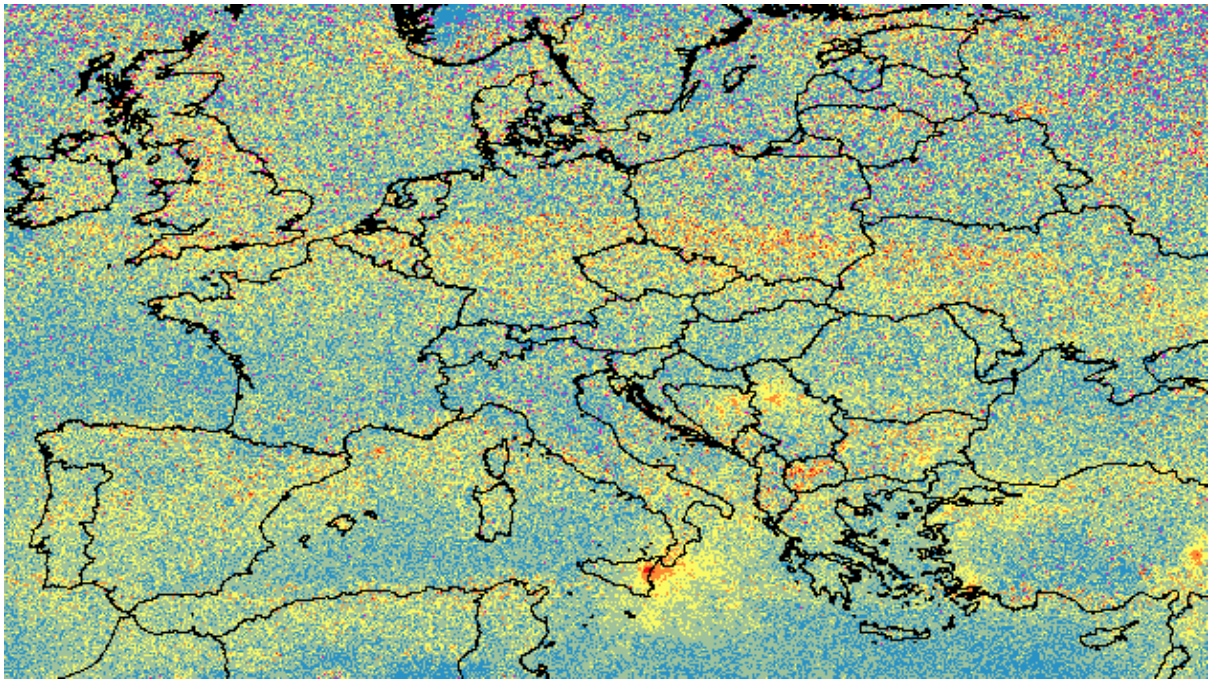


Figure S.7. Box plot of SO_2 (VCD) between different areas before the global cap (2018-2019) and after the global cap came into effect (2021-2022), with minimum, 25% percentile, median, 75% percentile and maximum. The four upper graphs include the maximum value, while the four graphs at the bottom demonstrate a zoom on the 25% and 75% percentiles.

A



B

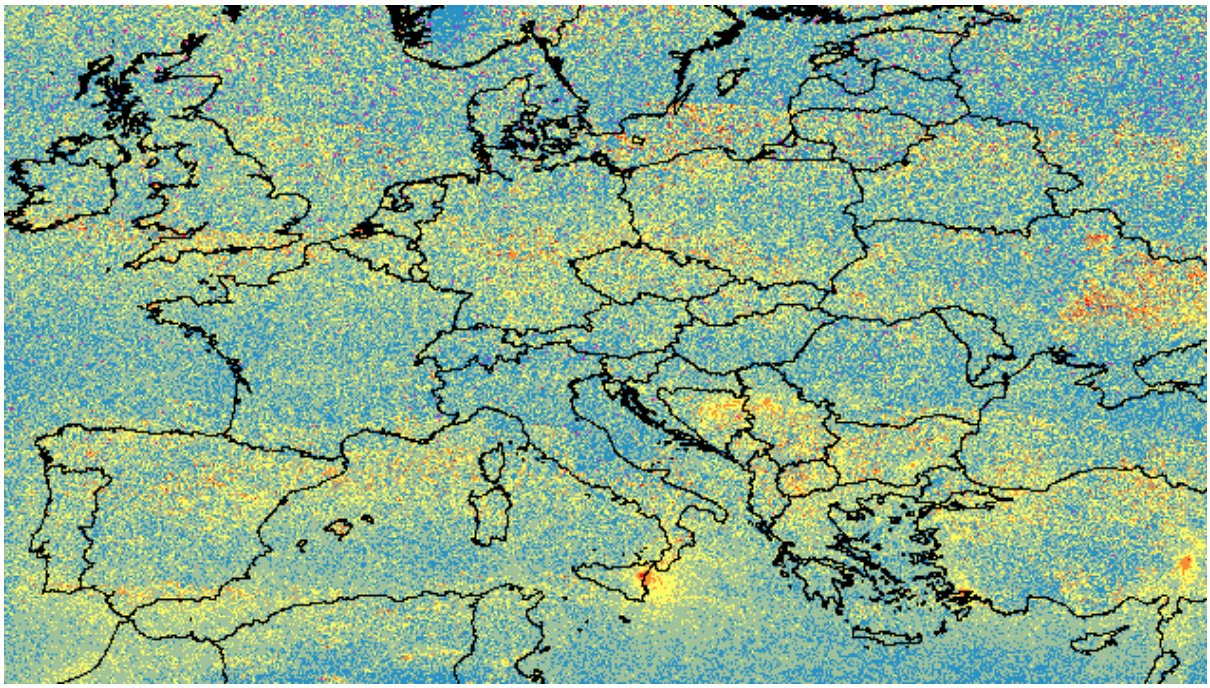


Figure S.8. TROPOMI Sentinel 5 combined SO_2 VCD maps for 2019 (A) and 2021 (B).

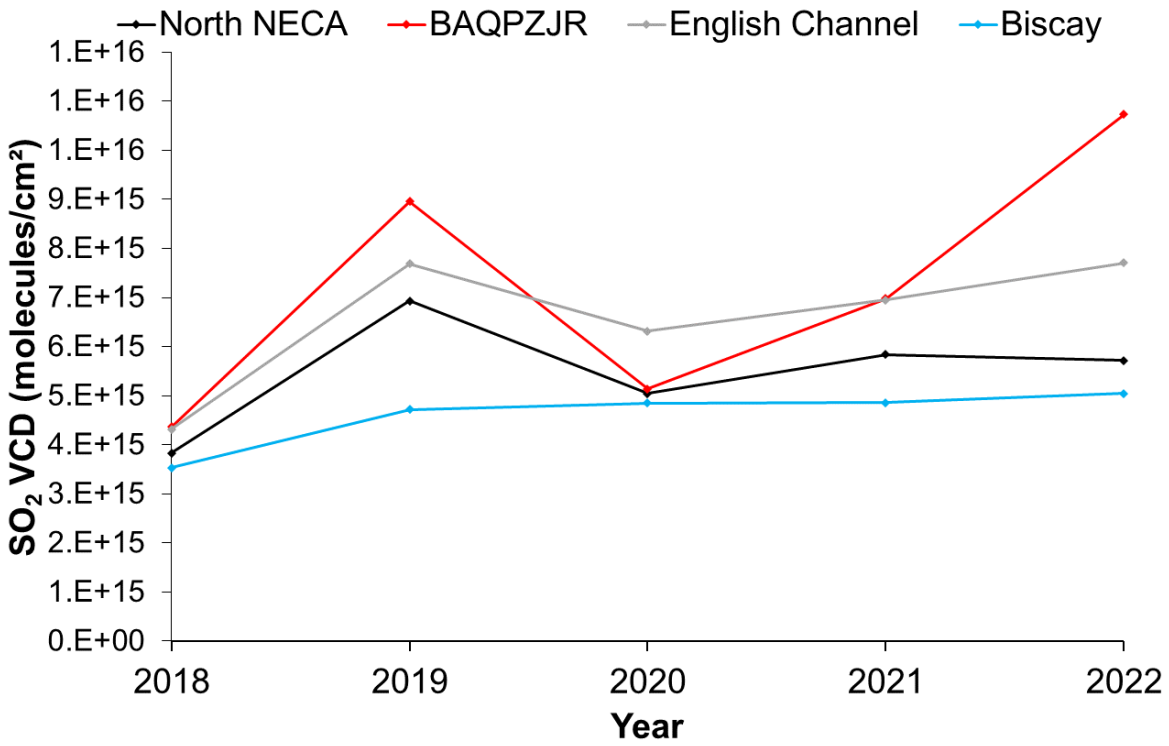


Figure S.9. SO_2 mean VCD levels from 2018-2022. For 2018 and 2022, not all months were available.

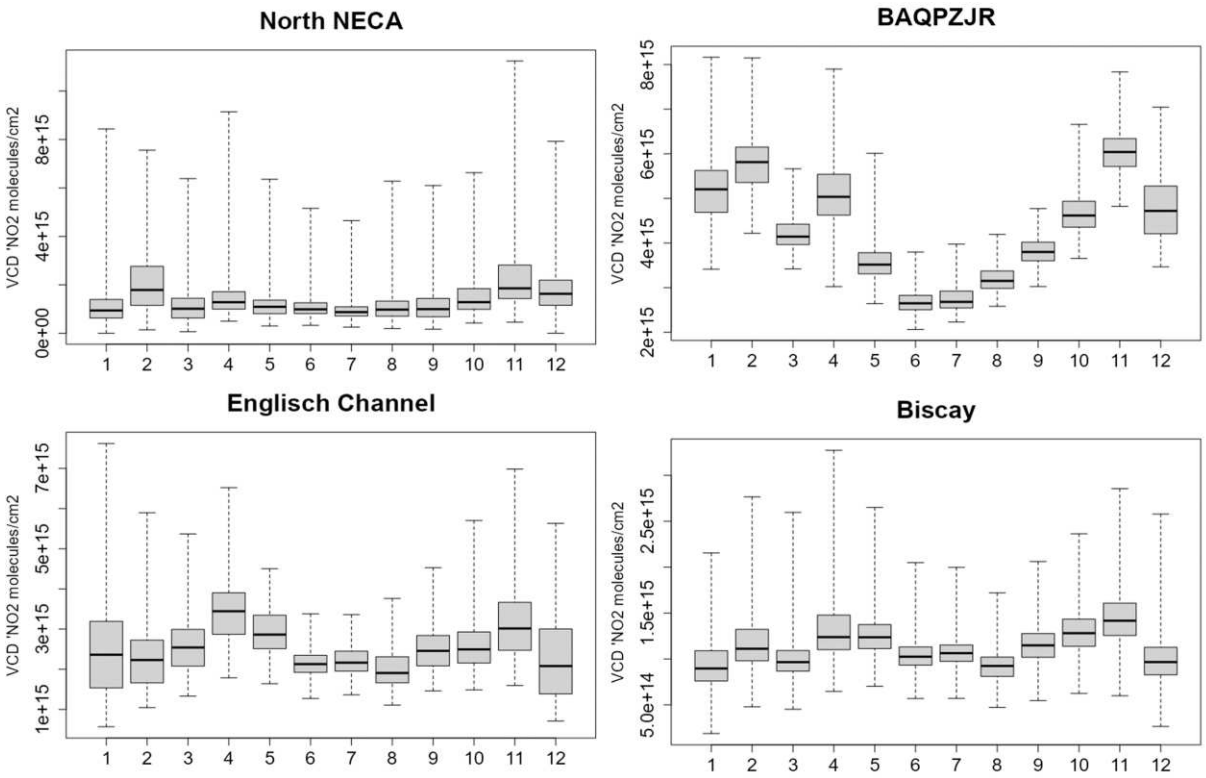


Figure S.10. Monthly NO_2 VCD for the four different zones before the NECA came into effect, with minimum, 25% percentile, median, 75% percentile and maximum.

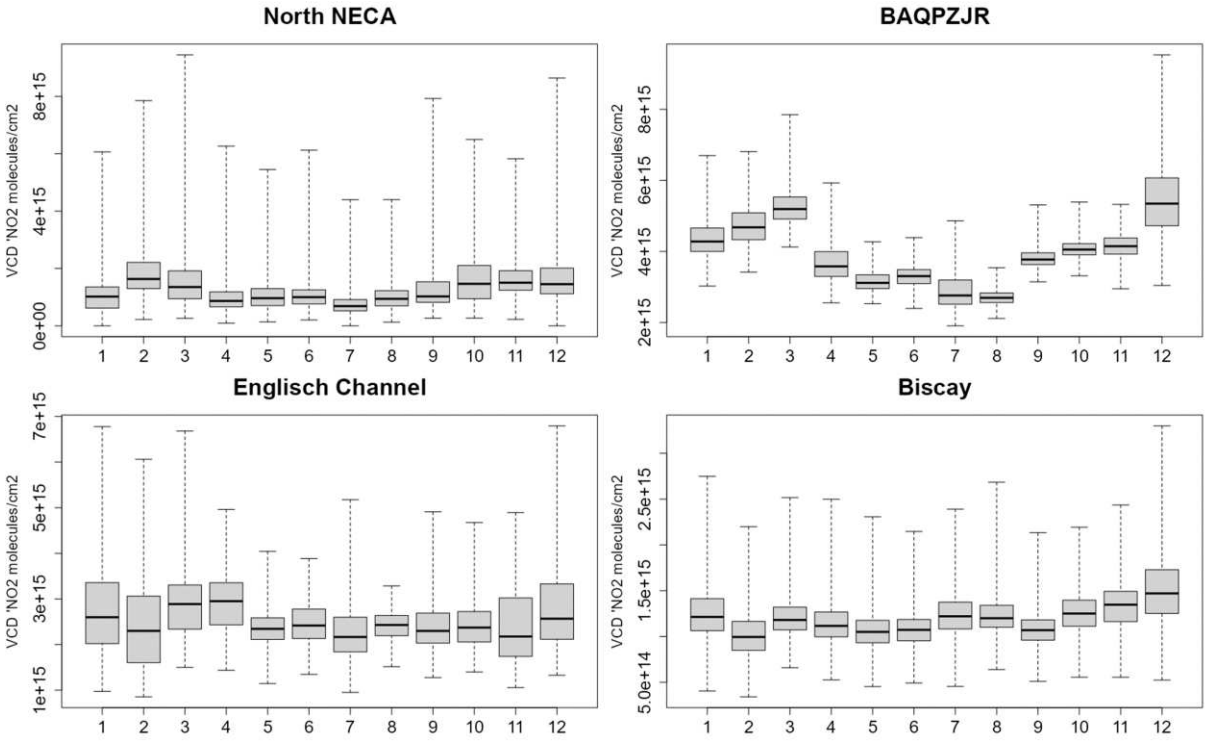


Figure S.11. Monthly NO_2 VCD for the four different zones after the NECA came into effect, with minimum, 25% percentile, median, 75% percentile and maximum.

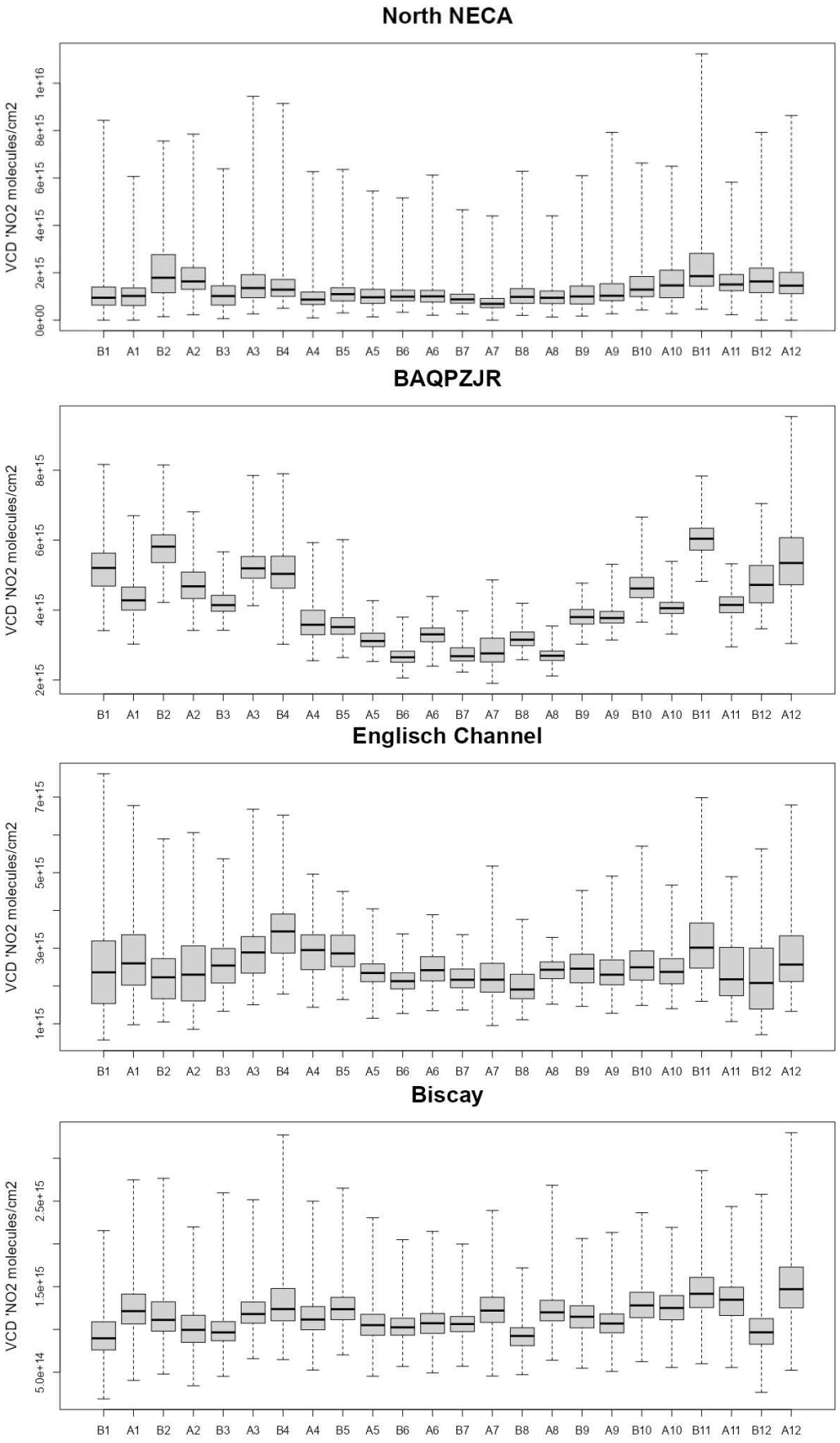


Figure S.12. Boxplots of the NO_2 VCD for four zones in the ECA per month before (B#) and after (A#) the NECA came into force, with minimum, 25% percentile, median, 75% percentile and maximum.

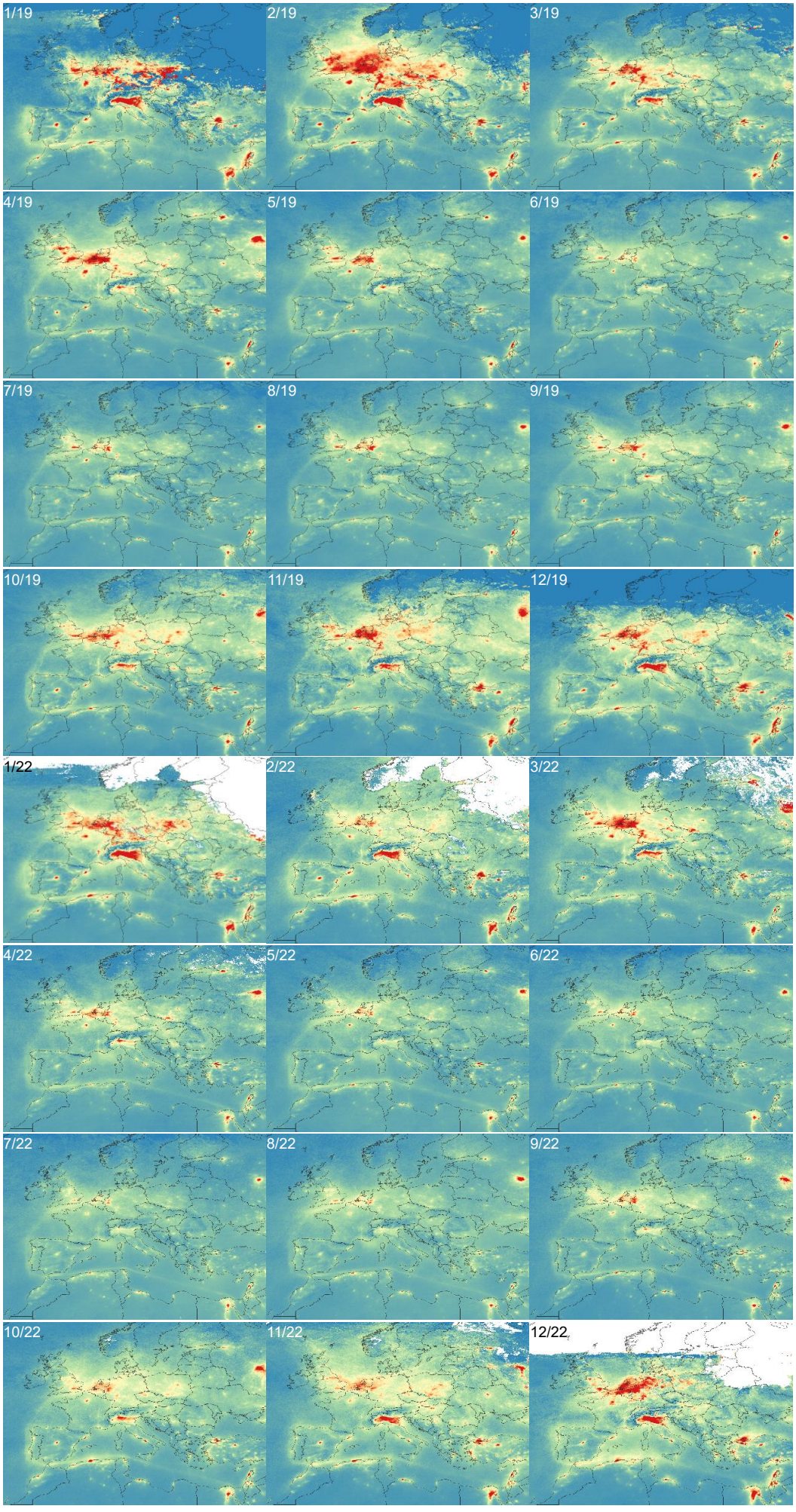
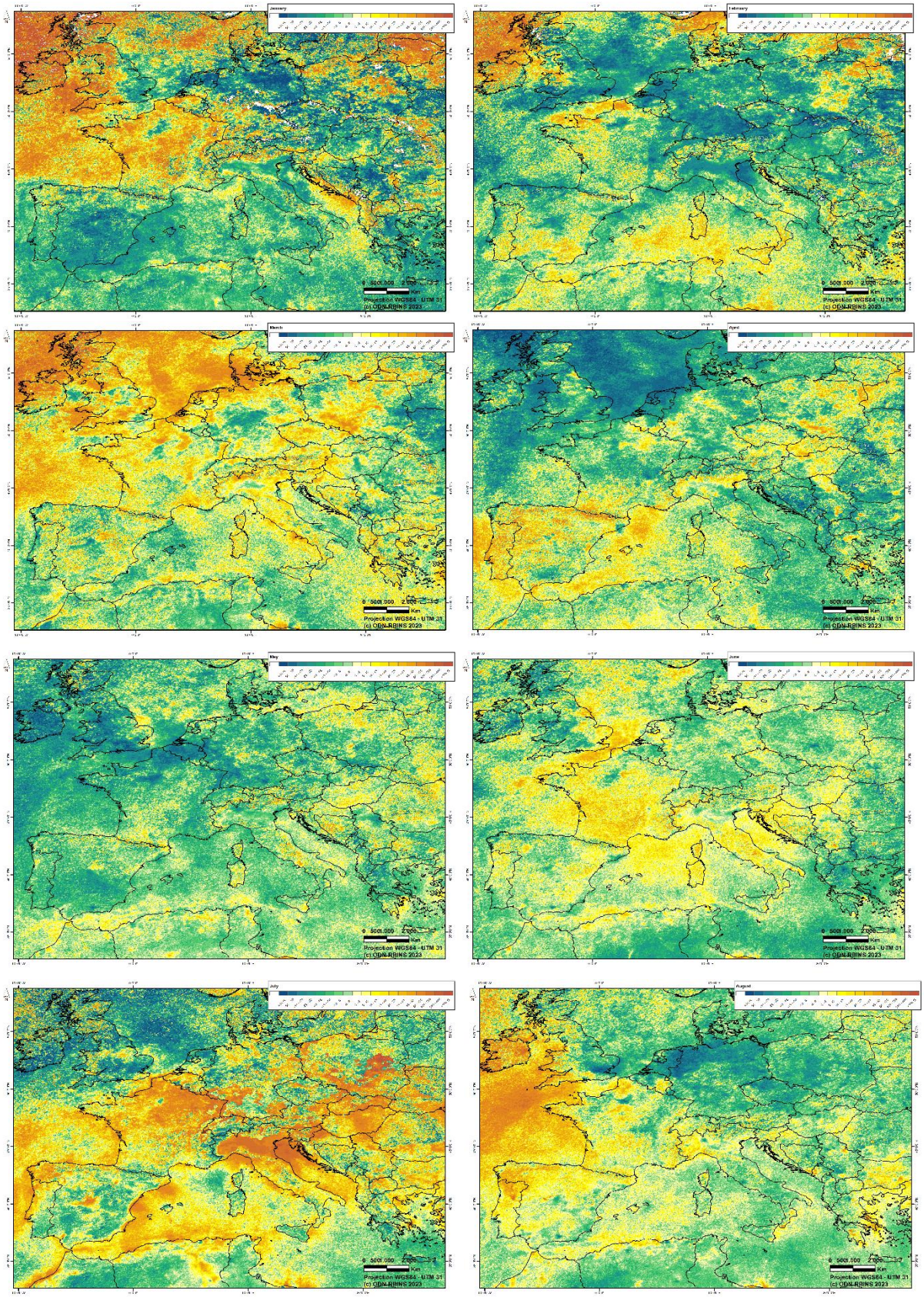


Figure S.13. Time series of NO_2 VCD per month 2022 based on TROPOMI Sentinel 5 data.


January
February
March
April
May
June
July
August
Projection WGS84 - UTM 31
(c) ODN-RBINS 2023

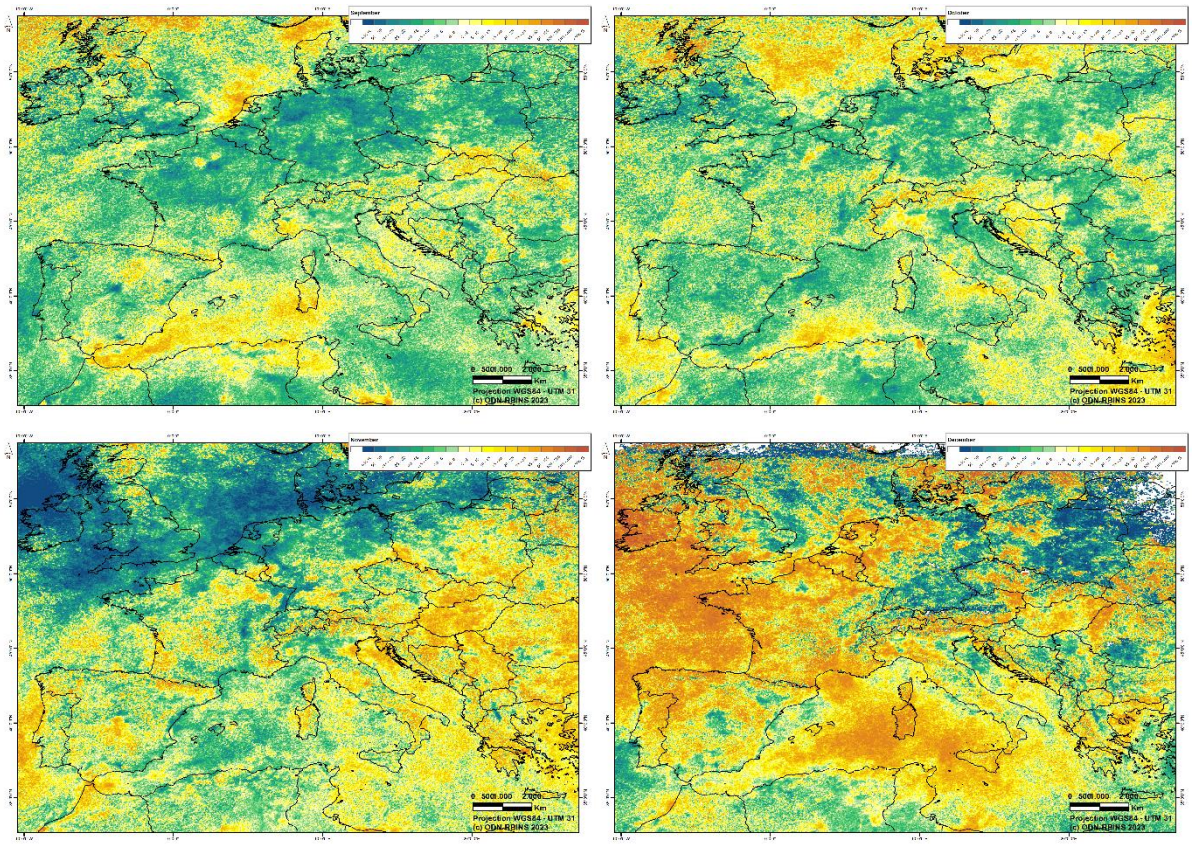


Figure S.14. Difference (expressed in %) in the average monthly NO_2 VCD from January until December between the period before (2018-2020) and after the implementation of the NECA (2021-2022).

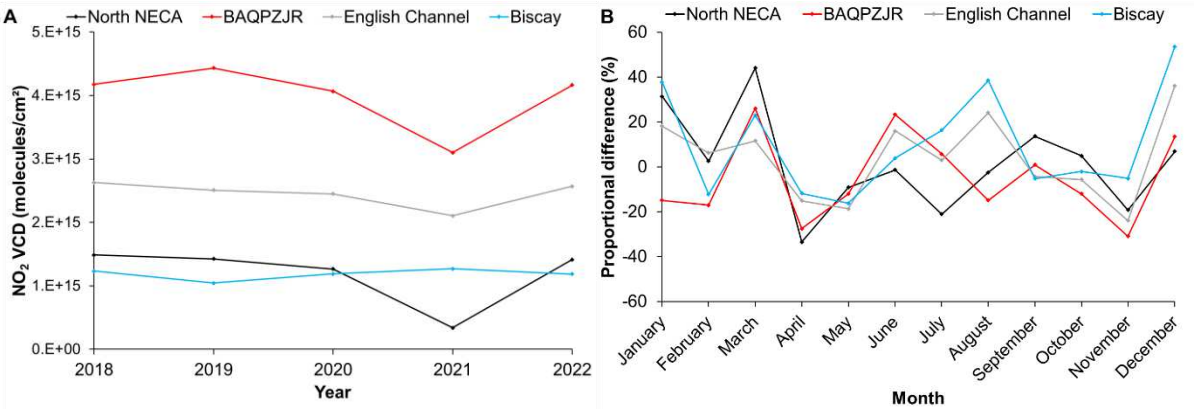


Figure S 15. Average yearly NO_2 VCD per zone (A). Average proportional difference per month per zone after the NECA came into effect (B). For 2018 not all months were available.

6.4. Supplementary tables

Table S.2. Overview of remotely monitored OGVs for FSC in the SECA from 2015-2020.

	BE AC	NL fixed	NL heli	DE fixed North Sea	DE fixed Baltic Sea	DE RPAS	DK heli	DK RPAS	DK fixed Great Belt	DK AC	FR RPAS	LT RPAS	Sum SECA
2015	114	70		1479						396			2059
2016	1219	199	327	2540					1691	853			6829
2017	887	147		5643			404		4155				11236
2018	1138	2958		6088	1557		614		3580				15935
2019	1232	8765		8815	2601		615	26	5458				27512
2020	405	4958		7713	2401		602	180	3910		67		20236
2021	1015	3343		6684	2506		600	3			308	142	14601
2022	951	4975		7103	2541	214	602				480		16866
Total	6961	25415	327	46065	11606	214	3437	209	18794	1249	855	142	115274

Table S.3. Correlation (R^2) between different remote measurement locations.

	BE aircraft	DK mini sniffers	NL Rotterdam	DE combined	DK Great Belt	SECA fixed	SECA airborne
BE aircraft	-	0.76	0.89	0.64	0.90	0.91	-
DK mini sniffers	0.76	-	0.29	0.11	0.64	0.48	
NL Rotterdam	0.89	0.29	-	0.72	0.68	-	0.70
DE (combined)	0.64	0.11	0.72	-	0.35	-	0.51
DK fixed	0.90	0.64	0.68	0.35	-	-	0.84

Table S.4. Correlation (R^2) between Belgian airborne data and other remote measurement locations.

Location	FSC>0.13	FSC>0.15	FSC>0.2	Mean
NL Rotterdam	0.91	0.91	0.85	0.89
DE (combined)	0.57	0.70	0.64	0.64
DK heli	0.51	0.78	0.62	0.64
DK Great Belt	0.85	0.93	0.93	0.90
DK Mini-sniffers	0.70	0.73	0.84	0.76
SECA average (excl. BE)	0.91	0.95	0.90	0.92

Table S.5. Constants and correlation factor for the fitting of the non-compliance rate in function of the distance to the SECA border (nm) based on the three non-compliance cut-off levels.

	All measurements			Airborne sniffers and mini-sniffers		
	FSC > 0.2%	FSC > 0.15%	FSC > 0.13%	FSC > 0.2%	FSC > 0.15%	FSC > 0.13
R^2	0.965	0.901	0.784	0.997	0.970	0.903
a	3.40	3.71	3.76	3.43	3.85	3.83
b	127.78	152.32	166.89	133.33	179.05	191.85
c	0.02	0.03	0.04	0.02	0.03	0.06

Table S.6. Constants and correlation factors for the fitting of the non-compliance in function of the distance to port (nm) for the three non-compliance cut-off levels.

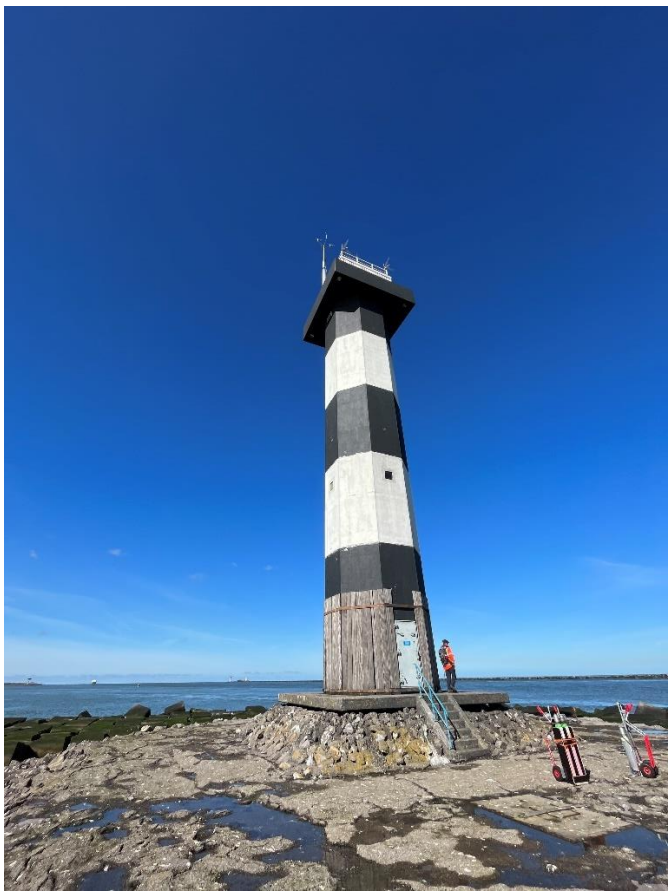
	FSC > 0.2%	FSC > 0.15%	FSC > 0.13
R^2	0.985	0.987	0.971
k	0.099	0.120	0.166
o	3.54	5.44	2.513
n	0.029	0.055	0.029
p	0.003	0.011	0.001

Table S.7. Proportional difference for the different zones after the implementation of regulatory measures.

	SO_2 annual difference (%)	NO_2 annual difference (%)	NO_2 monthly difference (%)
Northern SECA	-15.9%	+1.0%	+7.15%
BAQPZJR	-22.5%	-5.8%	+6.2%
English channel	-9.5%	+4.1%	+5.86%
Bay of Biscay	+3.0%	+14.4%	+9.59%

Part IV

Chapter 7: Current progress in developing a MARPOL Annex VI enforcement strategy in the Bonn Agreement through remote measurements



Personal picture taken at Hoek van Holland (NL) (15/03/23)

Current progress in developing a MARPOL Annex VI enforcement strategy in the Bonn Agreement through remote measurements

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Abstract

This article provides an overview of the current progress made by the Bonn Agreement (BA) Contracting Parties (CPs) in adopting MARPOL Annex VI under the scope of the BA. In 2019, the North Sea Ministers of the CPs of the BA formally agreed to include MARPOL Annex VI within the BA. Subsequently, in 2021, a Bonn Agreement MARPOL Annex VI expert workshop was convened, which identified a series of action points. To effectively address these action points, two working groups (WGs) were established: the Strategic Operational Working Group (SOWG) and the Technical Working Group (TWG). The primary objective, as identified throughout the action points, of the WGs is the exchange of best practices, monitoring outcomes and the harmonization of enforcement practices among the BA CPs, with the aim of implementing an efficient monitoring and enforcement strategy within the BA. The BA has recognized that remote monitoring operations play a pivotal role within this strategy. This article explores the extent to which remote measurements can contribute to the development of a regional enforcement strategy for MARPOL Annex VI within the framework of the BA.

1. Introduction

During the latter half of the preceding century, the International Maritime Organization (IMO) established the International Convention for the Prevention of Pollution from Ships (MARPOL) [1]. Concurrently, the Bonn Agreement (BA) was formed [2]. The BA, originating from the response to the Torrey Canyon incident in 1967, emerged as a regional cooperation to address oil pollution in the North Sea, resulting in the establishment of the Agreement for Cooperation in Dealing with Pollution of the North Sea by Oil in 1969. In 1983, the BA was expanded to include other harmful substances, including hazardous noxious substances, garbage, and solid cargo residues [2]. Through extensive collaboration among the Contracting Parties (CPs) of the BA, particularly within the Working Group on Operational, Technical and Scientific Questions concerning Counter-Pollution Activities (OTSOPA), notable reductions in oil pollution from ships in the North Sea area have been achieved. [3–5]. The Scientific Service Management Unit of the Mathematical Model of the North Sea (MUMM) of the Royal Belgian Institute of Natural Sciences (RBINS) assumes the position of the Belgian Head Of Delegation (HoD) within OTSOPA and has made substantial contributions to the aforementioned endeavor.

In the latter part of the last century and the early years of this one, work initiated within OTSOPA led to the increased use of remote monitoring data for the enforcement of MARPOL violations. In this regard, the BA developed the renown Bonn Agreement Oil Appearance Code (BAOAC), a method for estimating the extent of oil spills, used by numerous countries and still in use today. Increased cooperation among CPs has resulted in a regional oil pollution strategy. This cooperation included: 1) the development of procedures enabling the prosecution of cross-border pollution or pollution observed by neighboring countries; 2) the exchange of operational national information and development of best practices and counter pollution manuals; 3) operational assistance in pollution incidents and legal discussions in court cases; and 4) combined exercises and operations. This regional strategy combined

with the introduction of new regulations led to a drastic reduction of oil pollution in the area covered by the BA. Whereas the BA was once one of the most impacted regions for oil pollution, the situation is these days well under control [4–7]. The BA strives to attain a similar level of progress in the implementation of MARPOL Annex VI regarding air pollution from ships [8]. In this endeavor, the MUMM assumes a prominent role. One of the primary objectives is to establish standardized monitoring procedures and maximize the utilization of remote measurements to their fullest extent.

1.1. Adoption of MARPOL Annex VI under the Bonn Agreement

Since 2015, the MUMM has petitioned at OTSOPA to extend the BA to include air pollution from ships as described under MARPOL Annex VI. By sharing best practices and remote monitoring data, the MUMM aspired to enhance the enforcement capabilities of other CPs and persuaded the BA CPs regarding the benefits of incorporating MARPOL Annex VI within the jurisdiction of the BA. In October 2019, the Ministerial Meeting of the BA formally approved the extension of the scope of the BA to include MARPOL Annex VI. Therefore, recognizing the BA as the appropriate intergovernmental forum to roll out MARPOL Annex VI monitoring activities. Since the inclusion of MARPOL Annex VI entailed a change to the text of the BA, this was combined with the inclusion of Spain in the BA [9]. As of today, Spain and Sweden have yet to ratify the amended text formally adopting MARPOL Annex VI under the BA (Figure S 2).

It is important to note that the inclusion of MARPOL Annex VI in the BA occurred before the implementation of the revised MARPOL Annex VI in 2021. In addition, it must be noted that the majority of the further referred to remote ship emission measurements were conducted prior to the implementation of the 2021 revised MARPOL Annex VI. Nevertheless, the references made in this article pertain to the 2021 revised MARPOL Annex VI and not the 2008 revised MARPOL Annex VI. The distinction between the two versions is considered inconsequential for this article, as the primary emission limits discussed in this article, as stipulated under Regulation 13 and Regulation 14, are not subject to substantial variations between the two versions.

2. Remote MARPOL Annex VI measurements within the Bonn Agreement

Since 1991, Belgium has conducted aerial surveillance in the Quadripartite Zone of Joint Responsibility (BAQPZJR), which consists of the Belgian North Sea area and parts of adjacent waters in France, the Netherlands, and the UK (Figure S1, upper). The MUMM is recognized by Belgian Law as one of the legally competent authorities for the monitoring and enforcement of MARPOL [10]. Since 2015, the MUMM has been involved in monitoring SO_x and NO_x emissions from ships. The airborne monitoring outcomes from Belgium are recorded in multiple scientific papers that outline the methodology, accuracy, and results of the monitoring activities, along with the benefits derived from targeting inspections in ports and the impact of international regulation on the air quality in Belgium [11–17].

Additionally, several other CPs of the BA have actively participated in remote measurements of ship emissions. Denmark used both fixed sniffer stations (at the Great Belt Bridge) and airborne measurements with both fixed and rotary wing aircraft [18–25] in the past. Norway uses lightweight unmanned aerial vehicles to measure FSC in their fjords since 2018 [26]. Germany started the German ship emission monitoring network in 2014 with fixed sniffer stations at the port entrances of the ports of Hamburg, Bremerhaven, and Kiel. In addition, the German research vessel ATAIR is equipped with a sniffer sensor [27–29]. Sweden conducts fixed sniffer measurements at the Oresund Bridge. The measurements at the Oresund and Great Belt bridge are executed by Chalmers University, Goteborg, Sweden. In addition, Chalmers University has conducted fixed sniffer and aerial sniffer measurements at various locations in the Baltic Sea and North Sea since 2006 [30–35]. The Netherlands has been using a fixed sniffer station in the port of Rotterdam since 2014 [36–38]. The European Maritime Safety Agency (EMSA) launched its Remote Piloted Aircraft System (RPAS) program in 2019. The program

provides unmanned aircraft measurements to MS on request. So far, ship emission monitoring operations have been conducted in Denmark France, Germany, Lithuania, the Netherlands, and Spain [39].

3. Regional cooperation on MARPOL Annex VI within the Bonn Agreement

Despite the lengthy adoption process, MARPOL Annex VI has been on the agenda of the BA and OTSOPA since 2015. One of the tasks of the BA Strategic Action Plan 2019-2025 (BASAP 19-25), was the organization of a MARPOL Annex VI Experts Workshop defined under Task 3 "Consider developing minimum recommendations on surveillance operations in the BA area and outcomes expected (incl. MARPOL VI, RPAS)".

In addition, two working groups were established to work intersessional on MARPOL Annex VI issues as part of Task 11 of the BASAP 19-25: "Consider the development of a common technical strategy and operational approach for monitoring compliance for NO_x and SO_x." Moreover, MARPOL Annex VI has been recognized within the BA as one of the primary funding priorities, thereby conveying a compelling message to the EU to encompass MARPOL Annex VI within the scope of various funding programs' calls.

3.1. MARPOL Annex VI Experts Workshop

The BA MARPOL Annex VI Experts Workshop 2021 (MAVIEWS21) was held from 2 to 5 February 2021. The workshop was organized by Belgium, Germany, and the EU, represented by the European Maritime Safety Agency (EMSA). MAVIEUWS concluded with a set of recommendations to be further explored by two separate working groups (WGs) dealing with (1) strategic and operational aspects (SOWG) and (2) technical aspects (TWG) under the umbrella of OTSOPA. The recommendations of MAVIEWS21 were presented at OTSOPA21.

3.2. MARPOL Annex VI Working Groups

OTSOPA21 agreed to establish the SOWG and the TWG and to recommend the CPs to adopt the references of the SOWG (Bonn 21/03/06 Add.1) and the TWG (Bonn 21/03/06 Add.2) (Figure S1).The ToRs address a list of actions, divided into: 1) quick wins and in-kind actions, which require limited additional effort; and 2) project actions that require more resources and therefore require the preparation of a project proposal to be submitted to a funding program. All BA CPs have representatives in at least one of the WGs and most are represented in both WGs. During OTSOPA21, Belgium and Denmark agreed to jointly lead the TWG. During OTSOPA22, the Netherlands and France agreed to jointly lead the SOWG. Neither at OTSOPA21 nor OTSOPA22 an agreement was reached on the submission of a project proposal to address the list of project-based actions. Consequently, only in-kind actions were considered for the time being.

3.2.1. MARPOL Annex VI Strategic Operational Working Group

Within the SOWG the main task is the organization of joint offshore sub-regional surveillance programs and the development of a surveillance strategy building on existing national expertise and former projects, thus using the fully available toolbox for emission monitoring. To achieve this, the SOWG wants to promote remote measurements at sea in the BA area, looking for synergies between different assets with the goal to: 1) monitor many ships in high traffic density locations including port entrances, using airborne, shipborne and fixed sensors; 2) monitor fewer ships outside high traffic locations, but making use of a more unpredictable approach; and 3) develop and maintain an inventory of assets and monitoring capacities within the BA.

By improving the cooperation between the CPs on the deployment of RPAS by EMSA, the SOWG aims to increase knowledge and to work towards joint cross border campaigns within the BA. In

addition, the SOWG aims to improve the use and capability of EMSA's Thetis-EU port inspection database. For this reason, recommendations have been formulated to improve its operational use and functionality. One of the recommendations is to develop a more active alerting system, including automatic email alerts. Additionally, it was advised to incorporate a more comprehensive mechanism for reporting inspection results conducted on vessels equipped with an Exhaust Gas Cleaning System (EGCS). It was further recommended to consider whether Thetis-EU could improve data exchange, including the exchange of raw data, the development of advanced data export and reporting tools for CPs (for FSC and NO_x), and the development of statistical analyses.

The actions for which external funding may need to be considered were presented around one main theme: organizing a large-scale regional measurement campaign that will combine the EMSA RPAS with other national assets. This so-called Air Pollution Co-Ordinated Extended Pollution Control Operation (AIR-CEPCO) will in fact be like the CEPCO operations organized for several decades by the BA for oil pollution. It was agreed that it is key to first identify priority areas (e.g. shipping lanes, ECA borders) or high-risk areas using Automatic Identification System (AIS) data from ships, remote measurements, and satellite information. In addition to being able to use and compare the results of the different remote measuring equipment during this AIR CEPCO, a harmonized approach with standard operating procedures will have to be developed. For this reason a new chapter under the Counter Pollution Manual (CPM) with SOPs will be created, covering 1) a methodology on instrumentation and deployment, including calibration before operational use; 2) reporting procedures (incl. reporting templates) and data processing; 3) the best practice for airborne surveillance; 4) a list of competent authorities' focal points; and 4) an agreement upon thresholds indicating non-compliant ships.

3.2.2. MARPOL Annex VI Technical Working Group

The in-kind actions considered in the MAVI-TWG are aimed at sharing technical experience in sensor development, best practices (on FSC and NO_x) and the standardization of airborne measurements. In addition, three meetings have been held jointly with the MAVI-SOWG to discuss the technical and strategic/operational aspects of NO_x compliance monitoring. Recommendations on regulations have been prepared for discussion at OTSOPA23.

As part of AIR-CEPCO's project-based actions, MAVI-TWG will be responsible for developing common procedures for uncertainty calculation, sensor calibration and threshold definitions. The AIR-CEPCO will therefore function as a validation campaign to test the developed protocols in the field (for both, FSC and NO_x), to facilitate the sharing of data and to identify commonalities and differences between the remote measurement techniques, in order to check uncertainties of the different sensors (Figure S3).

3.3. Reporting of the Working Groups at OTSOPA

During the OTSOPA23 meeting convened in May 2023 in Copenhagen (DK), the BA MARPOL Annex VI Working Groups (WGs) provided updates on their ongoing work for quick win actions. They also presented the outcome of the discussion on formulating regulatory recommendations and outlined their proposed approach for submitting these recommendations to the IMO through a two-step process. The initial step entails presenting the outcomes of the studies conducted within the BA in an information (INF) paper to the Sub-Committee on Pollution Prevention and Response (PPR), with the aim to raise awareness about observed issues regarding air pollution from ships. In a second step, an output will be requested at the Maritime Environment Pollution Committee (MEPC) to support a proposal for amending MARPOL Annex VI and the accompanying NO_x Technical Code. Presently, the BA does not possess observatory status in the IMO concerning MARPOL Annex VI, thus precluding the BA from directly submitting a proposal to amend MARPOL Annex VI and the NO_x Technical Code. Instead, such submissions will have to be made by one or more of the IMO Contracting States. During

OTSOPA23, efforts were made to establish an alliance for either co-submitting or supporting these submissions at IMO.

Additionally, the WGs presented a concept proposal to address the project-based actions, aiming to find a project consortium and secure funding from a EU funding agency. The CPs acknowledged the advancements achieved by the WGs, but no agreement was reached concerning the submission of a project proposal to a funding agency. Consequently, for the time being, the efforts of the WGs will remain confined to the quick win and in-kind actions. While four CPs expressed their commitment and potential involvement in the project, six other CPs cited either insufficient expertise within their respective administrations or resource limitations as grounds for their inability to participate in the proposed project. It is of significance to highlight that during the OTSOPA23 plenary meeting the delegations of all, but two CPs included national responsible authorities or scientific experts regarding MARPOL Annex VI. This development can be deemed as a substantial advancement, considering that in preceding years, delegations seldom comprised national authorities or scientific experts in the field of MARPOL Annex VI.

3.4. North Sea Network of Investigators & Prosecutors

The BA WGs have recognized the importance of information exchange within the North Sea Network of Investigators & Prosecutors (NSN) and included it as one of their action points. Since 2015, the MUMM has voluntarily taken on the role of liaison between OTSOPA and NSN, specifically concerning matters related to MARPOL Annex VI. At the NSN23 meeting, held in Billund (DK), the MUMM presented the progress of the MARPOL Annex VI WGs and the compliance levels within the Bonn Agreement. Additionally, various completed and ongoing legal cases related to MARPOL Annex VI violations were presented by the CPs and discussed during the meeting.

4. Conclusion

This article highlights the pioneering role of the BA in addressing air pollution from ships. In recent years the BA made significant progress in developing a region-wide enforcement strategy for MARPOL Annex VI violations by consulting technical, operational and legal experts during a dedicated Workshop, which led to the creation of two MARPOL Annex VI WGs. Specific quick win and in-kind actions have been defined and are being actively addressed by the WGs. Other more elaborate actions like the organization of validation and monitoring campaigns in high-risk areas within the scope of EU funded project proposal are being discussed. The goal is to achieve a comparable reduction in air emissions violations for MARPOL Annex VI as was achieved for MARPOL Annex I oil pollution violations. However, given the limited resources available within the CPs of the BA and the decentralization of MARPOL Annex VI authorities within the CPs, the BA has not yet been able to take decisive action to implement comprehensive monitoring and validation operations for remote measurements, which is considered a crucial milestone in the implementation of an effective regional enforcement strategy.

In addition, the discussions within the WGs have yielded recommendations that will be presented to the subsidiary bodies of the IMO, namely the MEPC and the PPR. It should be noted that the BA is currently lacking observatory status in the IMO and cannot independently initiate and amendment to MARPOL Annex VI and the NO_x Technical Code. Nevertheless, the WGs, are committed, in combination with the national maritime authorities of selected CPs, to secure the necessary support for its initiatives aimed at revising air emission regulations. The goals of the WGs is to ensure that these regulations become more effective for the protection of the marine environment and safeguarding human health.

Author contributions: Ward Van Roy: Conceptualization, Investigation, Resources, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration; Kobe. Scheldeman: Writing - Review & Editing; Annelore Van Nieuwenhove: Writing - Review & Editing; Jean-Baptiste Merveille Van Roozendael: Writing - Review & Editing Ronny Schallier: Supervision; Frank Maes: Supervision, Writing - Review & Editing.

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6. Supplementary material

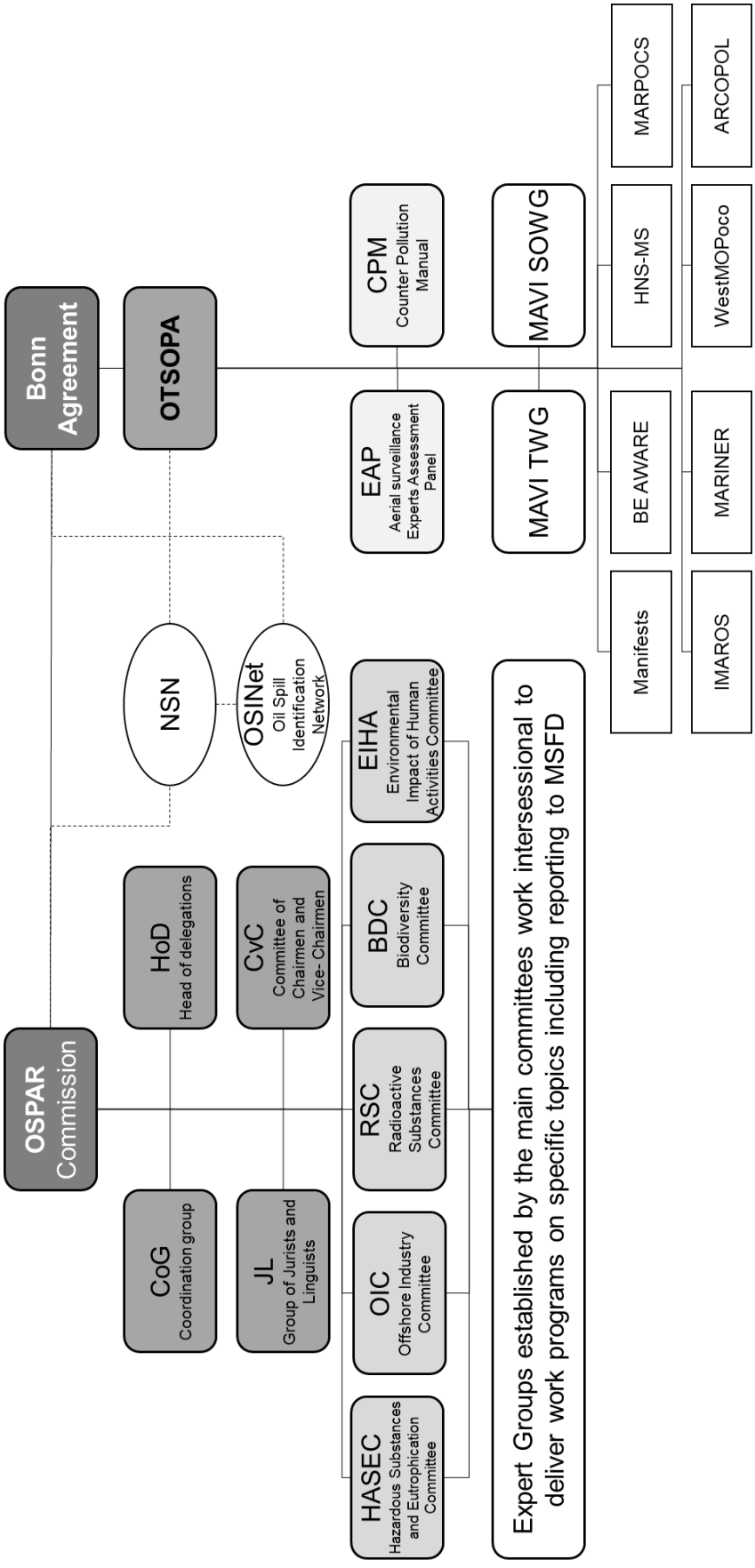


Figure S 1. Organigram of the Bonn Agreement.

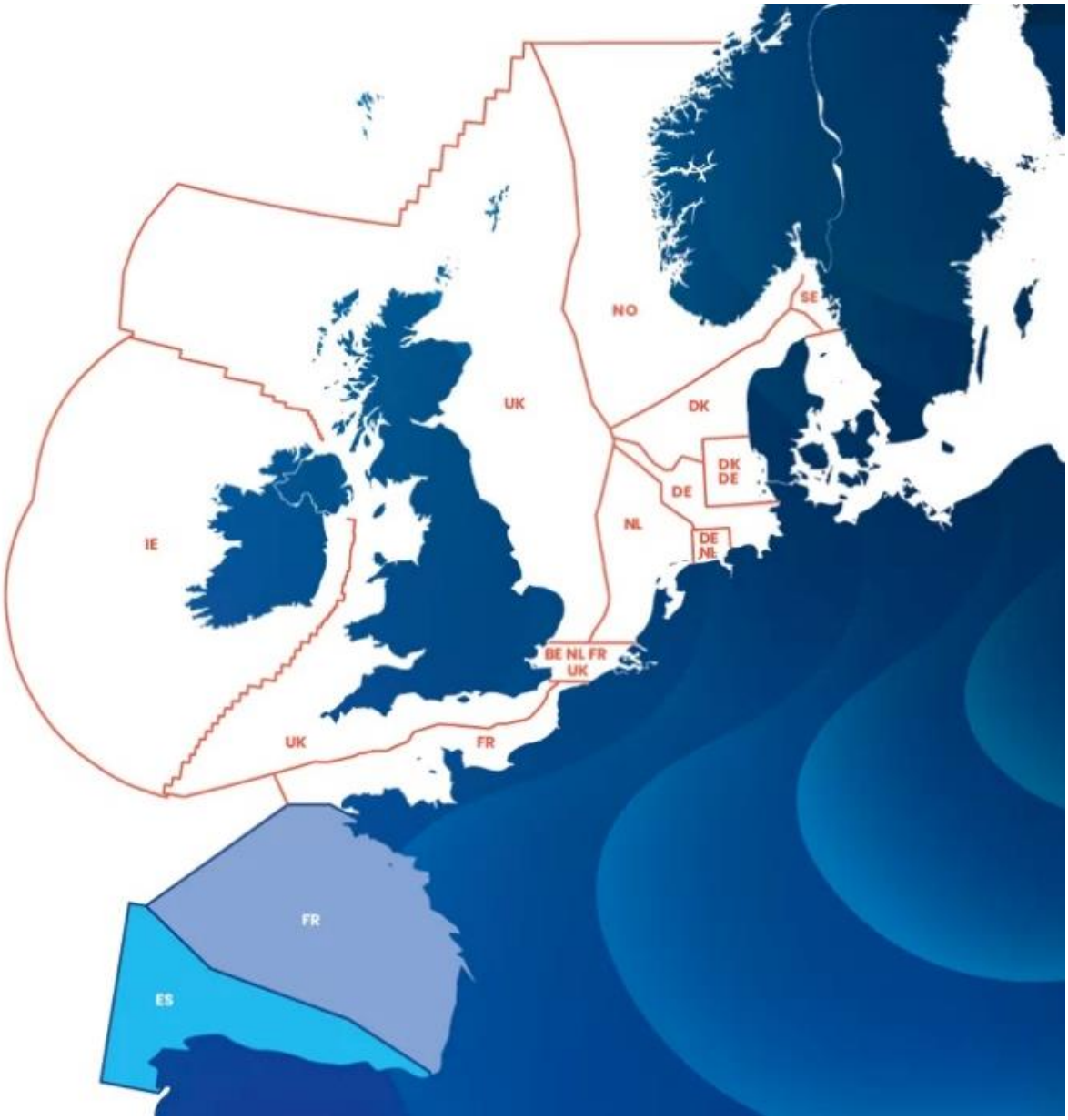


Figure S 2. BA area as of 2023 [9].

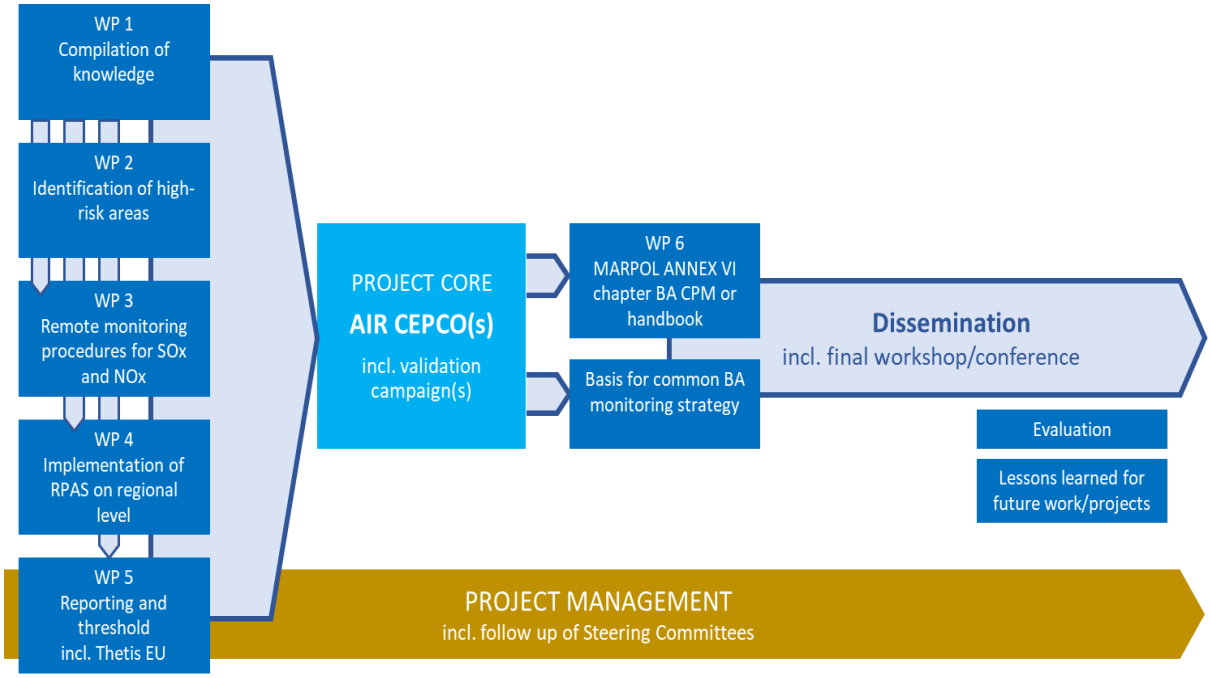


Figure S 3. Project Concept presented at OTSOPA21 and OTSOPA23.

Chapter 8: Policy Recommendations for International Regulations Addressing Air Pollution from Ships



Olle Akesson © - Picture taken at OTSOPA23 Copenhagen (DK) (23/06/23)

Policy Recommendations for International Regulations Addressing Air Pollution from Ships

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Abstract

Since 2015, Belgium has undertaken remote measurement activities to monitor ship emissions and to single out ships for on board inspections at ports. A significant challenge in the further improvement of the MARPOL Annex VI enforcement capacity lies in the utilization of these remote measurements as admissible legal evidence. Previous studies have demonstrated that when an appropriate measurement uncertainty is taken into account, remote measurements provide scientifically reliable evidence to verify compliance with MARPOL Annex VI obligations. Nonetheless, remote measurements have so far not been used for direct legal action. Moreover, while there are guidelines for fuel sampling in ports to enforce compliance with SO_2 emission standards, there are currently no legally recognized practical methods in place to verify and enforce exceedances of real-world NO_x emissions regarding the established NO_x emission limits. In this context, standardized remote measurement procedures can be a valuable tool in establishing an inspection mechanism for NO_x. However, this requires specific changes to the current NO_x regulations. Within the Bonn Agreement, the MARPOL Annex VI Working Groups discussed and identified certain regulatory gaps that need to be addressed in order to effectively reduce emissions from ships and improve coast and port State's enforcement capacity. This article presents a critical analysis of these recommendations and the results of these discussions towards new regulations. The proposed recommendations serve to facilitate the incorporation of remote measurements in the enforcement chain of MARPOL Annex VI and address specific regulatory gaps, thereby enhancing the likelihood of achieving the envisioned emission reductions by the shipping sector.

1. Introduction

The Protocol of 1997 to amend the International Convention for the Prevention of Pollution from ships (MARPOL PROT 1997) introduces a new Annex VI in the MARPOL Convention with the aim to reduce air pollution from ships [1]. MARPOL Annex VI includes a ban on the deliberate emission of certain Ozone depleting substances (Regulation 12), the reduction of emissions of Nitrogen oxides (NO_x) (Regulation 13), Sulfur oxides (SO_x) (Regulation 14) and Volatile organic compounds (VOCs) (Regulation 15). In addition, surveys (Regulation 5), certification (Regulation 6-9), port state control (PSC) (Regulation 10) and the detection of violations and enforcement (Regulation 11) are addressed as well. MARPOL Annex VI entered into force in 2005 and has subsequently been amended several times, with changes to the technical standards agreed by the Marine Environment Policy Committee (MEPC).

MARPOL Annex VI introduced Emission Control Areas (ECAs) in some densely populated areas. The first ECAs came into effect in the Baltic Sea (2006) and the North Sea (2007) (Figure Supplementary material (S).1, upper) [1–7], followed by ECAs that came into effect in North America (2012) and the US Caribbean Sea (2014) [2,4–9]. Initially these ECAs were limited to Sulfur Emission Control Areas (SECAs), later these SECAs were expanded by including Nitrogen Emission Control Areas (NECAs) in the North America and the US Caribbean Sea (2016) [4] and later on also in the North Sea and Baltic Sea (2021) [3–5,10]. On 1 May 2024, the Mediterranean SECA will enter into force [11]. A last full

revision of Annex VI took place in 2021 and entered into force on 1 November 2022 [1]. By 19 April 2023, MARPOL Annex VI was ratified by 105 Contracting States representing 96.8% of the gross tonnage of the worlds' merchant fleet [12].

Since 2015, Belgium has been engaged in airborne ship emission monitoring operations, carried out by the Scientific Service Management Unit of the Mathematical Model of the North Sea (MUMM) of the Royal Belgian Institute of Natural Sciences (RBINS). The outcomes of these monitoring operations have been documented in numerous scientific papers and reported to the Bonn Agreement (BA). This paper describes the recommendations that came forth from the Belgian monitoring efforts and the discussions conducted at regional level within the BA Working Groups on Marpol Annex VI (Figure S.2). The aim of these recommendations is enhancing the potential of the use of remote monitoring data for legal proceedings and improve the effectiveness of international ship emission regulations.

2. Regulations on air pollution from ships

2.1. Sulfur oxides

Regulation 14 of MARPOL Annex VI sets emission limits for SO_x by addressing the maximum permitted Fuel Sulfur Content (FSC) of marine fuels. In the Baltic Sea and the North Sea SECA, the maximum FSC was reduced from 1.5% prior to 1 July 2010 to 1% till 31 December 2014, and finally to 0.1% on 1 January 2015 [3,6]. Ships may also use natural gas or use an exhaust gas cleaning system (EGCS) to achieve similar emission levels as with low-sulfur fuels [1,13]. Dedicated EGCS guidelines were described to ensure that EGCS ship comply to the emission limits and allow authorities to verify compliance in port [14]. The sulfur limit outside ECAs was set at 3.5% from 1 January 2012 [2,6,15] and from 1 January 2020 the so-called "global sulfur cap" came into force, reducing the maximum allowable FSC to 0.5% [16]. (Figure S.1, middle). On 1 March 2020, the "carriage ban" came into force, prohibiting non-EGCS ships from carrying non-compliant fuel in bunker tanks [8]. Procedures for sampling and verification of the sulfur content have been adopted in 2020 [17], as well as guidelines for monitoring the worldwide average sulfur content of fuels delivered to ships [18].

2.2. Nitrogen oxides

Regulation 13 of MARPOL Annex VI sets NO_x emission limits. The merchant shipping fleet is divided into four tiers according to the keel laying date (KLD) or the date of a similar stage of construction (Regulation 2.19). For each tier, emission limits follow a decreasing curve as a function of engine rated speed (ERS or n) (Figure S.1, lower). It is worth noting that only the strictest limits (Tier III), that entered in to force on 1 January 2021, apply in the NECAs [1].

The NO_x Technical Code, first adopted in 2005 and revised in 2008, describes in detail the technical standards and verification tests for different engine types to meet the defined emission limits per tier [19]. The verification tests for the main engines are based on the weighted average of NO_x emissions from four engine load points with corresponding weighting factors (WF) (see Table S.1). Only for Tier III, a "not-to-exceed" limit (NTE) has been defined, which stipulates that the NO_x limit should not be exceeded by more than 50% for any of the individual engine load points of the main engines (Appendix II, MARPOL Annex VI) [19]. However, no emission limits have currently been set for any of the four tiers below 25% main engine load.

2.3. European legal framework

In the EU, SO_x emissions from ships are regulated by the EU Sulphur Directive ((EU) 2016/802) and the Commission Implementing Decision ((EU) 2015/253) [20,21]. These regulations serve as the means to incorporate the provisions of MARPOL Annex VI Regulation 14 into the legal framework of the EU. They encompass guidelines and rules for the inspection process carried out by Member States (MS). A fundamental aspect of these regulations entails specifying the mandatory number of inspections (Art 3

of (EU) 2015/253). It is explicitly stated that MS may reduce the required number of inspections by up to 50% when employing remote monitoring methods (Art 3.3(a) of (EU) 2015/253). Furthermore, these regulations have given rise to the establishment of Thetis-EU, which functions as the Union's database for sharing information to improve the effectiveness of inspections. Notably, Thetis-EU facilitates the exchange of remote measurements and reports alerts of possible non-compliance. Presently, no additional directive has been adopted by the EU concerning NO_x emissions from shipping, consequently excluding NO_x remote measurements and non-compliance alerts from the purview of Thetis-EU.

Another EU legal instrument is the Ship Source Pollution Directive (SSPD) (Directive 2005/35/EC on ship-source pollution) [105]. This directive ensures that ship-source discharges of polluting substances at sea are regarded as infringements. It also establishes a common framework to deal with penalties related to illegal discharges from ships. Although the directive makes direct reference to the definition of 'discharge' in the MARPOL Convention (Article 2 para 3 (a)), which includes emissions from ships, the directive itself deals exclusively with discharges of oil and chemical pollutants, considering as polluting substances only those covered by Annexes I and II of the MARPOL Convention. The directive is presently undergoing a review process. The revised directive should then include all relevant annexes of the International Convention for the Prevention of Pollution from Ships (MARPOL) [22,23]. Notably, for MARPOL Annex VI, only discharges of washwater from ships equipped with EGCS are currently considered for the revised directive (Art f of the proposal) [23].

The Directive on Ambient Air Quality (Directive 2008/50/EC) [24] is another relevant EU directive currently undergoing a revision process [25]. While the proposed revision of the Directive does not directly target air pollution originating from ships, reference is made to the EU Sulphur Directive (Annex XV). However, no reference is made to NO_x emissions from ships. The proposed revised directive intends to establish air quality standards, including for NO_x, in the EU which are closer aligned to the guidelines stipulated by the World Health Organization (WHO) by 2030 and to achieve clean air by 2050 (Art 13) [25,26]. Nevertheless, it can be argued that in the absence of a specific emphasis on addressing air pollution originating from ships, the attainment of these targets remains uncertain, partly due to other factors, such as the increasing trend in maritime transport and the higher NO_x emission Tier II ships compared to Tier I ships [27,28].

Regarding EGCS, there are other EU directives that are applicable. Notably, the Water Framework Directive (WFD) [31], this Directive aims to establish a framework for the protection and sustainable use of all bodies of water within the EU. Therefore, MS have to a achieve a good ecological and chemical status of the surface water, including the territorial sea for achieving the chemical status and up to 1 nautical mile from the coastline for the ecological status (Art. 4 and Annex V point 1.4.3) [29–31]. The WFD defines that priority substances listed in the Environmental Quality Standards Directive (EQSD) [29] require monitoring by MS [32]. Additionally, the WFD outlines a list of priority hazardous substances that should be completely eliminated (Preamble paragraph 43 and Article 1) [30]. EGCS wash water contains several of the aforementioned priority substances (such as lead and benzene) and priority hazardous substances (such as polycyclic aromatic hydrocarbons (PAHs), cadmium, and mercury) [13,31,33–42]. Consequently, EU MS have invoked the WFD to impose prohibitions on the use of open loop EGCS within their inland waters and ports. Furthermore, when closed loop EGCS are used, there must be enough storage capacity for the bleed-off water to be stored for the entire duration of the voyage within inland waters. Belgium, for example, specifically the region of Flanders responsible for WFD implementation in ports and inland water, has banned the discharge of washwater from EGCS by the Royal Decree implementing the WFD in Belgian law [43].

The Marine Strategy Framework Directive (MSFD), adopted on 17 June 2008 [32], is another EU directive relevant to EGCS. The primary objective of the MSFD is to attain a good environmental

status for all marine waters within the EU and to ensure the sustainability of economic activities reliant on the marine environment [44]. One of the descriptors outlined in the MSFD to achieve a good environmental status is that concentrations of substances should not reach levels that result in detrimental pollution effects (Annex I.8) [32]. Furthermore, the MSFD stipulates that those discharges outside territorial waters and coastal waters, impacting the chemical and environmental status for waters considered under the WFD, should be considered under the MSFD (Preamble 13 and Annex II). Research has demonstrated that the use of EGCS, particularly in the Baltic Sea, has the potential to elevate the concentration of certain priority hazardous substances [31,34–39,45].This would require that pollution pressure from EGCS should be monitored and followed up by the MS [31]

2.4. National Belgian laws

Belgium implemented MARPOL Annex VI, the EU Sulphur Directive, and the Commission Implementing Decision by Royal Decrees in 2020 [46,47]. It is important to note that, despite the lack of EU regulations on NO_x, Belgium adopted the inclusion of MARPOL Annex VI Regulations 13 on NO_x in 2020 [47]. In addition the use of EGCS is prohibited by federal law up to 3 nm from the coast.

3. Possibilities for the use of remote measurements in legal proceedings

To date, remote measurements serve primarily as a targeting system to enhance the efficiency of on-board inspections. However, this enforcement mechanism has limitations for ships not bound to EU ports as the EMSA hosted platform where data on FSC alerts is held, Thetis-EU, can only be accessed by EU MS. Additionally, Thetis-EU does not include the exchange of NO_x remote measurements and inspection results. Furthermore, ships alerted at sea as potentially non-compliant for FSC may already have undergone fuel change-over procedures before entering EU ports. Finally, the possibilities for on-board NO_x inspections in ports and inspections of ships equipped with EGCS-ships are in practice limited to document checks. To determine whether remote measurements could possibly serve as legal evidence, relevant national and international regulations were examined. While several arguments support the use of remote monitoring data in legal proceedings, there are several obstacles that need to be addressed through regulatory changes.

3.1. The Law of the Sea Convention and MARPOL Annex VI violations

According to the United Nations Convention on the Law of the Sea (LOSC), 'States have the obligation to protect and preserve the marine environment' (Art. 192) and coastal States are entitled to take action against ships that have polluted their territorial sea or exclusive economic zone. Those ships calling at a port of the coastal State may be investigated, and the State may institute proceedings in case of violations of the applicable rules and standards for the prevention, reduction and control of pollution from ships (Art. 220(1)) [48]. The LOSC implicitly refers in articles 220 and 218 to violations of the MARPOL Convention [49]. Article 218 (1) LOSC recognizes the universal jurisdiction of port States for ships voluntary entering the port of a MARPOL State in the case of MARPOL discharge violations committed by that ship outside the territorial sea or exclusive economic zone of that State. However, if the violation has taken place under the jurisdiction of another coastal State, that State must agree, by request, to the procedure instituted by the port State. That coastal State can also request to suspend the procedure initiated by the port State. The flag State needs to be informed by the port State. The records of the investigation carried out by the port State shall be transmitted upon request to the flag state or to the coastal State under which jurisdiction the violation took place (Art. 218 (4), LOSC).

Investigations of ships flying a foreign flag under articles 2018 and 220 may not delay the ship longer than necessary for the purpose of that investigation. A physical inspection of the ship always starts with a document inspection (certificates, records, ...) and is followed by a further physical inspection if the construction of the ship or its equipment is not in accordance with the documents, or if the certificates or records are invalid (Art. 226 (1)(a), LOSC). Regulations 10 and 11 of MARPOL Annex VI further

regulate respectively port State inspections and enforcement to ensure that ships comply with the operational requirements of Annex VI. A ship may be inspected in a port or offshore terminal by duly authorized or appointed officers to verify whether the ship has emitted a substance in violation of the provisions of Annex VI (Reg. 11.2, Annex VI), regardless if the flag State of the ship is a party to Annex VI. In accordance with article 5 (4) of the MARPOL Convention, no more favorable treatment shall be given to ships of non-parties. States Parties to Annex VI shall cooperate and use all practicable measures and environmental monitoring to detect violations of the provisions of this Annex and to enforce those provisions (Reg. 11.1, Annex VI).

In 2019, the MEPC adopted new Guidelines for Port State Control under MARPOL Annex VI [50], explaining which documents should be checked by PSC and when a more detailed inspection is possible, such as examining the specifications of the marine diesel engines, the sulfur content of the fuel and to verify the proper functioning of the EGCS if the ship is equipped with this installation. The 2019 Guidelines for PSC also specify detainable deficiencies, such as non-compliance with the relevant requirements while operating within a ECA for SO_x (2.7.2.6). If the investigation indicates a MARPOL violation, the ship shall be promptly released after an appropriate financial security or a deposit has been paid (Art. 226 (1)(b), LOSC) and the flag State shall be promptly notified and shall receive official records of the measures taken (Art. 231, LOSC).

Proceedings to impose penalties in respect of MARPOL violations committed by a foreign ship in or outside the territorial sea of the State initiating the proceedings are limited to monetary fines, except in case of a willful and serious act of pollution in the territorial sea (Art. 230 (1)(2), LOSC). Furthermore, the proceedings for violations beyond the territorial sea shall be suspended when the flag State requests the suspension of those proceedings and starts its own procedure to impose penalties for those violations, within six months of the date the first proceedings were instituted. There will be no suspension of the initial proceedings in case of major damage to the coastal State or if the flag State has repeatedly disregarded its enforcement obligation in respect of violations committed by ships flying its flag. The flag State instituting proceedings has the duty to inform the State that initially instituted proceedings about the full file of the case and the records of the proceedings. The suspended proceedings shall be terminated when the flag State proceedings have been concluded (Art. 228 (1), LOSC). A decision by the flag State not to proceed, for example due to lack of evidence, also closes the procedure.

MARPOL Annex VI requires that in addition to the Party that reported the alleged violation, the International Maritime Organization (IMO) is also notified of the measures taken by the flag State (Reg. 11.4). Physical inspection of a ship to gather information about a violation of MARPOL Annex VI, relies in practice mainly on PSC. Nevertheless, a ship navigating in the territorial sea or the exclusive economic zone of a coastal State may also be asked to provide relevant information as to whether a discharge violation has occurred, if there are clear grounds to believe that the ship committed an Annex VI violation in those zones (Art. 220 (3), LOSC). If the ship refuses to provide information or the information is manifestly incorrect and there is a substantial discharge that causes or threatens to cause significant pollution, a physical inspection of the ship at sea may take place (Art. 220 (5), UNCLOS). This article holds significant relevance as it grants coast Sate authorities the capacity to initiate radio communication with a ship to request specific engine parameters. An aspect which is important for the Belgian NO_x airborne monitoring operations.

However, H. Ringbom rightly doubts that a MARPOL Annex VI emission violation currently meets the ‘substantial discharge’ requirement necessary to physically inspect a ship at sea [51,52]. Nevertheless, the LOSC imposes no restrictions on the performance of airborne compliance monitoring, as long as the monitoring activities do not interfere with the ship's journey. Consequently, monitoring authorities should not force ships to alter their speed and direction [51].

3.2. MARPOL Convention

3.2.1. Marpol Annex VI Regulation 14

According to the MARPOL Regulation 14.5, non-compliance with regard to the sulfur content of used fuels must be demonstrated by analyzing a fuel sample using an X-ray fluorescence (XRF) instrument in a qualified laboratory (Reg. 18.8.2 and Appendix VI). Therefore, MARPOL does not appear at present to approve a FSC compliance verification procedure based solely on remote measurements. However, MARPOL Annex VI Regulation 14 also provides permission for the use of an EGCS allowing the use of fuel with high sulfur content. In this case, fuel sampling would be pointless and instead, SO_2 emissions from EGCS ships are regulated through the 2015 Guidelines for EGCS (MEPC.259(68)) replaced by the 2021 Guidelines for EGCS (MEPC.340(77)) [13,14,53]. The guidelines stipulate that the SO_2 to CO_2 emission ratios of EGCS-equipped vessels must be comparable to those of vessels operating on compliant fuel (Table S.3) [13,53,54]. A dedicated "Appendix 2, Proof of the SO_2/CO_2 ratio method" has even been included, which outlines the working mechanism and consolidates this method for EGCS-equipped ships [53]. The use of SO_2/CO_2 ratios by EGCS follows the same methodology as the FSC remote measurement method. Consequently, remotely measured SO_2/CO_2 ratios in ships' exhausts are already recognized in the regulations as a means of determining FSC content. Allowing the implementation of specific abatement technology based on a certain adopted methodology, while not allowing the adoption of corresponding enforcement procedures that are based on the same methodology may raise legitimate concerns.

3.2.2. Marpol Annex VI, Regulation 13 on NO_x

With regard to NO_x emissions, the 2008 NO_x Technical Code outlines protocols for conducting a quick onboard emission test (Chapter 6). Remote measurements follow similar procedures to a certain extent [19]. However, due to the intricate differences in scope and purpose, remote measurement do not fully align with this quick test method. Nonetheless, Regulation 13 provides certain options for enforcement through remote measurements. This is especially the case for Tier III ships. In contrast to Tier I and Tier II, for Tier III a not-to-exceed (NTE) limit of 150% has been adopted (Appendix II, MARPOL Annex VI), creating a clear maximum emission level independent of the weighted average emission level [55]. By applying a large measurement uncertainty due to certain minimal engine assumptions and by applying operational minimum requirements (i.e. minimum speed etc.), remote measurements are unambiguously capable of detecting gross emission violations [56,57].

Abatement technology is normally applied for Tier III, but unlike for EGCS, there are no guidelines for logging the emission measurement data by a Continuous Emission Measurement System (CEMS) [58]. This means that there are no operational methods in place to verify the effectiveness of the abatement technologies to reduce the real-world emissions. Nevertheless, most abatement systems are equipped in practice with a CEMS, on-board inspections can still find proof of non-compliance by inspecting the specific CEMS on board of the ship.

There are possibilities to improve enforcement of compliance also for Tier I and Tier II. The 2008 NO_x Technical Code mentions that quick test measurements should not deviate by more than 10% from the verification test that has become part of the certification process (6.3.11.2), and in no case shall the total granted allowance exceed 15% of the applicable limit value when non-standard fuels are used (standard fuel is ISO 8217, 1996, DM-grade) (6.3.11.3). These verification test results are therefore part of the technical file (2.4.1.5) and have to be stored on board for 3 months (2.3.4) in addition to the test report provided in Appendix V. Whenever a possible NO_x non-compliant ship is observed, an on-board inspection allows inspectors to compare the verification test results and the test report with the remote measurement results. If they deviate more than 15% (taking into account the measurement uncertainty) from the remote measurements, a new valid certification document may be requested or a fine may be

applied. However it must be noted that the test report (Appendix V) includes the overall emission test result and does not specify the NO_x emissions for the individual engine load points, as is the case for the verification test results and relevant for the not-to-exceed (NTE) limits which apply specifically at each individual mode point (Appendix II MARPOL Annex VI) [1]. However, often this data is included in the technical file, but it is not mandatory to do so.

3.2.3. Continuous Emission Monitoring Systems

In almost all cases, abatement technology such as EGCS for SO_x or SCR and EGR for NO_x, use CEMS to control the operation of the abatement system and to ensure compliance with emission limits, as mentioned previously. Consequently, emissions are measured and recorded. By utilizing remote measurements as alerts of potential non-compliant ships, port inspection authorities possess clear indications regarding the time and location of a potential non-compliant ship, thereby significantly enhancing the efficiency of inspections during the port visit of these ships. A notable advantage is that port inspection authorities do not necessarily have to physically board the ship for such inspections, as the log files can be digitally requested from shipowners by the relevant port or coastal State authorities. Furthermore, authorities may issue a public notice of non-compliance, after which the burden of proof shifts to the ship owner to demonstrate due diligence and the implementation of adequate measures to mitigate pollution.

An example of such a case was presented at NSN23 by Belgium, involving a large container ship. Based on airborne measurements the ship was found to be in a state of non-compliance in the Westerschelde (with a FSC ranging from 1.69% to 1.94%). Following a thorough examination of the EGCS log files, the competent authorities reached the conclusion that the ship had been in violation for a duration exceeding 9 hours, as evidenced by the SO_2/CO_2 ratios ranging from 69 to 90, whereas the limit is 4.3 (Art 1.3 Guidelines for EGCS) [14]. Subsequently, a public notice of non-compliance was issued. In response, the ship owner contended that the non-compliance was due to a technical malfunction, as specified in MEPC 1/Circ.883 [59]. It was asserted that the risk for a blackout was unacceptably high in inland waters. Remedial measures were undertaken post-arrival at the port, leading to a switch to compliant fuel in order to rectify the non-compliance. Furthermore, precautions were implemented to prevent the reoccurrence of such issues in the future, including the provision of additional spare parts on board. The maritime authorities concluded that "due diligence" was therefore demonstrated. Nevertheless, in this particular case, the port State authorities were not notified of the non-compliance, contravening the stipulations set forth in the guidelines outlined in Article 12 of MEPC 1/Circ.883 [14,59]. Since these guidelines had yet to be incorporated into Belgian legislation, no further legal action could be pursued.

3.2.4. MARPOL Annex VI compared to other MARPOL Annexes

The North Sea became a special area for MARPOL Annex I in 1999, prohibiting oil discharges above 15 ppm [60]. Oil appearance has been studied since the 1930s, with more research in the 90s and early 2000s showing that visible oil has a concentration above 100 ppm or 50 ppm in calm weather and that oil colors can be used to estimate thickness [61–65]. The Bonn Agreement Oil Appearance Code, used since 2004, standardizes volume estimations using color and thickness [66–69]. MARPOL Annex II, Regulation 13 categorizes noxious liquid substances into X, Y, and Z substances, prohibiting the discharge of X substances; requiring special discharge conditions for Y substances; and permitting the discharge of Z substances, in MARPOL Annex II special areas like the North Sea [70–73]. Annex V applies to solid waste, garbage and cargo residues, with the North Sea declared as a special area in 1991, prohibiting certain discharges, except under strict conditions [74,75].

The decrease in observed oil pollution is partly due to stricter international regulations, but also largely to rigorous enforcement at sea, which includes airborne and other remote surveillance programs. Remote

measurements are commonly used to detect MARPOL Annex I, II, and V violations in the North Sea based on the BA protocols. Potential illegal discharges detected through airborne surveillance lead to PSC inspections and possible legal proceedings. However, in some cases, a PSC investigation may not be possible and the flag state is therefore informed. On the other hand, a PSC inquiry may not always be essential and in some cases, it may even jeopardize the legal process. An exemplary case in this regard, was a well-documented substantial MARPOL Annex I discharge in Belgian territorial waters committed by a large bulk carrier, who was acquitted due to an inconclusive port investigation (Figure S.3). Of a total of 51 observed MARPOL Annex I, II, and V violations verbalized by MUMM or reported by MUMM to the coast and port State authorities of neighboring countries, 18 cases resulted in legal proceedings of which 6 without PSC investigation: two Annex I, two Annex II and two Annex V cases. However, a penalty was only imposed for two observations and it was not possible to obtain the results from the other cases. It is important to note that only one-third of all observations occurred in Belgian waters, underlining the need for regional cooperation.

In neighboring countries, other interesting cases were reported. In the Netherlands in the last 5 years, nine cases were followed up without PSC investigation. The success of the legal proceedings was highly positive, with 8 out of the 9 cases resulting in penalties with fines ranging from 15,000€ to 20,000€, and with one case still ongoing (Table 1).

Table 1. Legal proceedings of marine pollution based on airborne observations as the only legal evidence.

Country	Marpol Annex	Total cases	Conviction/ settlement	Dismissal	Acquitted
Belgium	Annex I	2		Unknown	
	Annex II	2	1	1unknown	
	Annex V	2	1	1unknown	
Netherlands*	Annex I	1		Ongoing	
	Annex II	6	6		
	Annex V	2	2		

* Data from 2018-2022

Although the list of successful legal proceedings is limited, this list shows that sound scientific research, combined with well-established and accepted standardized operating procedures (SOPs) and remote sensing information can be used as solemn legal evidence in successful legal proceedings dealing with marine pollution. In addition, France reported one specific case (NANDO case in 2007) were the PSC investigation was not in line with the airborne observations, but still resulted in a successful conviction and a penalty of 400.000€ [76]. At NSN23 France presented a case where it is pursuing the use of satellite remote data as sole evidence for the legal follow up of an illegal discharge of a chemical substance (MARPOL Annex II). In contrast to the other BA CPs, Germany emerges as an exceptional example. While it is technically true that, as per Section 224, Paragraph 2 of the German Code of Criminal Procedure, courts are permitted to consider any form of evidence in constructing a decision. However, both criminal or administrative proceedings will not be deemed legally valid without the conclusive findings obtained from a port State investigation. This requirement applies not only to violations concerning MARPOL Annex VI but also includes all infractions associated with MARPOL. Consequently, Germany does not recognize the utilization of remote measurement data or visual observations as singular evidence for establishing culpability.

3.3. European directives

3.3.1. EU Sulphur Directive and Commission Implementation Decision

The EU Sulphur Directive and the associated Commission Implementation Decision primarily focus on the responsibilities of port inspection authorities and are specifically tailored to on-board inspection

measures. Consequently, these legal instruments do not conclusively describe the use of remote monitoring as admissible legal evidence. Nonetheless, remote monitoring alerts are recognized as a valid basis for conducting on-board inspections and fuel sampling. Additionally, in terms of enforcing EGCS regulations, remote monitoring alerts offer precise information about the location and timing of potential violations, thereby enhancing the efficiency of investigations into EGCS-related infractions. This is an important advantage in cases of EGCS violations, since log files must be retained on board for a period of 18 months (Art 7.4, Guidelines for exhaust cleaning systems) [53]. This extended timeframe enables the tracing of possible violations long after they have occurred, in contrast to violations related to fuel usage.

3.3.2. Ship Source Pollution Directive

As previously stated, the revised SSPD will only include violations of MARPOL Annex VI pertaining to water discharges [22]. Consequently, this new directive will offer limited opportunities for utilizing remote monitoring as admissible legal evidence. Nevertheless, in specific scenarios, airborne monitoring may yield substantial evidence for legal actions in accordance with this directive. For instance, when EGCS ships are observed within inland waters, remote measurements indicating the utilization of the EGCS in open loop mode could be utilized as legal evidence. Considering that EGCS violations are primarily linked to air pollution, and the difficulty in detecting violations concerning discharges into the sea, it is expected that such specific occurrences will be rare. Consequently, the reporting of MARPOL Annex VI violations associated with water discharges under the Ship Source Pollution Directive (SSPD) is likely to be ineffective.

3.4. Belgian national legislation

In accordance with Belgian legislation, the Federal Public Service (FPS) Mobility and Transport, which serves as the Belgian maritime authority, holds the authority to use any form of evidence to initiate an investigation. If the evidence is deemed compelling, the section for administrative penalties has the possibility to impose an administrative fine. However, the accused party possesses the right to appeal to this administrative penalty, leading to the transfer of the case to a civil court. Therefore, it is crucial to exercise caution, as convincing a civil court to consider remote measurement data as the sole valid evidence may pose challenges. It should be noted that, although legally permissible, to date, the FPS Mobility and Transport has not imposed sanctions solely based on remote measurement data.

3.4.1. Thresholds

For legal prosecution based on nominal evidence (i.e. lab analysis), often a confidence interval is used to express the uncertainty. The most used confidence intervals for legal prosecution are 95%, 99% and 99.9% [77]. The confidence levels describe the risk of Type I errors, i.e. the probability of false positives or in this case the risk, defined as "α", of a ship being considered falsely non-compliant [57,77,78]. The probability needs to be divided by two because a Type I error can only happen when the value falls below the legal limit. In the event of an error in the opposite direction, the ship would still be non-compliant.

$$\alpha = \frac{(\mathrm{CI} - 1)}{2} \tag{1}$$

False negatives, also known as Type II errors, are unfortunate but their consequences are comparatively less severe. When composing the airborne measurement thresholds, different confidence intervals (CIs) were used to create the color flags. The yellow flags were intended to provide alerts with a low confidence interval of 68%. The reason these low confidence flags were included, was to provide low priority alerts to port inspection authorities to be investigated in absence of other alerts. The orange flags with a confidence interval of 95% were created to provide high reliable alerts for port inspection authorities to

investigate with a high priority. The goal of the red alerts with a confidence of 99% was not only to provide high priority alerts for gross emission violations, but also to pave the way for using these red alerts for legal follow up. It should be mentioned that the CIs reflect the lowest level of the threshold color flag, when the value is above the threshold, the CI also increases.

In other words, a measurement of 0.3% FSC is considered non-compliant with a confidence interval of 99%. This means that the probability of the ship being compliant is less than 0.5%. A ship that is measured at 0.4% FSC on the other hand has an actual CI of 99.99% of being non-compliant meaning there is only a 0.005% probability that the ship is compliant. To avoid the need to calculate the CIs for every non-compliant measurement, uncertainty levels are calculated based on the minimum CI of a threshold color flag. Furthermore, it can be noted that for the case of airborne measurements, it is possible to conduct multiple measurements, which further decreases the uncertainty substantially [79].

4. Recommendations for improved regulation

This section presents a series of recommendations aimed at enhancing the utilization of remote monitoring data for legal action regarding MARPOL Annex VI violations and to enhance the effectiveness of the current measures in reducing ship-generated air pollution. Most of these recommendations have emerged from scientific and strategic discussion within the BA Working Groups, while some have already been proposed in other forums or projects, notably the Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations (SCIPPER) project [56]. Furthermore, it is important to note that certain recommendations have already been deliberated within the subsidiary bodies of the IMO [80].

4.1. Recommendations for IMO regulations

4.1.1. Exhaust gas cleaning systems (EGCS)

Ships equipped with EGCS have proven to present challenges for inspections in ports [79,81]. Moreover, when these ships are found to be non-compliant, the emission levels are considerably higher than non-EGCS ship [78,79]. Furthermore, it has been observed that CEMS logs do not always reflect the actual emissions, often the logs contain zero values or unreliable results [79]. As the inspection of EGCS-ships fully relies on the evaluation of the log data, questions can be raised on the trustworthiness of the inspection protocol. EGCS have to follow a maintenance scheme and the CEMS are regularly calibrated. However the results of the calibration and maintenance is not part of the mandatory reporting of non-compliance. Therefore, an EGCS- ship might be non-compliant for a substantial period of time before it becomes compliant again. The ships' non-compliance during this period can however not be examined nor be enforced. It can therefore be recommended that a clear assessment of the ships non-compliance be carried out before maintenance and calibration is executed by an independent classification society, which should be reported to the flag State and stored on board of the ship. In addition, the guidelines fully rely on the logged emission data end do not describe an enforcement mechanism for PSC to verify if the logged data is reliable [14]. As remote measurement methodologies applied by fixed stations and mobile platforms are using the same methodology as EGCS. The use of remotely calculated SO_2/CO_2 ratios should be recognized as a valid remote monitoring mechanism for PSC. Finally, it is advisable to require EGCS-ships to carry out regular tests of the EGCS CEMS system for a certain time, by using ultra-low sulfur fuel oil (ULSFO) in the ECA or very low sulfur fuel oil (VLSFO) outside the ECA and compare the SO_2/CO_2 ratios with the expected ratio (e.g. a ratio of 4.3 for a ULSFO with an FSC of 0.1%). When the ratio differs substantially from the expected ratio, a maintenance and recalibration should be performed. The results of the CEMS logs are stored on board for 18 months (Art 7.4, Guidelines for exhaust cleaning systems) [53]. If these real sailing tests are conducted at regular intervals, properly recorded in the logbook and identifiable in the CEMS logs, this would provide port inspections

a proper tool to assess the real sailing emissions and evaluate whether appropriate action has been taken to correct any anomalies or malfunctions.

4.1.2. Describe FSC compliance check based on the remote monitoring of SO_2/CO_2 ratios

The use of SO_2/CO_2 ratios to calculate the FSC is recognized by MARPOL Annex VI regulation 13 to verify the compliance of EGCS-ships. The same practice can very easily be transposed to non EGCS-ships, but this requires amending MARPOL Annex VI Regulation 13.

4.1.3. Limit the time difference between keel laying year and built year

It has been noticed that some ship owners have exploited the definition of the KLD to delay the implementation of Tier III [57]. Based on the Global Integrated Shipping Information System (GISIS) from IMO (GISIS) and EMSA's Thetis-EU data, it was observed that 79% of the planned and constructed ships between 2021-2025 have a KLD prior to 2021. The average time between KLD and built year increased from 1.15 years in 2015 to 3.91 years in 2023 (Figure S 4).

Certain BA CPs have taken steps to decrease the chances of ship owners registering ships with a KLD prior to 2021 and constructing them post-2021 by implementing a maximum period between the KLD and the construction year (Table 2). Belgium is however the only CP to have already implemented this in its legislation [47]. Since this decision is the responsibility of the flag State, it cannot be enforced by the port State during port inspections of other flags. Consequently, it is advised to establish a universal maximum time limit for the duration between the KLD and the year of construction (e.g., 5 years). Should this time limit be surpassed, the ship in question must comply with all relevant regulatory obligations corresponding to the year of construction subtracted with the implemented maximum time difference. Within the BA, in addition to Belgium, France and the Netherlands are also in favor of more prescriptive regulations for the KLY. The legislative process on this matter is already underway in the Netherlands.

Table 2. Current implemented maximum time period between built year and keel laying year for ships under the flag State regime and position against installing a harmonized approach within the BA.

Flag State	Max time (BY-KLD)	In legislation	In favor of BA recommendation
The Netherlands	6 years	Not yet	In favor
Belgium	5 years	Yes	In favor
Germany	No period	-	-
Denmark	No period	-	-
Sweden	No period	-	-
France	No period	-	In favor
Ireland	No info	-	-
Norway	No info	-	-
Spain	No period	-	-
United Kingdom	No period	-	-

4.1.4. Implement mandatory on board continuous emission monitoring systems (CEMS) for NO_x

At present, compliance with NO_x regulations is verified solely through document checks, which are not sufficient to verify actual real-world NO_x emissions during sailing. CEMS are already used for Tier III vessels in combination with abatement technologies like selective catalytic reduction (SCR) and exhaust gas recirculation (EGR). Emission monitoring systems are already used on EGCS-ships, but Tier III lacks guidelines on how to record the emission data. Using CEMS on all ships, including Tier I and Tier II, with well-defined guidelines for the logging of emission data would significantly enhance the enforcement capabilities for inspectors in ports.

4.1.5. Include not-to-exceed limit for Tier I and Tier II

At present, an absolute highest allowable limit, known as the NTE, is established only for Tier III ships. This NTE stipulates that the NO_x emissions for all engine load points may not exceed the applicable NO_x limit by more than 50% (Appendix II of MARPOL Annex VI) [1]. This NTE is very important for the enforcement of Tier III and in particular for the potential use of remote monitoring as an enforcement mechanism, as it creates a clear maximum level independent of the engine load. It must be said that this NTE is only valid for engine loads above the lowest engine load point of 25% (see section 4.1.8). Without an NTE, remote monitoring of NO_x emissions would remain limited to targeting and could only in very rare occasions, when extremely high values are measured, be considered as a reliable enforcement mechanism for legal follow up. In addition, even when guidelines would be included for the mandatory use of CEMS on board of Tier I and Tier II ships, without a NTE these CEMS would still pose significant challenges for verifying compliance in ports. This is because port inspectors would still need to assess the actual weighted average emission over various engine load points to verify compliance. Thus, it is considered crucial to include a NTE limit for Tier I and Tier II engines to facilitate the use of CEMS for enforcement and to provide the possibility to develop a remote monitoring compliance verification mechanism.

4.1.6. Use of NO_x emission factors based on CO_2 or kg fuel

Presently, NO_x emission limits are based on the power consumption of ships, measured in kWh. To evaluate compliance, remote monitoring uses the NO_x/CO_2 ratio to define the emission factors based on fuel consumption. To transform the emission factor to the unit used in the emission limits, knowledge is required on the specific fuel consumption (SFC) expressed in kg fuel/kWh. However, remote compliance monitoring could be made more implementable by utilizing emission factors expressed in g NO_x/kg of burned fuel or NO_x/CO_2, like is the case for EGCS. This recommendation would not require any changes to the existing limits but would need an additional amendment. For deriving the maximum NO_x/CO_2 ratios a default SFC can be applied in combination with a NTE limit. The NO_x/CO_2 ratios with a NTE of 150% and different SFC values for Tier I, Tier II and Tier III are provided in Table 3. It is recommended to use either an average SFC of 0.2 or a low end ratio of 0.16.

Table 3. $NO_x/CO2$ ratios (ppm/% volume) for different SFC (g/kWh) values per Tier with a NTE of 150%.

Tier level	ERS = n (rpm)	NO_x/CO_2 ratio (ppm/%) per SFC (g/kWh)					
		0.24	0.22	0.2	0.18	0.16	0.14
Tier I	<130	319	348	383	425	479	547
	130-2000	$845 \cdot n^{-0.2}$	$921 \cdot n^{-0.2}$	$1014 \cdot n^{-0.2}$	$1126 \cdot n^{-0.2}$	$1267 \cdot n^{-0.2}$	$1448 \cdot n^{-0.2}$
	>2000	184	201	221	245	276	315
Tier II	<130	270	295	324	360	405	463
	130-2000	$826 \cdot n^{-0.2}$	$901 \cdot n^{-0.2}$	$991 \cdot n^{-0.2}$	$1101 \cdot n^{-0.2}$	$1239 \cdot n^{-0.2}$	$1416 \cdot n^{-0.2}$
	>2000	145	158	173	193	217	248
Tier III	<130	66	72	79	88	99	113
	130-2000	$169 \cdot n^{-0.2}$	$184 \cdot n^{-0.2}$	$203 \cdot n^{-0.2}$	$225 \cdot n^{-0.2}$	$253 \cdot n^{-0.2}$	$290 \cdot n^{-0.2}$
	>2000	38	41	45	50	56	64

4.1.7. Describe method for NO_x compliance enforcement through remote monitoring

Research has shown that state-of-the-art remote monitoring methods are capable of measuring NO_x emissions in ship exhausts [57,82–87]. Nevertheless, current regulations do not describe the use of remote measurement data for enforcement purposes. The incorporation of NTE limits and NO_x emission factors based on fuel weight may alleviate these practical obstacles. Additionally, clear guidelines on acceptable remote measurement protocols, including operational and quality assurance methodologies, would

improve the effective enforcement of Annex VI regulations by responsible authorities controlling NO_x regulations.

4.1.8. Revision of the engine cycles to include low engine load and reflect real sailing conditions

Currently, the NO_x emission regulations for main engines are based on four engine loads: 25%, 50%, 75%, and 100% [1,19]. This means that ships operating at an engine load of less than 25% are considered off-cycle, with no restrictions on their NO_x emissions during actual operation. Ships operating in ECAs are usually not far from their port of destination, which often requires sailing at loads under 25% for operational reasons. Also when entering ports, ships operate at low engine loads. Additionally on 1 January 2023, the energy efficiency existing ship index (EEXI) came into force (Reg 23, MARPOL Annex VI), Incorporating the use of engine power limitation (EPL) to optimize energy efficiency, which will encourage ships to operate more often at lower loads [1,88]. In Belgian waters it was observed that 20% of ships are already operating at engine loads below 25%, which means that their NO_x emissions are not regulated. Furthermore, the current weighting factors (WFs) assume that most ships operate at 75% engine load, which is why the 75% engine load has the highest weighting factor (0.5). As a result, ships and engine constructors are less inclined to reduce NO_x emissions at the 25% and 50% engine loads as these loads have lower WFs (0.15). In addition, with modern engines with electronic injection, it is possible to use multiple engine operational profiles (MEOP). With this questionable tactic ships are certified according to different engine cycles and can change the engine settings based on the voyage plan. Although this practice is mainly used to optimize fuel efficiency it also leads to higher NO_x emissions, as ships switch between profiles during their voyage. Hence, vessels employing this MEOP are in practice not abiding to the emission limits. Thereby undermining not only the idea of the weighted average approach but also opening the door for its misuse.

These are some of the factors that have led to newer ships (Tier II) having higher NO_x emissions in the ECA area than older ships [57,82,89]. To address this issue, it is recommended to update the emission cycles with WFs that reflect the real sailing conditions and include a low engine load point. The relevance of these questions is confirmed by the discussions that took place at the 10th session of the IMO Sub-Committee on Pollution Prevention and Response (PPR10) in preparation of MEPC80. During this meeting, the Sub-committee requested to MEPC80 the extension of the output to amend NO_x technical Code in order to address MEOP and test cycles (possibly by adding a new chapter 8 or amending existing chapters). In addition, Canada has submitted a document to MEPC80 inviting it to establish NO_x Tier III test cycles to better reflects real world ship operations within ECAs which is in line with wat is stated here above.[80].

4.2. Recommendations on EU regulations for NO_x enforcement

4.2.1. Include NO_x emission regulations from ships in the EU regulatory framework

Currently there exists no EU NO_x directive to implement the MARPOL Annex VI Regulation 13 in EU legislation. As a result, there are no guidelines nor mandatory number of inspections for NO_x enforcement in the EU. As previously mentioned, discussions were held to include MARPOL and its annexes in the revised EU Directive 2005/35/EC [22]. However, it was currently not deemed beneficial for the SSPD to include air pollution as it would render the directive un-implementable. In addition, NO_x could be considered under the new EU emission trading system (ETS) as it includes non-CO_2 greenhouse gases (GHGs). Currently though only Methane (CH_4) and Nitrous oxides (N_2O) are considered. The exact impact of NO_x as GHG is still debated as the Global Warming Potential (GWP) of NO_x is influenced by the location and altitude of the emissions [90]. For ground source emissions, the average GWP of NO_x over 20 year (GWP_{20}) is 30-33 compared to CO_2, therefore demonstrating a substantial impact on climate change [90,91]. The airborne measurements indicate that average NO_x emissions are 46 g NO_x/kg fuel [57]. With an average GWP_{20yr} of 31.5 $CO_{2\text{-eq}}$, this would mean that

NO_x emissions from ships have a GWP_{20yr} in the order of magnitude of 45% of their CO_2 emissions. However, about 1% of the observed ships exceed 30 g NO_x/kWh [57]. For these ships the GWP_{20yr} of their NO_x emissions exceeds their CO_2 emissions. It's worth noting that the GWP of the NO_x emissions from ships far exceed the GWP attributed to their N_2O emissions, which in contrary to NO_x, are considered in the revised ETS, and yet are projected to represent only approximately 1% of the GWP_{20yr} compared to NO_x. [28,92,93]. Including NO_x in the ETS would therefore provide a powerful incentive for businesses and industries to reduce their emissions. Moreover, as NO_x is a transboundary pollutant that can travel long distances and affect air quality in neighboring countries, its inclusion in an ETS can also help promote international cooperation and coordination in reducing emissions.

4.2.2. Include NO_x in Thetis-EU

At this moment NO_x data are not included in the Thetis-EU platform as there is currently no EU Directive in place for NO_x emissions from ships. Including NO_x in the Thetis-EU platform can provide a comprehensive and transparent mechanism for reporting NO_x emission alerts and increase inspections across the EU, as demonstrated for the sulfur regulations. This would allow better enforcement and improve ships' compliance with international emission regulations. Moreover, the inclusion of NO_x in Thetis-EU can help to identify areas of non-compliance and support the development of targeted policy measures to reduce emissions from ships. This can lead to more effective and efficient reduction strategies.

MS can agree to request EMSA to include certain NO_x data attributes under Thetis-EU and allow MS to submit voluntary NO_x data. OTSOPA23, agreed to request EMSA to include a list of variables under Thetis-EU (Table S.4).

But the exchange of NO_x remote measurements is not all what EMSA could do to improve the enforcement of NO_x emission regulations. EMSA could also use the Thetis-EU database to exchange important information to be used to facilitate NO_x monitoring. The first being the inclusion of the KLD in the database, as this is very important to obtain the exact Tier level. In addition, EMSA could use the Thetis-EU platform to compile a list of engine parameters (ERS, total power, maximum speed,...) and even provide dedicated engine factors, which monitoring agencies can use to calculated a modelled SFC (kg fuel/kWh), actual power (kW) and the engine load (%). This will require a great deal of work and resources and will necessitate the adoption of a European directive on NO_x.

5. Conclusions

This article takes a critical look at the potential use of remote ship emission measurements as evidence in legal proceedings related to ship emission violations. The findings indicate that while international regulations regarding SO_x do not explicitly exclude the use of remote measurements for assessing compliance, the current International and EU regulations do not incorporate remote measurements as established evidence for legal proceedings and need to be amended in order to do so. That being said, onboard emission measurements are included within the EGCS guidelines. This article proposes the inclusion of a standardized remote monitoring methodology, aligned with the procedures outlined in the EGCS guidelines. The article emphasizes the importance of exercising caution when imposing sanctions based on remote measurement to mitigate the risk of Type I errors, where compliant ships are wrongly deemed non-compliant. To reduce this risk to an acceptable level, it is recommended to use high confidence intervals (e.g. 99%) in remote measurements intended for use in legal proceedings.

This article further demonstrates that in the context of NO_x emissions, a legally recognized methodology for verifying actual ship emissions by port inspection authorities does not exist yet. Consequently, remote measurements can serve as a valuable instrument, not only for evaluating compliance patterns across various regions, but also for addressing the existing lack of enforcement measures regarding real-world

NO_x emission violations. This article recommends to draw practical guidelines for monitoring NO_x emissions during navigation by means of continuous emission measurement systems. The article also draws attention to the lack of an EU regulatory framework on NO_x. The experiences from the EU regulations on SO_x emissions have demonstrated that EU regulations can be very effective in tackling ship emissions and creating an enforcement framework for EU MS' port State authorities. It is therefore strongly recommended that decisive action is taken at EU level to address NO_x emissions from ships.

Moreover, the article describes the existence of certain regulatory gaps related to air pollution from ships, some of which were already highlighted by previous studies. The present article puts forth multiple recommendations aimed at addressing these regulatory gaps and to enhance the effectiveness of existing international ship emission regulations that prevent or reduce air pollution. The article highlights the important potential of using remote monitoring of ship emissions for expanding the enforcement capacity of the port State and coast State for MARPOL Annex VI. The recommendations put forth in this article provide important practical monitoring and enforcement guidelines and suggest improvements to the current emission regulations which, when adopted, would contribute to further reducing the adverse environmental and human health impacts from shipping.

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7. Supplementary material

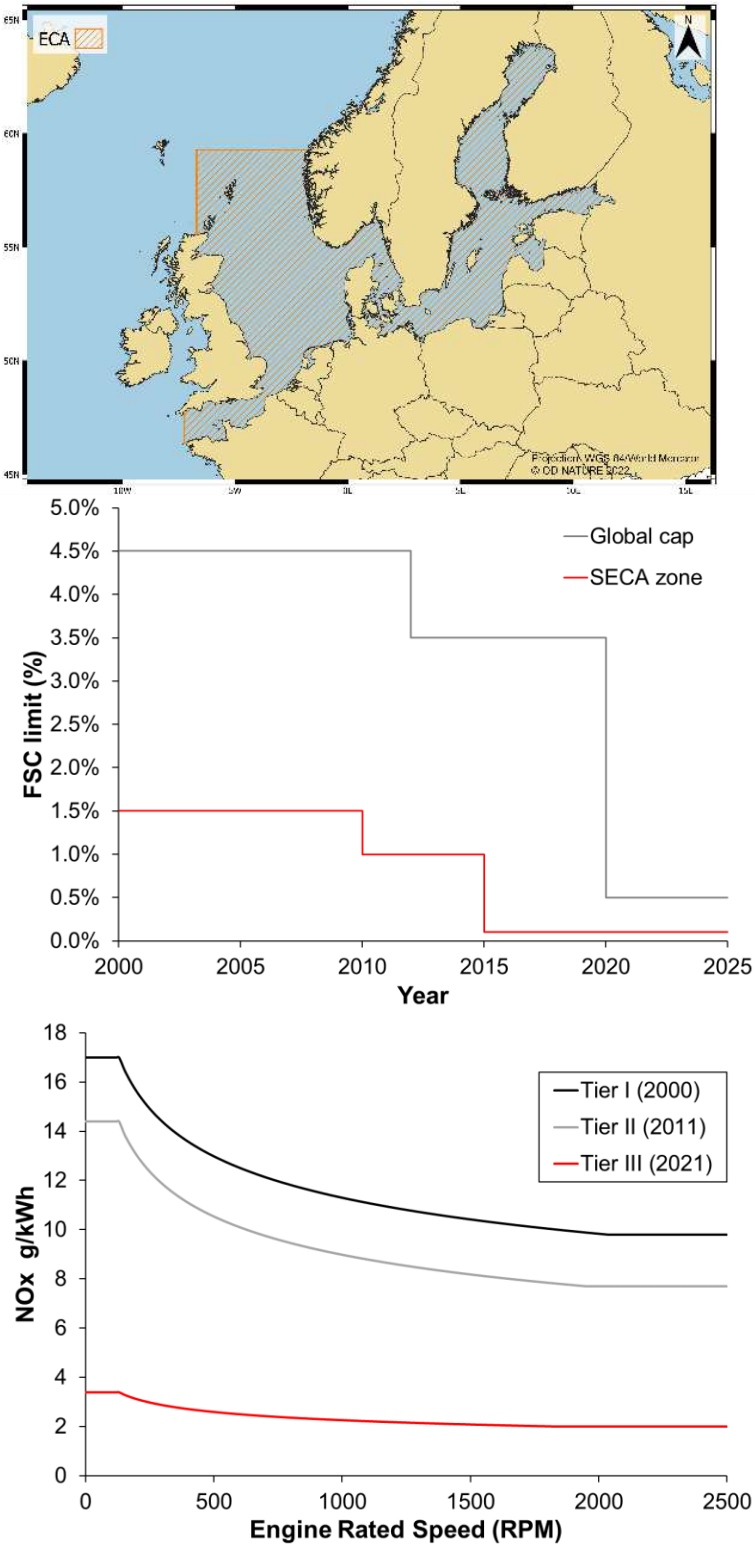


Figure S.1. Upper: Emission Control Area (ECA) as defined by MARPOL Annex VI. Middle: Limits on the fuel sulfur content of marine fuels according to the MARPOL Annex VI Regulation 14. Lower: NOx emission limits according to MARPOL Annex VI Regulation 13 [1].

Figure S.2. Organigram of the Bonn Agreement.

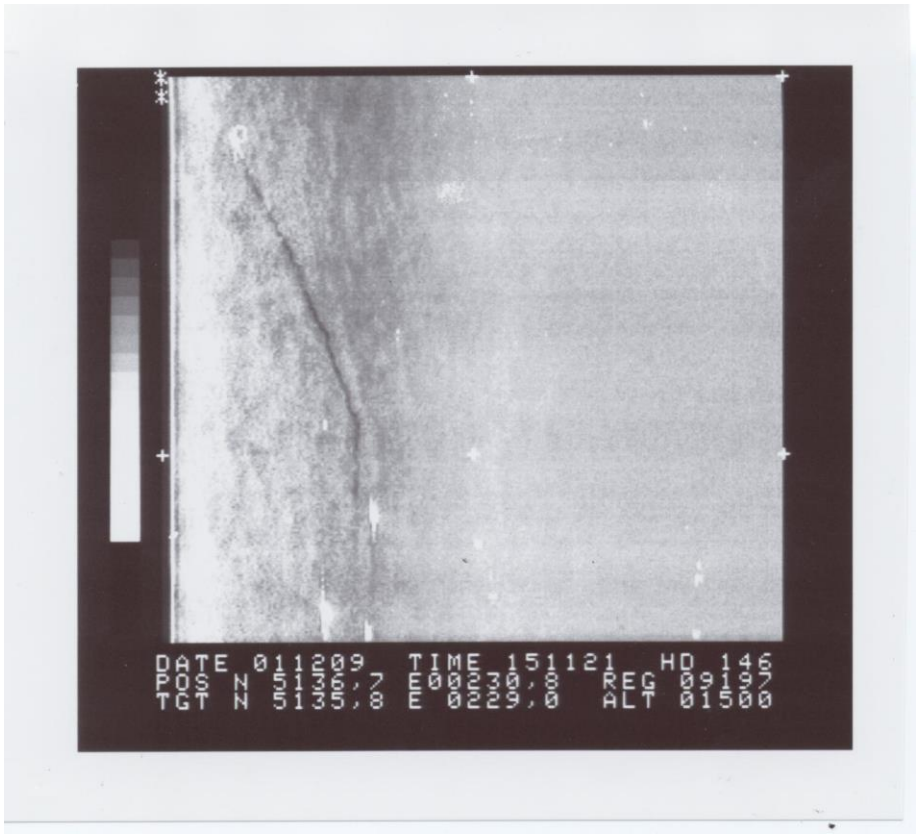

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Figure S.3. Pictures of the observed pollution from the KAPITAN KUDLAY. The radar image and photographs clearly demonstrate the type and extent of the discharged substance (oil).

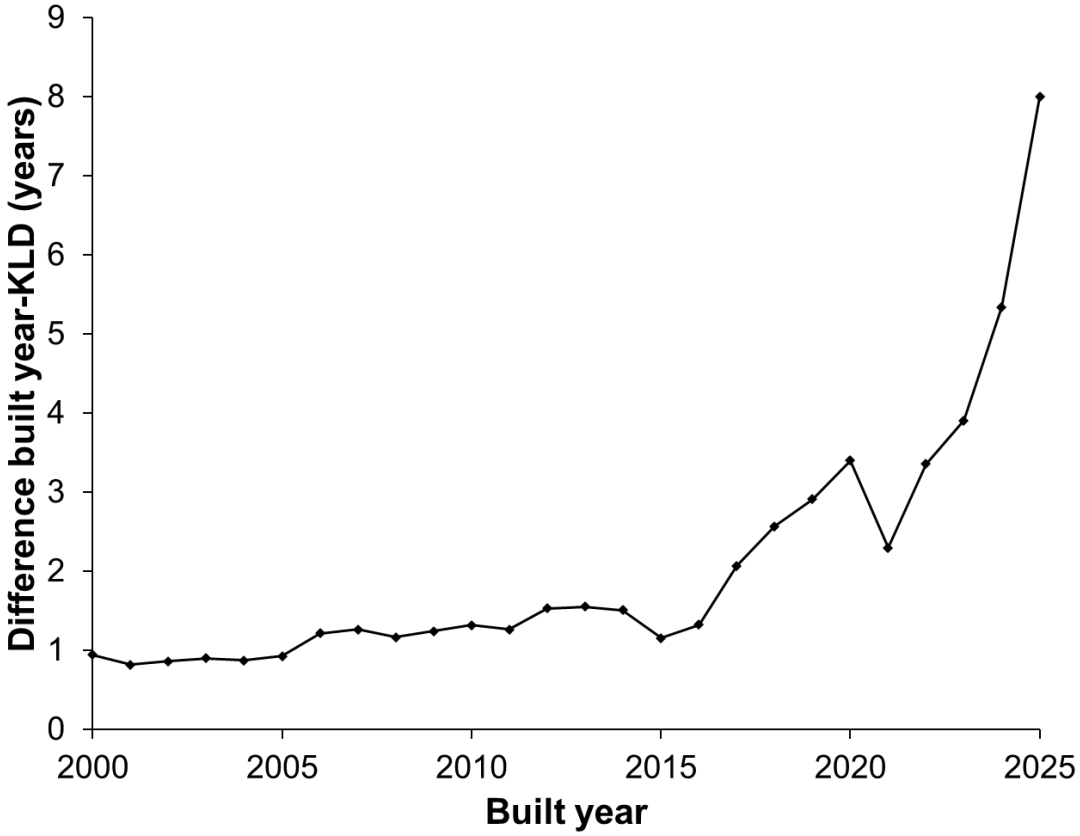


Figure S 4. Evolution of time difference between year built and KLD [89].

Table S.1. Test cycles and weighting factors according to the NO_x Technical Code [19].

E2	Speed	100%	100%	100%	100%
	Power	100%	75%	50%	25%
	WF	0.2	0.5	0.15	0.15
E3	Speed	100%	91%	80%	63%
	Power	100%	75%	50%	25%
	WF	0.2	0.5	0.15	0.15

Table S.2. Applied thresholds for FSC and NOx compliance monitoring [79].

			FSC		NO_x		
Color flag	CI	σ	$T_{ops\ <\ 2020}$ (%)	$T_{ops\ >2020}$ (%)	$T_{ops\ Tier\ I}$ (g NO_x/kWh)	$T_{ops\ Tier\ II}$ (g NO_x/kWh)	$T_{ops\ Tier\ III}$ (g NO_x/kWh)
Yellow	68%	1	0.15	0.13		20	6
Orange	95%	1.96	0.20	0.20	35	30	8
Red	99%	2.576	0.40	0.30	55	45	9

Table S.3. Emission ratios for EGCS systems [14].

Fuel oil sulfur content (% m/m)	Ratio emission SO_2(ppm)/CO_2(% v/v)
4.5	195
3.5	151.7
1.5	65
1	43.3
0.5	21.7
0.1	4.3

Table S.4. Variables recommended to be included in Thetis-EU to exchange NO_x remote measurements.

Variable	Unit
NO_x EF measurement	g/kg fuel
NO_x measurement	g/kWh
Fuel Consumption	metric ton/hr
Used method	Empiric/modelled
Power use	kW
Used method	Empiric/modelled
Total Power	kW
Engine load	%
Rated Engine Speed (n)	rpm
Specific Fuel Consumption (SFC)	g fuel/kWh
Tier- level	0,I,II or III
NO_x uncertainty (with σ = 1.96)	g/kWh

General Conclusions



RBINS-MUMM © State Secretary for Science Policy Thomas Dermine visiting the OO-MMM and its crew 16/05/2023

"It always seems impossible until it is done."
– Nelson Mandela

"Success is not final, failure is not fatal: It is the courage to continue that counts."
– Winston Churchill

"Fall seven times and stand up eight."
– Japanese Proverb

General Conclusions

The shipping industry plays a crucial role on the global stage, connecting economies and cultures around the world [1]. However, it is also one of the biggest contributors to global air pollution [2]. In response, there have been global efforts made to establish regulations that reduce ship emissions [3]. Nevertheless, it can be argued that without an effective enforcement strategy, regulations remain mere words on paper. This was the underlying reasoning for writing this doctoral dissertation titled:

"*Application of remote measurements for compliance monitoring and enforcement of SO_2 and NO_x emissions under MARPOL Annex VI*".

This doctoral dissertation analyses the feasibility, added value and cost efficiency of using airborne measurements to detect SO_2 and NO_x emission violations from ships. Additionally, the measurements were used to answer the question of whether the applicable MARPOL Annex VI regulations have had an impact on air quality in Belgium and the wider European Emission Control Areas (ECAs). Finally, some recommendations on regulations are formulated for policy makers. In these general conclusions, a helicopter view is provided based on the various parts of the dissertation. This thesis outlines the various stages involved in establishing a monitoring and enforcement strategy for ship emissions regulations in Belgium and the Bonn Agreement (BA). It focuses on the airborne monitoring operations that are conducted by the Belgian coastguard aircraft, serving as a common thread throughout the research. The first part, which is made up of three chapters, focuses on the technological and methodological aspects of airborne emission measurements from ships. The second part, which contains one chapter, analyzes the effects of the airborne monitoring efforts on port inspections. The third part, made up of two chapters, explores the impact of international regulations on air quality in Belgium and the broader ECA region. The final part, consisting of two chapters, describes the efforts undertaken to establish a monitoring strategy for the BA and offers recommendations for improving the current international legal framework (Figure 1).

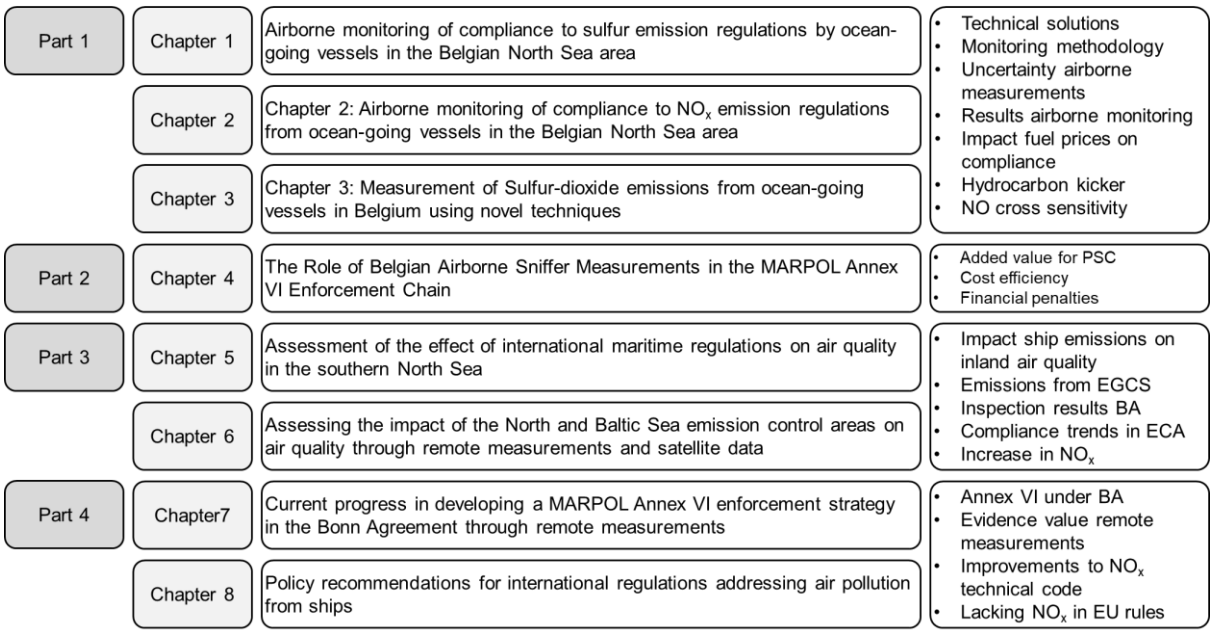


Figure 1. Overview of the different chapters of the dissertations.

1. Methods for airborne ship emission monitoring

Part 1 of the dissertation is divided into three chapters, which focus on the technological aspects of airborne monitoring methodology for measuring SO_2 and NO_x emissions in an operational setup. The three different chapters provide uncertainty calculations and quality assessment based on a harmonized approach. The methodologies, uncertainty calculations, maintenance procedures and data management are described in the Sniffer Quality Management System (see Supplementary Material).

Based on input from port inspectorates in Belgium and the Netherlands, it became clear that not only the alerts with the highest degree of certainty are of interest for targeted inspections by port inspection authorities, but that targets with a lower degree of certainty can also be of interest in the absence of other indicators of non-compliance. However, it is considered impractical to provide detailed information on the level of non-compliance, its quality and the confidence interval used. Instead, a more concise reporting mechanism, based on a four-color flag system, is developed in cooperation with the Belgian port inspection authorities. The colors (green, yellow, orange and red) indicate not only the level of non-compliance, but also reflect the degree of uncertainty and relate to the emission limits defined by Belgium authorities to initiate legal follow-up by port inspection authorities. While this system works well at national level in Belgium, it might not be the best approach for implementing a regional harmonized reporting mechanism [4].

The quality of the measurements is not quantified but is assured based on clearly defined minimum quality standards for emission measurements, according to the recommendations of the SCIPPER project [4]. These standards include: the successful linking of a plume to a ship, a comparable response time, sufficient sampling times for all gas sensors, a good signal to noise ratio and no interference from land-based sources or other pollution sources. The research conducted in these three chapters demonstrates that by applying a sufficient uncertainty margin, the developed methods could ensure high-quality measurements for gross polluters (red flags) with a certainty that is beyond reasonable doubt. This means that these red flags can scientifically qualify for legal prosecution or administrative sanctions.

Chapter 1 contains the results of the fuel sulfur content (FSC) measurement over the period 2015-2019, the average measured FSC was 0.10% FSC which is identical to the legal limit. Thus, suggesting that, although numerous ships exceed the regulated limits, the shipping industry in general demonstrates a good compliance to the regulatory provisions. The overall compliance rate in that period was 92%. The number of possible non-compliant ships observed decreased significantly, and the severity of non-compliance also reduced over the researched period (Figure 2A). However, it is essential to note that 8% of the ships monitored at sea were prone to be in violation, highlighting the need for effective enforcement and the alerting of potential offenders for port inspections. The research could not identify clear patterns of violators, but it did show that more non-compliance occurred at sea than in ports. In addition, cargo ships such as container ships were more often found to be non-compliant than tankers (Figure 2B). An explanation why container vessels were more prone to be in violation was not formulated in the article. However, Svein Erik Enge of the Norwegian Maritime Authorities suggested that a different carrier strategy could be at the basis of this difference, where time charters are more often used by tankers and voyage charters are more used by containers. As the fuel cost of time-chartered vessels is at the charge of the charterer and the fuel cost of voyage-chartered vessels are borne by the ship owner, this provides a possible explanation for the observed difference in compliance behavior. It should be noted that in Chapter 5 of the dissertation, the data for the period 2015-2019 was recalculated to eliminate the NO cross sensitivity and correct for the measurement bias, resulting in an average FSC of 0.083% FSC and a non-compliance rate of 9.2%

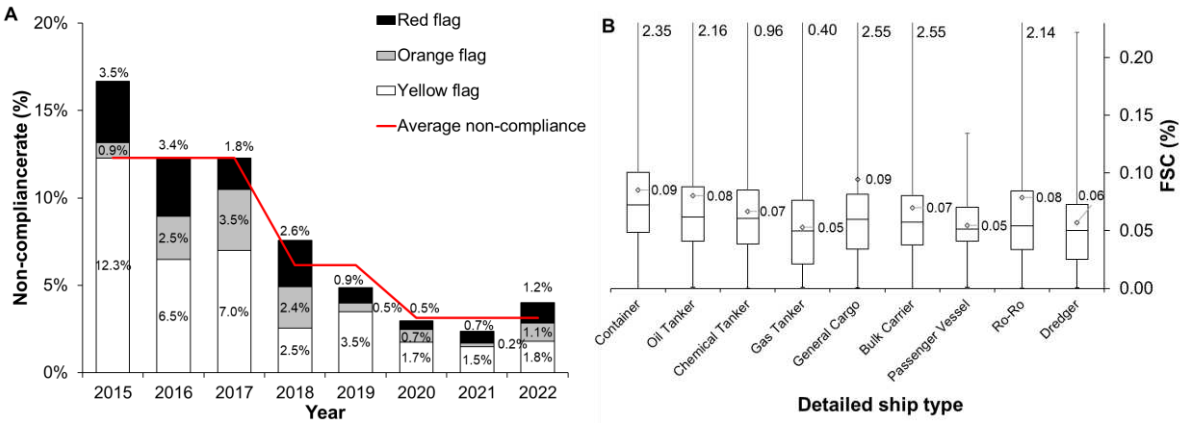


Figure 2. Overview of FSC compliance rate (A) and FSC emission factors per ship type (B) over overall period of the dissertation (2015-2022).

Chapter 2 examined NO_x emission levels and compliance with NO_x emission regulations. This was particularly important as enforcement of NO_x emission regulations in ports is currently limited to document inspections. As the NO_x emission measurements are more complex compared to the SO_2 emission measurements, the measurement methodology needed to be expanded and a large set of thresholds was defined based on different factors impacting the emission limits, such as the keel laying date (KLD), the engine rated speed (ERS) and the engine load. The research demonstrates that the updated airborne monitoring methodology for NO_x emission measurements is scientifically proven and reliable, and therefore provides opportunities for the enforcement of real-world NO_x emissions from ships at sea.

The research covering the period 2020-2021, found that predetermined emission reductions for Tier II ships, as described in MARPOL Annex VI Regulation 13, were not realized. Although, the average NO_x emission factor was with 13.0 g/kWh under the described maximum emission limits for both Tier I and Tier II ships; it was higher than the results from previous benchmark studies, which was based on on-board measurements [5]. Moreover, Tier II ships are found to have significantly higher NO_x emission levels and are more frequently found to be non-compliant. These results have implications on pollution models that may use underestimated NO_x emission factors [6]. The study also shows that average NO_x emission factors do not differ significantly between 2020 and 2021, demonstrating that shipowners have not changed their behavior since the entry into force of the North Sea NECA in 2021. For this chapter TROPOMI satellite data are also analyzed, showing a notable reduction of NO_2 levels in the northern part of the North Sea in 2021 compared to 2020. Although this reduction coincided with the introduction of the NECA, it is unclear if this reduction can be attributed to the NECA implementation. Again, it can be noted that the results were updated in later chapters. Chapter 5 provides updated emission information. These updated figures confirm the observed trends and previous findings, the average NO_x emission factor for 2022 even increased to 13.9 g NO_x/kWh which is due to the increased share of Tier II ships from 36% to 40% in 2022 (Figure 3). Chapter 6 contains updated satellite analysis that delves deeper into the impact of the implementation of the NECA on NO_x air pollution levels.

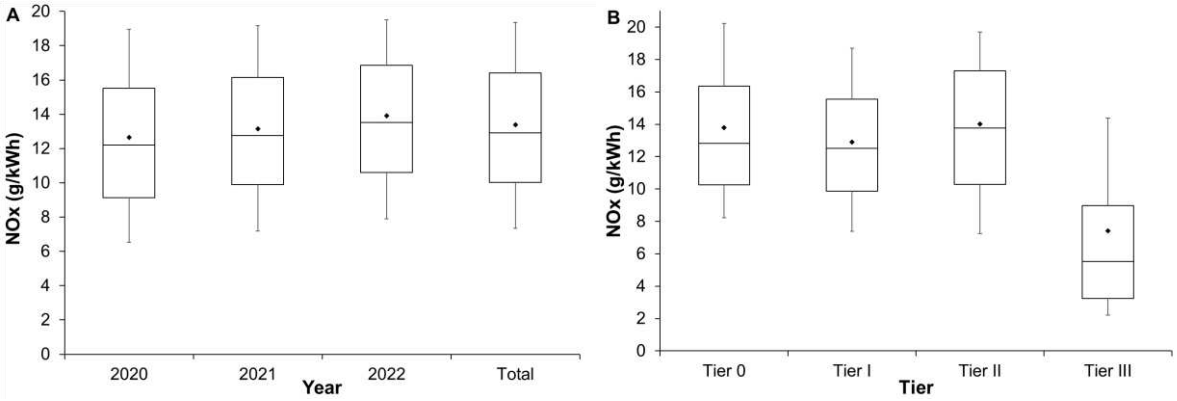


Figure 3. Average NO_x emission factors per year (A)and per tier (B)

Chapter 3 of Part 1 described modifications to the measurement techniques that substantially improved the methodology for monitoring SO_2 emissions from ships. The air pump was replaced by a more powerful model, the NO_x sensor allowed to remove the NO cross sensitivity [7], a custom-made high-volume HC kicker was added to remove the VOC interference, and with a plume simulation mixture the sensor bias was eliminated. Thanks to these novel techniques, the measurement uncertainty is reduced, and compliance thresholds are lowered to 0.13% FSC for yellow flags and 0.3% FSC for red flags.

Furthermore, it was observed that the compliance levels for 2020–2021 are significantly higher than for 2019, with an overall compliance rate of 97.3%, compared to 95.9% in 2019. However, the actual improvement in compliance is even higher due to the difference in applied thresholds and measurement bias. This improvement in compliance coincides with the implementation of the Global Sulfur Cap in January 2020, though the collapse of fuel prices in 2020 and the monitoring and enforcement activities conducted by different European member states also played a role. Nevertheless, concerns regarding gross polluters continue to persist, leading to a specific focus on EGCS (Exhaust Gas Cleaning System) ships. These ships attract particular attention due to their higher mean FSC and non-compliance levels.

The average FSC for 2020 was lower than for 2021, this can be linked to a low price spread between very low sulfur fuel oil (VLSFO) and low sulfur marine gas oil (LSMGO) in 2020. The war in Ukraine creates an unprecedented high price spread, therefore it was suggested at the start of 2022 that non-compliance in 2022 could increase again, and indeed, the 2022 results described in Chapter 5 and Chapter 6 confirm this predicted increase in non-compliant vessels in Belgium and other BA CPs.

In conclusion, Part 1 of the dissertation provides a scientific basis for using airborne measurements as legal evidence for sulfur emissions and demonstrates the reliability of the airborne sniffer monitoring methodology for sulfur and NO_x emissions measurements in an operational setup.

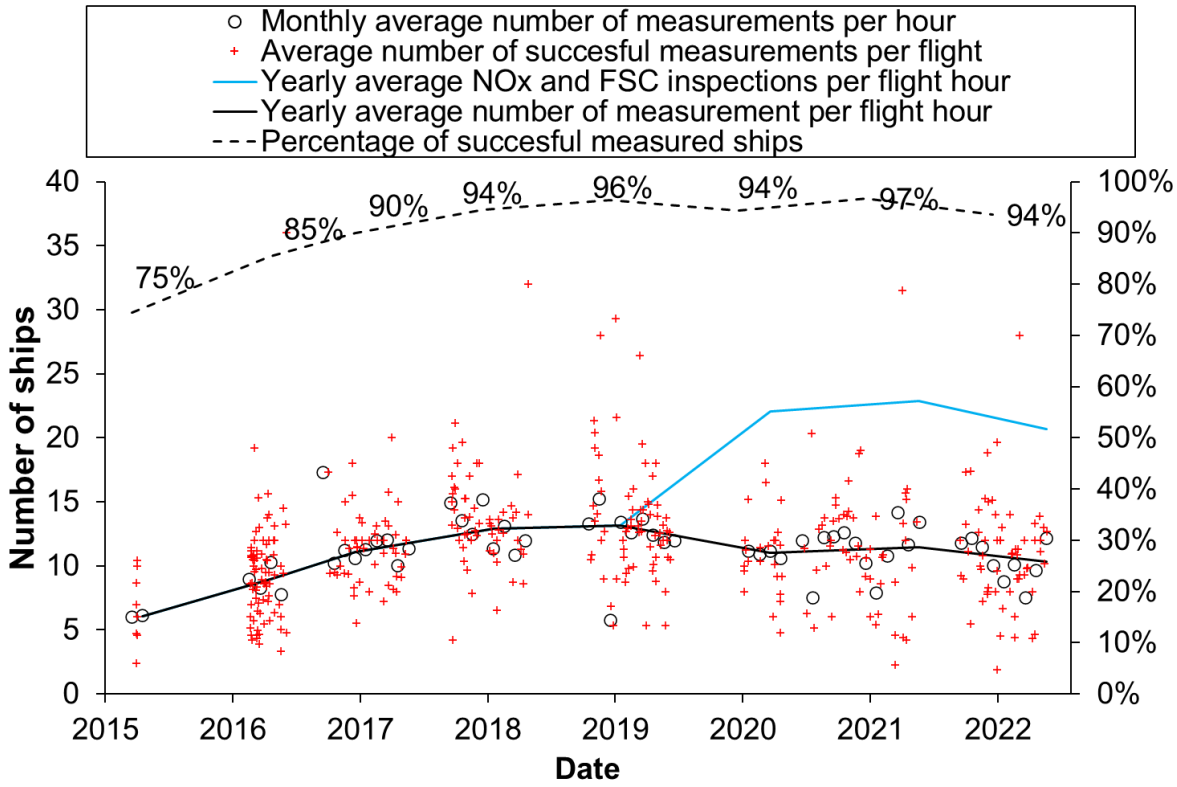


Figure 4. Overview of measured ships in relation to the flight time and the success rate of the measurements attempts over period covered in the dissertation.

2. Improving port inspections using airborne measurements

Chapters 1-3 have demonstrated the technical possibilities of using airborne monitoring techniques for the monitoring of MARPOL Annex VI Regulations 13 and 14. In Chapter 4, the added values of airborne monitoring for the enforcement of non-compliant ships in port is investigated. This chapter aimed to bridge the gap between the scientific and technological developments with the enforcement side of MARPOL Annex VI Regulations 13 and 14 during port inspections. This was done by evaluating the relationship between the results of the airborne sniffer measurements and the results of the latter inspections.

First, this chapter demonstrated that there were significantly more non-compliances at sea than in ports, highlighting the importance of effective enforcement and targeting potential violators for port inspections to ensure maximum and sustainable compliance with the emission limits.

The chapter further showed that by including airborne alerts in the enforcement chain, the number of non-compliant detections in Belgian ports increased by 53% (Figure 5A). Additionally, 41% of all MARPOL Annex VI issued fines were a result of airborne alerts However, it is demonstrated that up to 80% of all observed potential non-compliant ships were not followed up or when followed up, the inspection (with a fuel sample analysis) could not confirm the observed non-compliance. Often the latter is a result of a delayed follow-up in ports. This highlights the strong incentive to further explore the use of remote measurements as legal evidence to tighten the MARPOL Annex VI enforcement chain. This chapter also examined compliance and follow-up of EGCS ships, which had, by that time, increased significantly since the introduction of the global sulfur gap. It is found that inspections of EGCS ships after airborne alerts improved the inspection results drastically, and airborne alerts accounted for 2/3 of the sanctioned EGCS ships in Belgium.

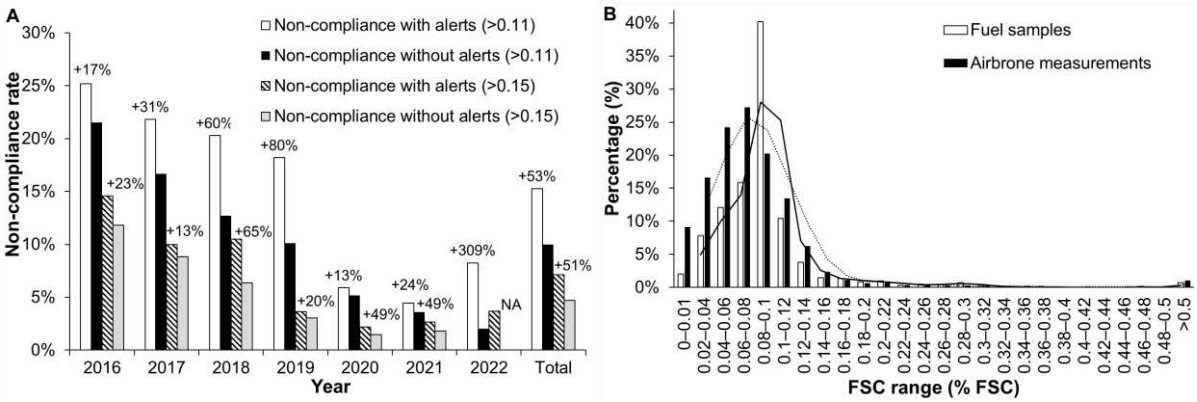


Figure 5. Improvement of PSC inspections thanks to the airborne alerts (A). Histogram of the FSC values from fuel samples and airborne measurements (B).

The distribution of the remote measured FSC and the FSC obtained from fuel samples were highly comparable (Figure 5). To investigate the actual variation of the remote measurement compared to the actual values, a field validation analysis was performed in this chapter, in which the results of the airborne measurements are compared with 1) the results of the fuel sample analysis taken during port inspections, and 2) logged emission data obtained from EGCS ships [8]. This shows that the actual measurement uncertainty was better than the, more theoretically, calculated uncertainty that was assessed in Part1.

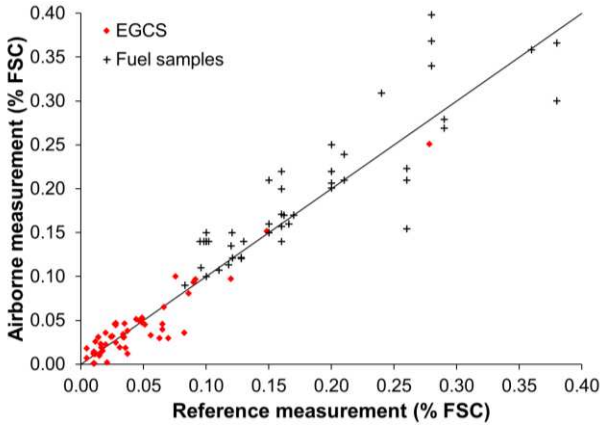


Figure 6. Field validation of the airborne FSC measurements with data from EGCS and fuel samples.

In addition, the cost-effectiveness of using airborne monitoring is compared to the cost of onboard inspections. The Belgian coastguard aircraft monitored SO_2 and NO_2 emissions from ships in Belgian and neighboring waters at an average rate of more than ten ships per flight hour, proving to be an efficient and usable asset in the MARPOL Annex VI enforcement chain. Airborne measurements were found to be significantly less expensive than onboard inspections, potentially reducing the cost per detected violation by 40-50%. While airborne monitoring is less cost-effective than fixed stations per inspection [9], it provides more flexibility and opportunities to obtain legal evidence.

The situation for NO_x is different due to the lack of a practical compliance check mechanism in port described in the IMO regulations [10] and the absence of EU regulations, as is the case for sulfur [11,12]. As a result, only limited NO_x inspections are carried out in EU ports and when carried out, the inspections are only based on document checks [10]. Therefore, non-compliances observed by aircraft remains only indicative and cannot be effectively compared with the results of port inspections. Consequently, it is strongly advised to conduct additional large-scale field validation experiments for

both SO_2 and NO_x emission measurements. These experiments serve multiple objectives, including scientific validation, operational assessment, and the establishment of a standardized remote measurement approach with legally recognized evidence status. It is crucial to emphasize that the effectiveness of airborne monitoring can be significantly enhanced as it can incorporate the monitoring of compliance of multiple emission regulations. Currently, only SO_2 and NO_x are subject to international regulations. However, if additional regulations for particle matter (PM), Methane and black carbon (BC) [13] are introduced in the future, the number of regulations inspected per monitored ship would significantly increase without requiring substantial additional effort.

In conclusion, Part 2 has demonstrated the effectiveness of using airborne sniffer measurements in enforcing MARPOL Annex VI regulations. It also highlights the potential of airborne monitoring to provide reliable legal evidence and improve the enforcement chain. However, more large-scale field validation experiments are needed, and regulations need to be improved to allow the assessment of real-world NO_x emissions and compliance verification by port inspection authorities.

3. Assessing the impact of ship emission regulations on air quality

In Part 3, Chapters 5 and 6 answer the question of whether the SO_2 and NO_x emission regulations have led to an improvement in the air quality in the Belgian part of the North Sea and the wider European ECAs. Firstly, Chapter 5 analyzes the impact of the international regulations on Belgian waters and the inland Flemish region. Secondly, Chapter 6, looks at the impact of the international regulation for the wider BA area and European ECAs.

Chapter 5 first needed to merge FSC measurement data for the entire period 2015-2022. Since two different methods were used in the period 2015-2019 and the period 2020-2022, the data for 2015-2019 had to be corrected first. This is done by linear correction based on the 2020-2022 period, for which the measurements are compared that were conducted based on the two different methodologies. The resulting time series for the overall period 2015-2022 confirms that the introduction of the global sulphur cap contributed to a reduction in SO_2 emissions and improved compliance rates.

By comparing the 2015-2022 FSC time series with land-based air quality measurements [14], it is proven that not only the implementation of the SECA and the consecutive reductions in the maximum allowable FSC are reflected in the inland SO_2 concentrations, but also that the effect of the global sulphur cap can be confirmed, with an absolute minimum contribution of 3% from shipping to the total inland SO_2 pollution. However, SO_2 emissions from shipping are also predicted to rise to 7% by 2030. This is an undesirable side effect of the global sulphur cap, as it has led to an increased use of EGCS. In the process, these have been shown to emit higher levels of SO_2 than ships without EGCS. Moreover, EGCS-equipped ships are more prone to non-compliance, and when non-compliance is detected, FSC values tend to be much higher than those of standard ships.

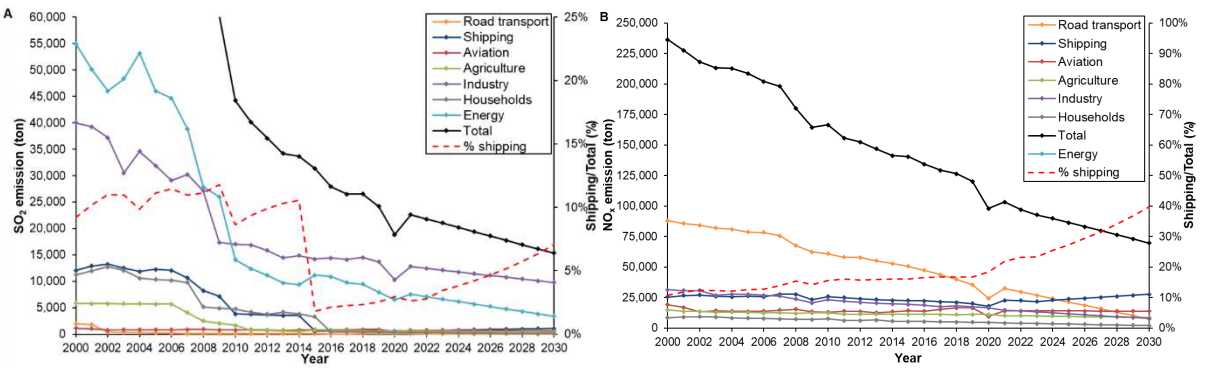


Figure 7. Share of SO_2 and NO_x emissions from shipping for Flanders

Chapter 5 also shows that the implementation of Regulation 13 of MARPOL Annex VI has not led to a successful reduction of the average NO_x emission factors of ships, but rather to higher NO_x emissions. Furthermore, the data analyses from the inland stations [14] shows that the regulations had no effect on the air quality measurements for NO_x in Flanders. It thus confirms the findings in Chapter 2. By adding the 2022 data, the upward trend in real world average NO_x emissions is even more pronounced. As mentioned before, it is believed that this is due to the ineffective way the regulations were established.

The future predictions for NO_x are even less positive than for SO_2. While most other NO_x sources follow a decreasing trend, the expected growth in maritime transport combined with the increase in average NO_x emissions from ships will make shipping the largest contributor to inland NO_x emissions in Flanders by 2025. It is estimated that shipping will be responsible for 40% of total inland NO_x emissions in Flanders by 2030. Moreover, EGCS is found to not only increase SO_2 emissions, but also lead to higher average NO_x emissions and greater non-compliance with NO_x regulations. Although higher NO_x emissions for EGCS ships were observed in previous case studies, the research in Chapter 5 has proven this effect on a larger scale [15].

Chapter 6 examines the impact of the implementation of a number of international air emissions regulations in the broader ECA area. In order to accomplish this, a comprehensive analysis was conducted on remote monitoring data obtained from the other BA Contracting Parties (CPs) (Figure 8), as well as the outcomes of port inspections which includes the number of infringements and associated penalties from the BA Cps (Figure 9A). Additionally, the data collected for the European Commission by EMSA on the results of sulfur inspections conducted by EU Member States (MS) is analyzed (Figure 9B). The remote monitoring data obtained from the other CPs exhibits a comparable downward trend when compared to the Belgian airborne remote monitoring data. Notably, the moment when the different international regulations became effective was apparent within the datasets. By analyzing the results of inspections carried out by both the BA CPs and the EU MS, a significant decrease in the number of ships that fail to comply with the FSC requirements is apparent. Nevertheless, the various analyses also reveal a modest increase in non-compliance cases during the last one to two years. This finding demonstrates that it is imperative to remain vigilant and ensure a continued enforcement.

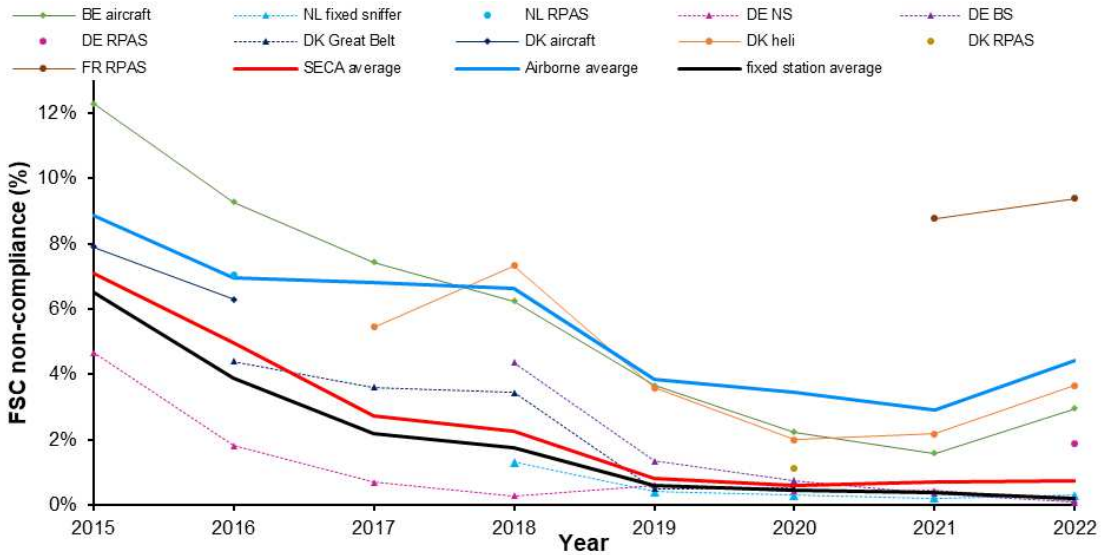


Figure 8. Evolution of the FSC non-compliance in the European SECAs, based on the remote measurements conducted by the BA CPs.

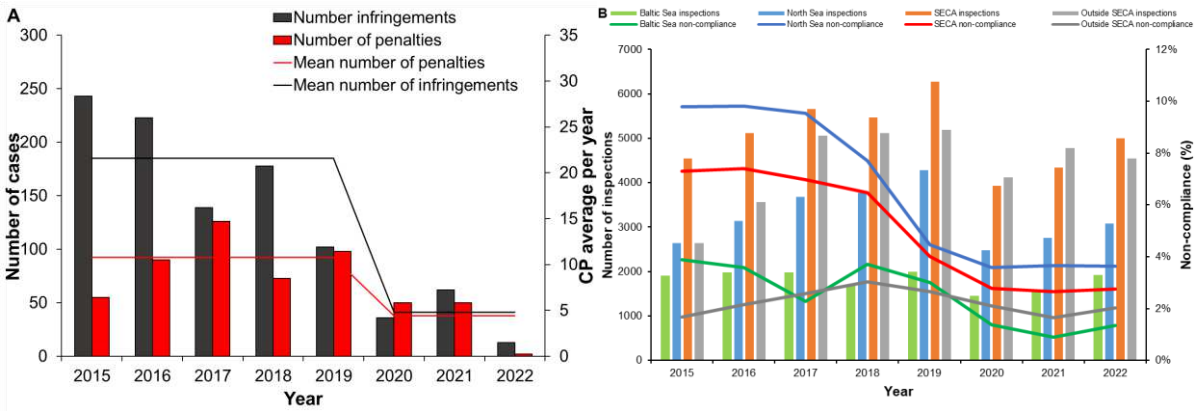


Figure 9. Observed infringements and executed penalties in the BA (A) and number of document inspections and compliance in the EU (B)

Additionally, Chapter 6 explores the impact of the emission regulations on the air quality within the ECA areas, based on a spatiotemporal analysis of TROPOMI satellite data. The spatial examination revealed distinct variations in SO_2 and NO_2 concentrations within the different regions encompassed by the ECA and between the ECA and areas outside its boundaries. In addition, it was found that the implementation of the global sulfur cap resulted in a (limited) reduction of SO_2 levels, in particular in the densely navigated areas in the North Sea ECA. In contrast, no significant reduction in NO_2 pollution levels was observed between 2019 and 2022, indicating that the implementation of the NECA did not lead to a decline in NO_x pollution within the European ECAs (Figure 10).

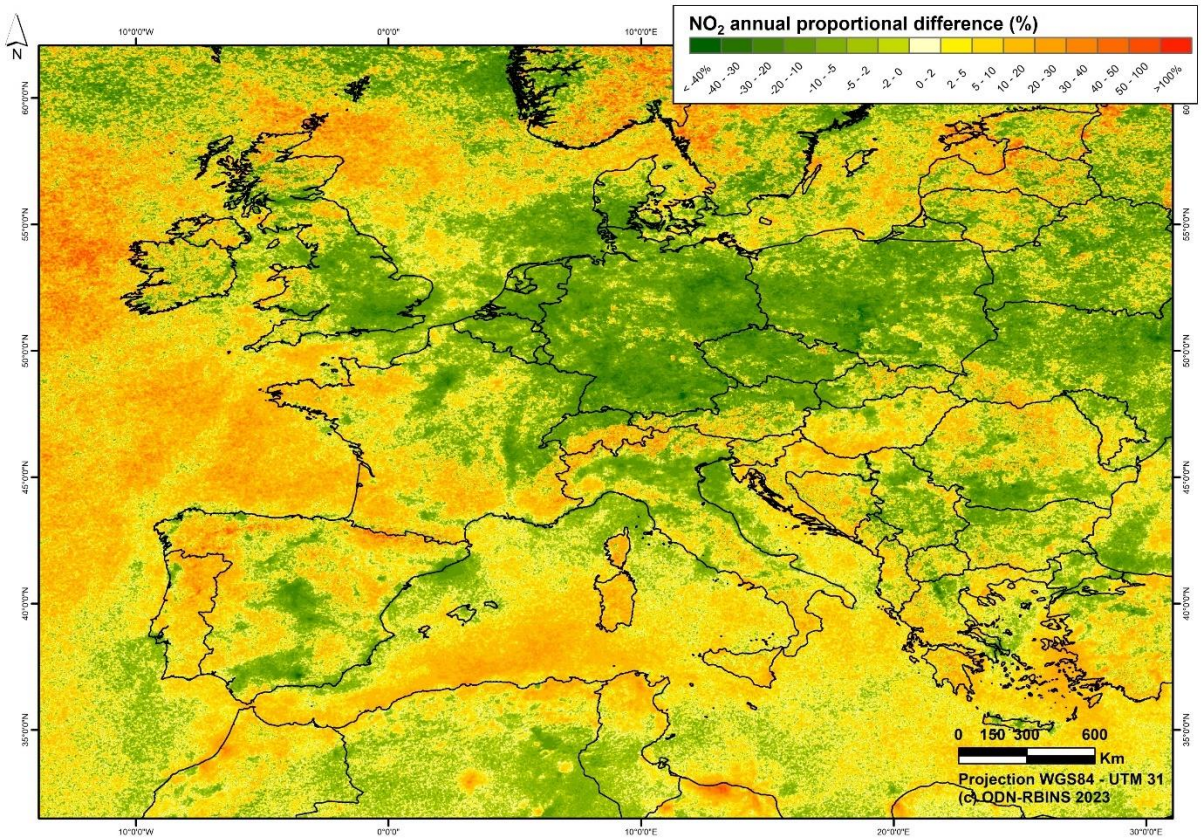


Figure 10. Proportional difference in annual NO_2 Vertical Column Density (VCD) between 2019 and 2022 visualizing the impact of the NECA implementation (2021), based on TROPOMI Sentinel 5 satellite images.

To conclude Part 3, it can be stated without doubt that global air emission regulations for ships help to improving air quality. However, the application of clear limits and guidelines is key in this regard. The regulation of SO_2 emissions from ships can be considered a success story so far. Clear IMO regulations and guidelines alongside an effective EU legal framework, made enforcement of "sulfur" emissions a priority for port inspection services in the EU and ECA countries. Through remote monitoring, port inspections and legal follow-up, the problem of SO_2 emissions within the European ECAs is now clearly under control.

In contrast, the established regulations aimed at reducing NO_x emissions from the shipping industry are proven to be largely ineffective due to the intricate nature of the international NO_x regulations, insufficient available operational enforcement mechanisms, and the absence of an EU legal framework on NO_x emissions from ships. Conversely, several regulatory gaps[2] and the need for improved energy efficiency have only increased the overall NO_x emissions from the shipping sector. It is important to note that the pursuit of improved energy efficiency, resulting in reduced CO_2 emissions, to counteract global warming are more or less offset by the increased NO_x emissions. As NO_x is also a potent greenhouse gas, the impact on climate change might be even more drastic as assumed. Despite prior efforts to raise awareness at the EU and international levels, it remains crucial to sustain ongoing awareness-raising efforts and prioritize NO_x as a key issue within the discussions of diverse international organizations dealing with the implementation of ship NO_x emission regulations.

4. Developing a monitoring strategy in the Bonn Agreement and legal recommendations

In the fourth and last part of this thesis, Chapter 7 addresses the progress made by the BA in creating a regionwide comprehensive monitoring and enforcement strategy for MARPOL Annex VI. Furthermore, Chapter 8 puts forth recommendations for regulations that can enhance monitoring and enforcement efforts and effectively decrease ship emissions in the near future, following some of the recommendations put forward by the SCIPPER project [16].

Chapter 7 describes the pioneering role of the BA in addressing air pollution from shipping, thereby becoming the first regional agreement to include air pollution in its scope. By engaging technical, operational, and legal experts, the agreement has identified specific strategic, operational, and technical measures that are being addressed by two Working Groups (WGs) — the Strategic Operational Working Group (SOWG) and the Technical Working Group (TWG). The ultimate goal of the BA is to achieve a comparable reduction of violations for MARPOL Annex VI, as was the case with MARPOL Annex I.

Chapter 8 presents recommendations to enhance the effectiveness of international emission regulations for ships. These recommendations address some of the regulatory gaps highlighted in earlier chapters, but also include some recommendations that were discussed at the SOWG and TWG, alongside certain recommendations put forth by the SCIPPER project. The most significant recommendation is to establish a legal framework that recognizes remote measurements as a compliance verification practice. It should be noted that BA CPs are already using remote monitoring data as sole evidence, for the legal

[2] It is important to acknowledge that the use of the term "regulatory gap" may legally speaking not apply to all the mentioned issues. While in certain instances the term accurately describes the intended or non-intended misapplication of certain regulatory provisions, some issues pertain the absence of described applicable enforcement measures in the regulatory framework, thereby indicating rather "enforcement gaps". Nonetheless, the term "regulatory gap" is retained as a broad descriptor due to its adoption by other initiatives (e.g. SCIPPER) and discussions at international fora (e.g. BA).

follow-up on violations related to the other MARPOL Annexes. However, not all BA CPs follow this practice.

It is suggested that the use of remote monitoring for both SO_2 and NO_x enforcement should be recognized and stimulated by international and EU regulations. This is particularly crucial for NO_x emissions since there is currently no recognized enforcement method to verify real world NO_x emissions from ships in ports. To address this enforcement gap, a remote monitoring method based on the same principles used for EGCS regulations should be implemented [17]. However, when imposing sanctions, care should be taken to ensure that compliant ships are not wrongly classified as non-compliant. To mitigate this risk, it is advisable to use high confidence intervals (e.g., 99%) for remote measurements that are used in legal action. Although, for targetting ships for inspections in port, lower confidence intervals (68% and 95%) remain useful [4].

In addition, several technical recommendations are proposed to address NO_x and EGCS regulatory and enforcement gaps in existing regulations. These gaps, mainly policy and engineering driven, have unintentionally contributed to an increase in NO_x emissions from newer ships. Given that ships have a lifespan of up to 30 years [18], it is essential to promptly find solutions to address these gaps. The presented recommendations include: the implementation of a maximum time limit between the built year and the keel laying date (KLD) (Figure 11A); the implementation of additional emission limits at engine loads below 25% (Figure 11B); the implementation of a not-to-exceed (NTE) limit for Tier I and Tier II vessels; the compulsory use of continuous emission monitoring systems (CEMS) on board of Tier I and Tier II ships; and the creation of clear guidelines for its use and logging of the data. For EGCS the main recommendation is to develop a protocol for the verification of effective real-world emissions that would not only allow the shipowner to check the proper working of the EGCS system, but also enables port inspection authorities to assess whether the emission limits are being effectively met or not.

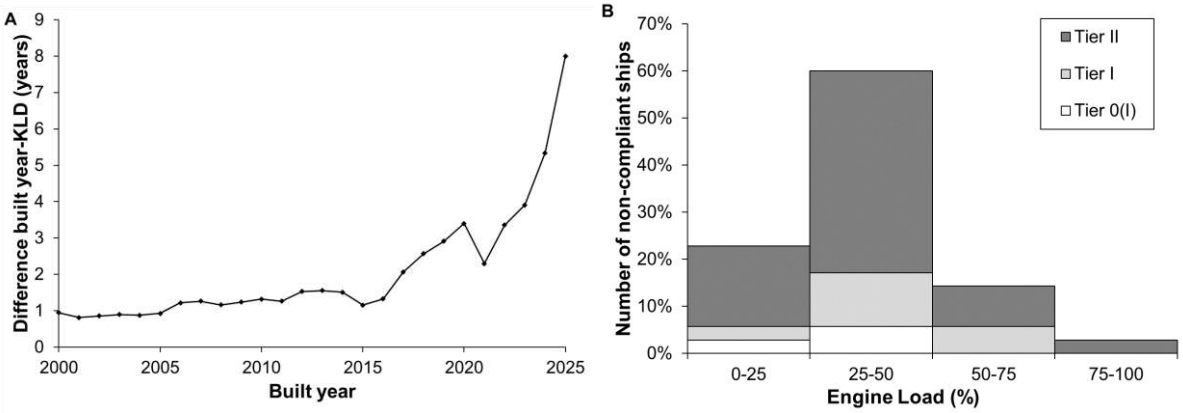


Figure 11. Increase of time between built year and keel laying year as a result of a regulatory gap that defines the start of the Tier III implementation based on the KLD (A). Distribution of NO_x non-compliant ships based on their engine loads demonstrating that 23% of the non-compliant ships are non-regulated loads, the graph further demonstrates the substantial higher amount of Tier II ships at the low engine loads (B).

To conclude Part 4, it is strongly recommended that the EU institutions establish a legal framework for monitoring and regulating NO_x emissions from ships, following the success of the EU rules on sulphur. The introduction of such a NO_x framework would facilitate the development of effective NO_x enforcement mechanisms. In addition, it would enable the inclusion of NO_x in Thetis-EU [19] and facilitate the monitoring of NO_x by EMSA's RPAS program [20]. Moreover, it would increase the involvement of EU MS in the implementation of a remote monitoring strategy for NO_x emissions, similar to what has been achieved for SO_2. It must be said that the resulting high FSC compliance levels and

the reduction in SO_2 emissions would not have been achieved without the EU Sulphur Directive and the Commission Implementation Decision.

An overview of the main findings and recommendations is displayed in Figure 12.

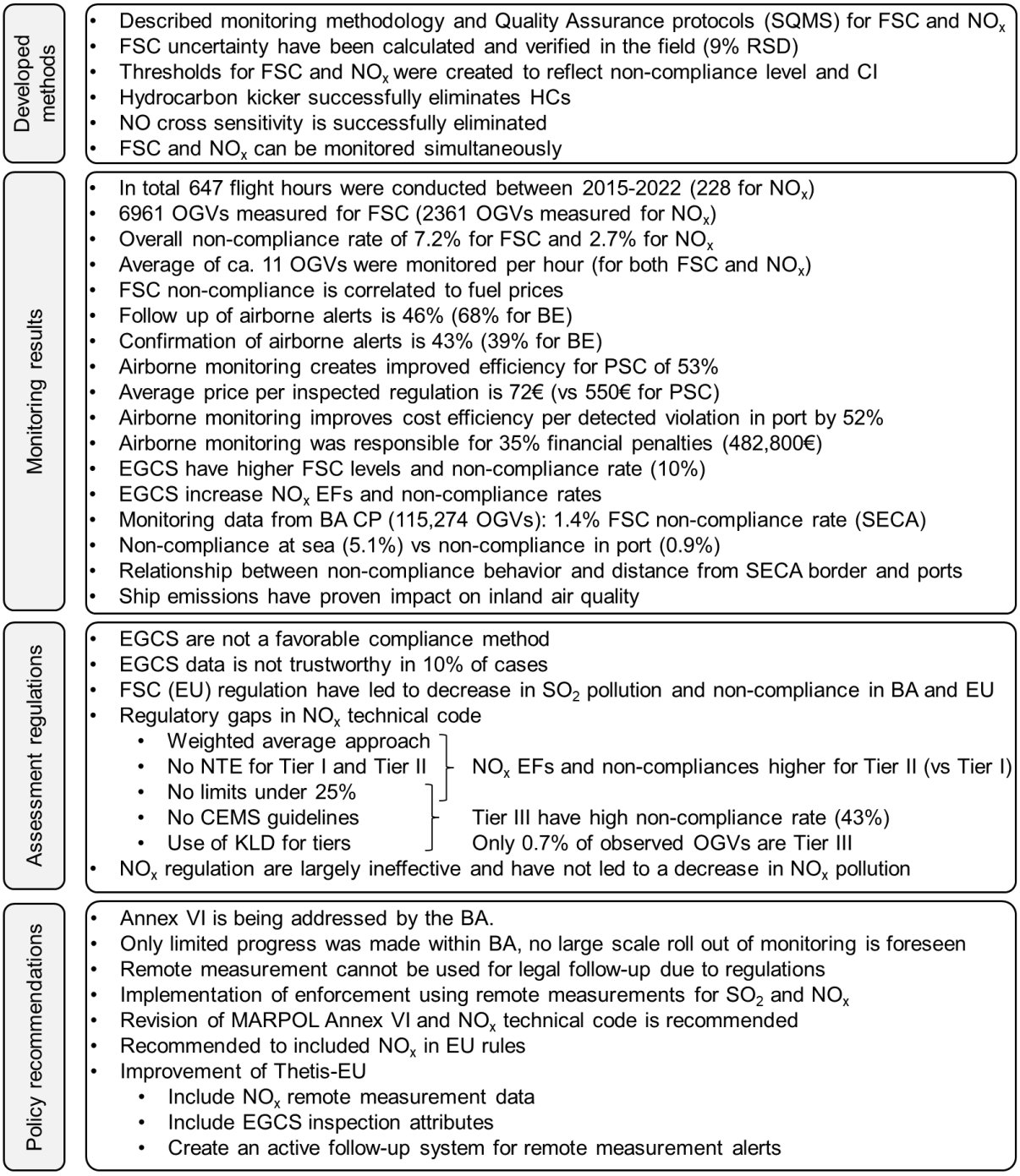


Figure 12. Overview of the main findings and recommendations of this dissertation.

5. Prospective and personal reflection

This doctoral research can, in a way, be seen as my professional life's work. I started researching the use of airborne monitoring techniques for ship emission measurements with the Belgian coastguard aircraft in 2011. Although the actual start was with the CompMon project from 2014-2016. More than 7000 measurements and countless hours in the aircraft, lab and workshops passed, but most of the work happened during my daily life, thinking about procedures, finding technical solutions, troubleshooting observed issues and most importantly imagining.

As a result, my experiences and insights gained on this matter are not achieved by many others. One of the main reasons why the RBINS is so committed to the BA is precisely to share our gained experiences and best practices. It is our hope that the developed methods will also find continuation in other countries. That is also the reason why I have attended numerous international meetings and conferences from one side of the world to the other. Also for this reason, I signed up as a co-convenor for the MARPOL Annex VI Technical Working Group.

Furthermore, in light of this objective, a very detailed sniffer quality management system was compiled and made available to the public. The described standard operational procedures are not only important to ensure that all measurements are carried out according to a harmonized approach and with the highest possible certainty. The procedures described can also be used by other countries setting up their own airborne monitoring operations. Although the described standard operational procedures (SOP) are highly adapted to the sniffer system used by the Belgian coastguard, they can also serve as a model for other countries when establishing their own procedures.

It is important to note that the work does not end here. The Belgian remote monitoring operations have already been extended to measure black carbon (BC) since 2021, and since 2023 we are also measuring airborne microplastics. In the future, this could be further expanded to include nitrogen particles, particulate matter (PM), methane and N_2O. In addition, we hope to continue upgrading the measurement systems with state-of-the-art sensors to further improve measurement uncertainty, however most likely this will be part of the next Belgian coastguard aircraft.

6. Final words

This doctoral dissertation serves as a call for action to the International Maritime Organization, its committees and subcommittees, regional agreements, national and local governments, port authorities, and shipping companies to work together to reduce the environmental and human health impacts caused by shipping. This thesis highlights the importance of taking a comprehensive approach in tackling air pollution from shipping, and the need to persist in advancing the development of efficient enforcement strategies and compliance monitoring methods. With the right measures in place, it is possible to achieve a cleaner and healthier future for all.

"We need to create a world that is equitable, that is stable and a world where we bear in mind the needs of others, and not only what we need immediately. We are all in the same boat."

- Kofi Annan, the former Secretary General of the United Nations (UN).

Hopefully, this doctoral dissertation has, albeit modestly, provided a contribution to the current efforts in reducing the environmental impact of shipping on human health and the environment, by providing technical solutions for the enforcement of international ship emission regulations, assessing the impact of these regulations and identifying gaps in the legal framework.

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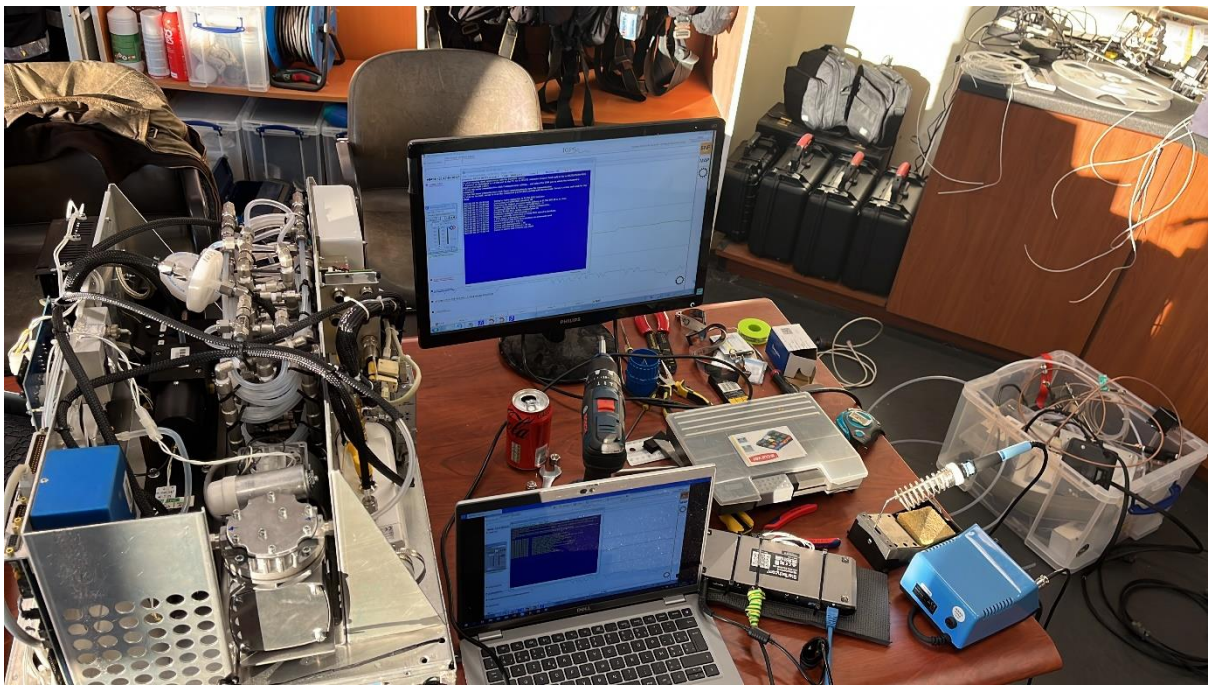
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Supplementary material:

Sniffer Quality Assurance and Maintenance Manual



Personal picture (08/02/2023)

Sniffer Quality Assurance and Maintenance Manual

The Sniffer Quality Assurance and Maintenance Manual (SQMS) can be downloaded from the following link

Or by copy pasting the address in your internet browser:

https://surv.naturalsciences.be/d/4ed9fde41783489ea795/

SNIFFER QUALITY MANAGEMENT SYSTEM

RBINS-MUMM-SURV

Responsible author: Ir Ward Van Roy

Brussels - 2023



ABOUT THIS MANUAL

The Sniffer Quality Management System was developed by MUMM to be used with the sniffer installation on board of the Belgian Coastguard Aircraft, a BN Islander (BN2A) with call sign OO-MMM. The manual consists of 3 sections. The sections can be easily accessed from the links in the table below and can then subsequently be browsed from the respective indexes or from the list of Standard Operational Procedures (SOPS). To go back to this page a link is available in the header.



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SNIFFER QUALITY MANAGEMENT SYSTEM

SECTION 1.

SNIFFER OPERATION MANUAL



REVISIONS

Revision Date	Chapter - section	Page	Description
17/1/2022	Chapter 3 3.2.3	3-8	Update Threshold table
15/2/2022	All		Adding of NOx sensor
25/7/2022	Chapter 2 SOP 1.6	2-10	Adding of plume simulation gas mixture

ABOUT THIS MANUAL

The Sniffer Flight Operation Manual was developed by MUMM to be used with the sniffer installation on board of the Belgian Coastguard Aircraft, a BN Islander (BN2A) with call sign OO-MMM. The Sniffer Operation Manual constitutes to Section 1 of the Sniffer Quality Management System (SQMS). The Sniffer Quality Management System was specifically designed for the Belgian Marpol Annex VI monitoring program, entailing the proper functioning of the sniffer system on board of the Belgian Coastguard Aircraft and the provision of accurate and consistent data collection. The Quality Management System consists of in total 3 Sections, Section 2 - Quality Assurance Manual of the Sniffer system describes in detail the technical specification of the different components of the sniffer and their respective maintenance aspects. Section 3 - Data Management Manuel, consists of the data management aspects (see Figure 1). For every section a detailed manual is developed and available on the Seafile folder "0. SNIFFER QMS" under the Seafile library 05-Instrumentation/05-FluxSense_Sniffer

In this manual, detailed information and step to step instructions are provided about the operation of the sniffer sensor. The manual is organized in different chapters and annexes to provide direct access to specific information, hyperlink bookmarks are used to move to selected objects.

- "**Chapter 1 Sniffer sensor system setup"** describes in brief the sniffer sensor setup on board of OO-MMM aircraft and its components.
- "**Chapter 2 Pre-Flight Mission Preparation"** describes all aspects of the preparations of a surveillance flight, including weather checks and all steps in preparing the aircraft for operation.
- "**Chapter 3 In-Flight operation**" includes the procedures during flight when conducting ship emission measurement operations.
- "**Chapter 4 Post-Flight Mission Operation**" describes all reporting and post flight operation procedures.
- "**Chapter 5 Post Flight Analysis**" Includes basic post flight reprocessing procedures.
- "**Annex A – Technical Fiche OO-MMM**" gives an overview of the coastguard aircraft.
- "**Annex B - Block Diagram**" gives a diagram of the sniffer system setup.
- "**Annex C - Radio communication checklist**" provides the marine VHF questionnaire for NOx.



Figure 1 Sniffer QMS Structure

The sniffer sensor system manufactured by FluxSense (Sweden), consists of a compilation of components from different soft and hardware providers. This manual was composed by the scientific Service MUMM of the Royal Belgian Institute based on the extensive experience of operating the sniffer sensor system on board of the Belgian Coastguard Aircraft and the nature of the Belgian North Sea Aerial Surveillance Program, as a result it is possible that this manual does not fully reflect the official opinion of the manufacturers.

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CHAPTER 1. SNIFFER SENSOR SYSTEM SETUP

The sniffer sensor system is the complete equipment setup used for airborne Marpol Annex VI monitoring executed by the Belgian Coastguard Aircraft. The sniffer sensor system is installed in a BN Islander type B2-A with matriculation OO-MMM.

- BN Islander (with antennas, pitot tube and avionics)
- Sniffer sensor
- NOx sensor (Ecotech)
- Client station (Laptop+VM on Console) with IGPS software

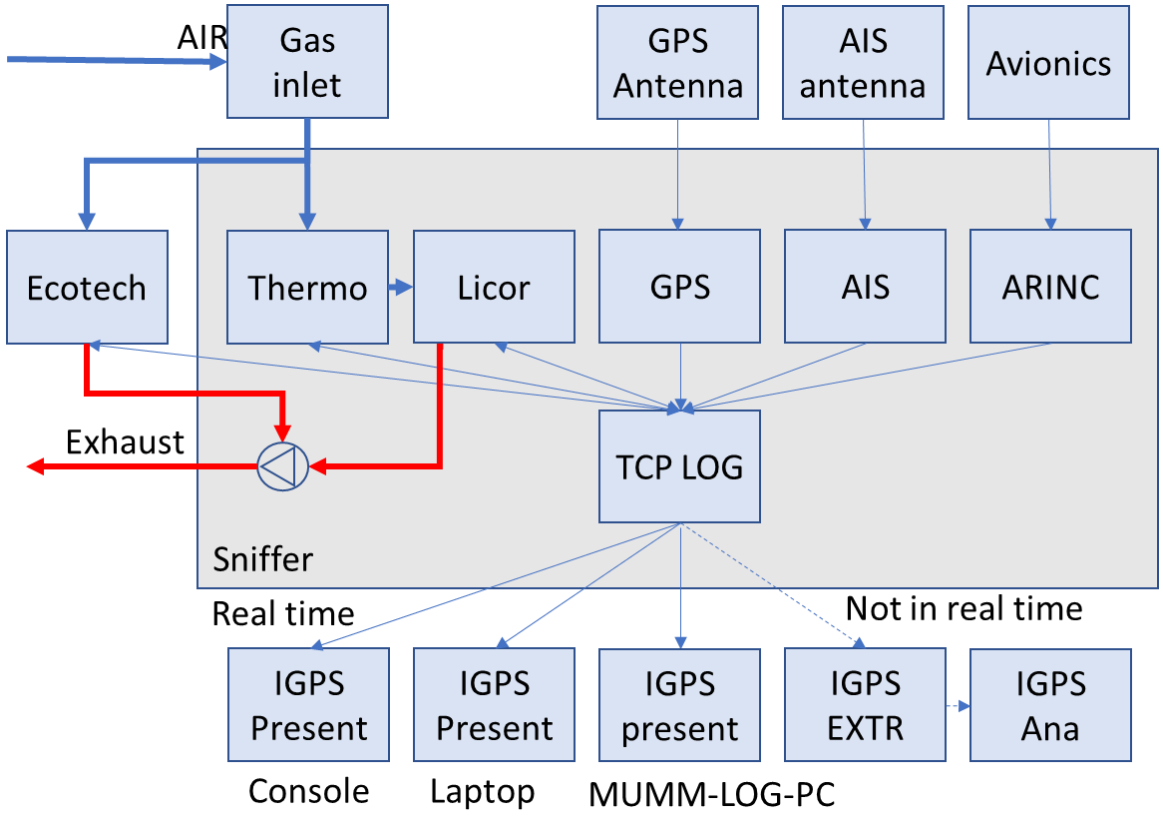


Figure 2 Schematic view of the sniffer setup

1.1. BN Islander

The Belgian Coastguard aircraft OO-MMM is a Britten Norman Islander BN2-B, a twin piston engine propeller aircraft, the two engines provide 300 bhp and 70 Amp of electrical power. The aircraft has a MTOW of 3000kg, can handle 5 persons (2 pilots, 3 observers). The aircraft is a so called high wing aircraft, enabling a good peripherical view. The size of the wings (14m) is relatively long compared to the length (10m), this makes it an excellent STOL aircraft (Short Take-Off and Landing), with very low stall speed (35kts), the fixed and robust landing gear further complete the "island" hopper characteristics. (See **Annex A – Technical Fiche OO-MMM**).

1.1.1 Aircraft power

The Sniffer has an actual power consumption of ca 10 Amp but is connected to a 20 Amp circuit. The sniffer is connected to the "Utilities" bus, a relay connected to the "Survey power" is powering the sniffer, a dedicated Circuit Breaker (CB) (20A) is installed in the cockpit for the Sniffer. A connector for the powering of the sniffer is installed in the ASP connector panel on the left side of the aircraft, behind the sniffer (ASP-CON-07). The sniffer can be switched off by a remote switch on headset connector panel of the main operator. To switch of the EPS for the pumps a switch is installed in the middle of the right side of the console For more information on the sniffer wiring see Section 2 of the Sniffer Quality Management System.

1.1.2 GPU

The Sniffer can be powered on ground by using a GPU (Startpac 53050) connected to the AC external power bus (See Figure 3). An additional connector is installed on the GPU to power the sniffer sensor independent from the AC power supply (connection to the external battery) or outside of the AC (connection straight to the Sniffer sensor 28V input connector).



Figure 3 Start Pac 50 Amp GPU used for powering the aircraft systems on ground

1.1.3 Avionics

The sniffer sensor system is connected to the aircraft avionics, more specifically to the Garmin GTN650 GPS system via Arinc 429. The wind information is provided on labels 315 and 316. Furthermore, an HDMI output on the sniffer internal computer (MUMM_LOG_PC) is connected to the MAP2 of the Avalex AVM 4095 Cockpit display, this allows to present the charts off the IGPS-present (MAP). An addition video input is available on the Garmin G600 for the presentation of the graphs of the IGPS software (SNF) from the Virtual Machine on the Console. An overview of the video signals is provided in Figure 4. More schemes can be found in Annex D of Section 2 of the SQMS.

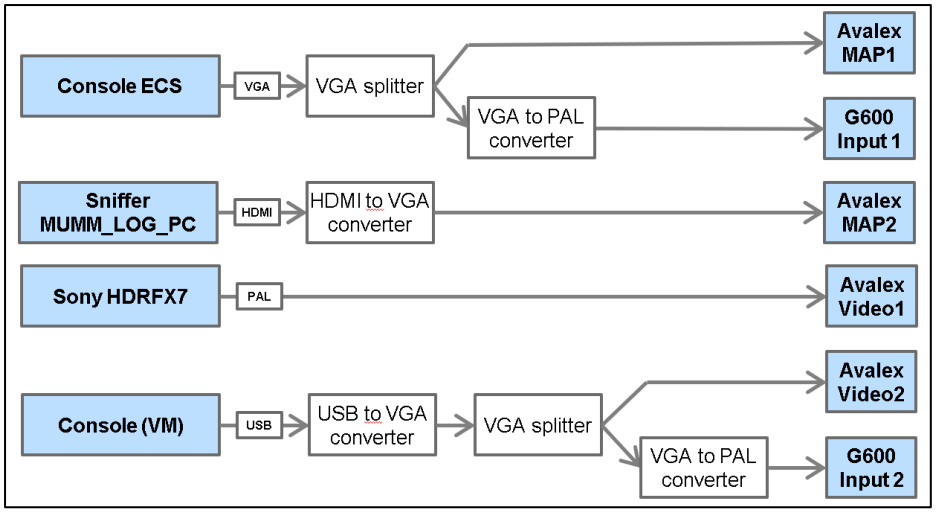


Figure 4 Video signal setup of the avionics

1.1.4 Pitot tube

The gas inlet tube or pitot tube is installed on the bottom of the aircraft, right under the sniffer sensor. The Stainless Steel 3/8-inch tubing is connected to a 1/4-inch PVC tube. That goes straight to the AIR inlet of the filter box.

1.1.5 Filter box

A filter box is installed after the pitot tube, the filter box filters particles and water. A toggle valve is installed in front of the box to switch between AIR mode and ground (GND) mode. When the valve is in GND mode, air passes through a carbon/purafill filter to avoid contamination of the sniffer sensor.

1.1.6 Antennas

The sniffer sensor is equipped with an internal AIS/GPS receiver. This receiver is connected via coax cabling to a GPS antenna on the top of the aircraft and an AIS antenna on the belly of the aircraft.

1.2. Sniffer sensor

The main component of the sniffer sensor installation is the sniffer sensor. The sniffer sensor was developed by Chalmers University and commercialised by FluxSense (Sweden).The sniffer sensor is a collection of different components and sensors that are installed in a custom made casing (see also **Annex B - Block Diagram**). The sensors consist of certified equipment used for ambient air quality monitoring that has been disassembled from its original case and reassembled in the sniffer sensor. The different components have been specially adapted for the purpose of airborne monitoring of ship exhausts. Therefore, some components were either reduced in size or removed, also the sample rate of the sensors has been increased to allow high speed continuous air quality measurements on board of fixed wing aircraft. The main sensors are the Thermo 43i TLE for the measurement of SO2 and the LICOR 7200R for the measurement of CO2. The different components are described in detail in Section 2 - Quality Assurance Manual of the Sniffer Quality Management System.



Figure 5 Sniffer 19" Equipment rack

1.2.1 MUMM_LOG_PC

Inside the Sniffer a compact computer is installed (Zotac Nano ID64). This computer collects all the sensor data from the different components and redistributes the log data to the different client stations via Ethernet. Also the IGPS-Present is running on the MUMM_LOG_PC, this is used for the visualisation of the charts to the pilots. The MUMM_LOG_PC can be accessed using TeamViewer or Remote Desktop. For trouble shooting a HDMI or VGA monitor can be connected to the HDMI port and a computer mouse and keyboard can be connected to the USB port.

1.2.2 Sniffer power distribution

The sniffer system uses transforms the 28VDC of the aircraft to 115VAC,

4 circuit breakers are available on the casing of the sniffer:

- CB 1 (5A): External 115V connector (J211) for NOx sensor
- CB 2 (5A): Traco power converters, air pump (1&2) and MUMM_LOG_PC
- CB 3 (5A): NOx airpump (KNF N 022 ATE)
- CB 4 (5A): Thermo 43i TLE

Following internal fuses are included:

- Fuse 1: Inverter 50 A
- Fuse 2: LICOR 2.5A

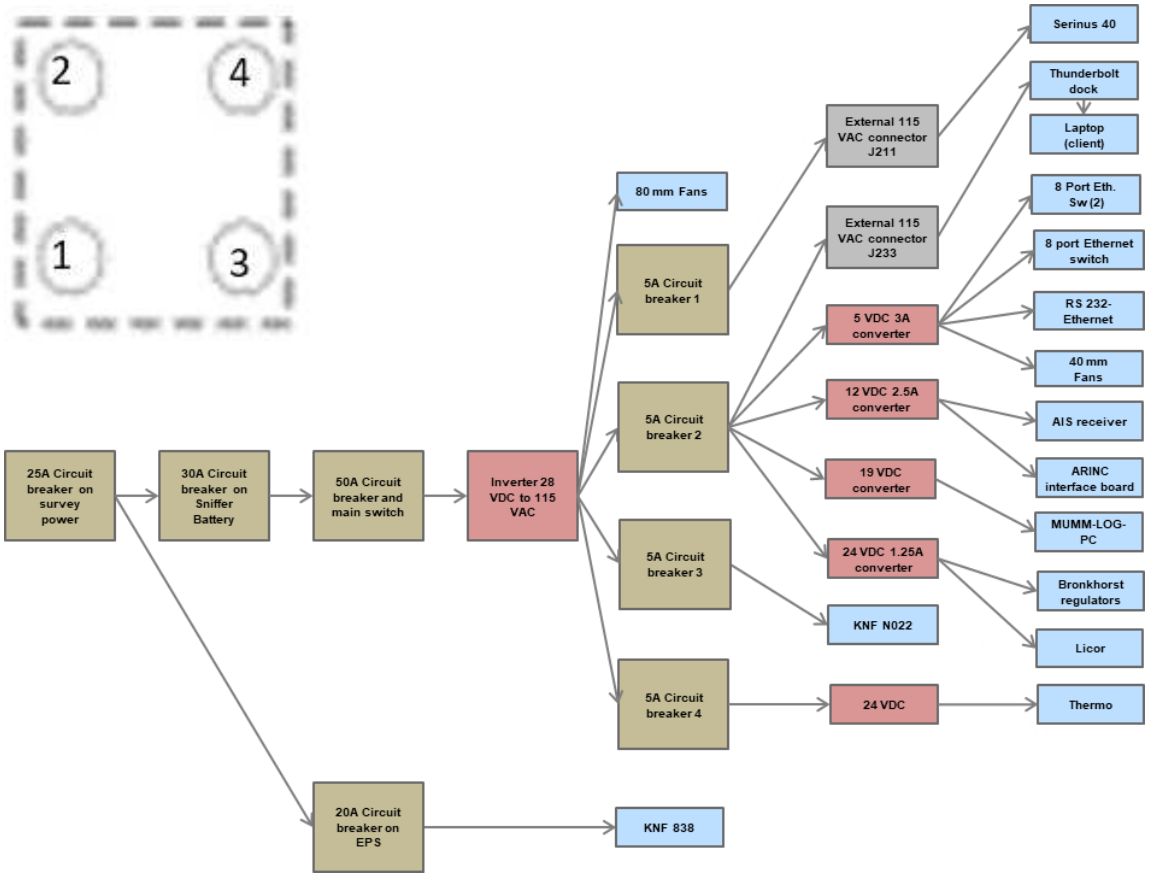


Figure 6 Overview power distribution and circuit breakers inside the sniffer sensor system

1.2.3 Connecting to the sniffer

The Sniffer sensor setup is based on a network environment, all data is logged on the sniffer sensor internal computer MUMM_LOG_PC, this data can be accessed from different client stations following client stations are used during operations:

- MUMM_LOG_PC: for visualisation of the MAP to the cockpitdisplay (on MAP2)
- Operator Laptop: for manual calculation of the FSC
- Console: for strategic overview, guiding pilots and plotting graphs on VIDEO 2 on cockpitdisplay

To connect different client stations to the sniffer sensor a set of predefined IP addresses need to be used (Table 1), for more information on how to set the IP address see Section 3 of the SQMS.

Table 1 IP addresses for external connection to the sniffer sensor

IP addresses	User
192.168.1.230 -239	available
192.168.1.240	Console via VM
192.168.1.241	PC Ward via Thunderbolt dock
192.168.1.242	PC Kobe via Thunderbolt dock
192.168.1.243	PC Annelore via Thunderbolt dock
192.168.1.244	PC Benjamin via Thunderbolt dock
192.168.1.245	PC Ward via cable
192.168.1.246	PC Kobe via cable
192.168.1.247	PC Annelore via cable
192.168.1.249	PC Benjamin via cable

1.3. NOx sensor

A NOx sensor was added to the sniffer sensor system. The sensor is an Ecothech Serinus 40. The sensor is installed in the back of the aircraft. A protection plate is installed in the front of the sensor protecting it from accidental touches on the control buttons. All commands go through a smartphone with the Serinus application connected through Bluetooth.



Figure 7 NOx sensor installed in the rear luggage compartment (here displayed without the protective front panel)

1.4. Client station

In theory a vast amount of client stations can be connected to the Sniffer by using ethernet. For operational use, only 2 client stations are connected to the sniffer. The first being the console and the second being the operator laptop via Thunderbolt dock. This means that together with the MUMM_LOG_PC constantly 3 computers are receiving the sensor data and can be used for navigation and analysing the measurements.

1.4.1 Console (MMU)

The MMU is the main console in the aircraft used for the Medusa system. The MMU runs on a tailored Open Suse Linux Platform and is therefore not suited for the installation of the IGPS software. A Virtual Machine (VM Player) with a Windows XP installation is installed on the MMU to allow to run IGPS on the console.

To enable direct Ethernet connection from the VM to the Sniffer sensor an additional Ethernet cable was installed (from J221 to an Ethernet hub inside the console). The IGPS software is installed on the “C:” drive of this VM XP distribution. The firewall has been deactivated for the IGPS software.

An additional USB to VGA adapter is installed on the VM. This allows the presentation of the VM display (SNF view of the AISPresent.exe) to the cockpit display and G600 (Video 2).

1.4.2 Laptop with RAM mount and WiGig dock

The operator laptops (Dell Lattitude 5420) have been specially selected and purchased for the conduction of sniffer flights. A special RAM laptop mount has been installed on the right side of the cabin to allow the laptop operator to work freely. To avoid issues with multiple cables a Startech

thunderbolt docking station has been installed on the front side of the console, the laptop is connected to a 2 m thunderbolt cable providing, data (ethernet, USB, HDMI) and power. The thunderbolt dock and laptops are powered by 115V power connector on the Sniffer (J233).



Figure 8 RAM mount for installation operator laptop

1.4.3 IGPS software

The IGPS folder is installed on the "C:" drives of the operator laptops and are synched through Seafile on all the operator laptops. This way all operators use the same software version and have the same emission data. The different software directories and files are:

- "Charts" Directory: folder with Open source charts of the world
- "Missions-Data" Directory: folder with generated reports of observations
- "MAIL" Directory: not used by SURV
- "AIS_EX8.exe" program: tool used for extraction of TCP-LOG files
- "AISPresent.exe" program: main software program used in flight and during calibrations
- "IPGSAna44.exe" program: software for post flight analysis (extraction required)
- "AISPresent.ini": this is the settings file for AIS present (can be read and edited using Notepad)
- "IP-configuration-SURV.txt" file: this document contains the used IP addresses for the different clients
- "Emissiondata_xxx.txt" files: are generated by the different clients (ODN-WVR, ODN-KS, ..) and contain the FSC measurements
- "Mail_Sniffer_SO2_Man_Meas.csv" file: contains the evaluation (High/Low/Not detected) of the manually marked ships
- "Comments _xxx.txt" contain the stored comments (old comment files are stored in "Comments" directory
- "wakeuplan.txt" file: contains the Mac address of the MUMM_LOG_PC in the sniffer sensor and can be used to wake up by lan
- "Optical_SO2_Man_Meas.txt" file: not used by SURV
- "STATICSHIPDATA_xxx.txt" file: contains a record of the observed ships per operator
- "borlndmm.dll", "cc32230.dll", "cc32230mt.dll", "Fetchlog.txt", "Logfile.txt", "Memo1-1.txt": are other additions files
- MMSI_Date: This file contains the Keel Laying Dates of tens of thousands of ships

The data storage, data processing, … is described in detail in Section 3 of the Sniffer Quality Management System.

CHAPTER 2. PRE-FLIGHT MISSION PREPARATION

In this chapter all the preparatory operational aspects about conducting sniffer flights are described, from the mission planning starting one day before the flight, up to the last preparations just before take-off.

2.1. Flight planning (12 am, 1 day before take-off)

2.1.1 Weather minima check

It is recommended to only plan MARPOL Annex VI monitoring flights with favourable meteorological forecasts, Visual Meteorological Conditions (VMC) conditions are required for conducting sniffer flights. Obviously, weather conditions should be followed up by operators and pilots before and in flight and flights should be cancelled in case the weather conditions become unfavourable.

SOP 1.1. Weather check

1. **Wind speed**: maximum wind force of 30 kts at sea, a forecasted maximum windspeed of 25kts in EBOS is a practical threshold, but not conclusive.

Note: A small amount of turbulence is often felt when passing through a smoke plume, which in a way gives a good indication for the crew to recognize the moment when the aircraft flew through the plume to sample the exhaust gases. Certain ships however, for instance roll-on/roll-off (RORO) ships may provide severe turbulence downwind of the ship. When flying too close with strong winds this may result in turbulent ship approaches. This turbulence effect depends on the physical characteristics of certain ships: the impact of the structure of the ship on the wind may cause a strong “mechanical” turbulence, such as with RORO ships. For such types of vessels, this mechanical turbulence can already be severe during wind conditions of 25 kts (especially with crosswind). This aspect should be kept in mind when selecting vessels for compliance monitoring under strong wind conditions.

2. **Visibility**: a minimum visibility of 5 km
3. **Cloud coverage:** clear of clouds, furthermore it is advised to have a cloud base at least 200 ft higher than the cruising altitude (ca at 600-700 ft).
4. **Precipitation**: light precipitation should not pose any problems for the monitoring, but heavy rain, snow or hail can result in low visibility or clogging of the sensor filters and should therefore be avoided.

Note: Rain may reduce the FSC measurements by 20-30% because of the washing out SO2.

5. **Temperature:** no measurements can be made during icing conditions, so during humid and freezing conditions.
6. **Inversion layers**: in normal conditions, air temperature decreases with altitude. But when air temperature increases at a certain altitude an inversion layers may occur. Weather forecast do not give any information of the occurrence of inversion layers, but this typically happens with wind-still cloud-free conditions during summer. At an inversion layer, air pollutants concentrate and form smog. If these inversion layer occurs at low altitude (<500 ft) they may interfere with FSC measurements as the background values for CO_2 and SO_2 may not be stable

in this case a change in the flight route or planning might be necessary. For instance, the monitoring could be shifted to another area or the afternoon (more stable atmosphere).

2.2. Flight routing

Optimally the organisation off the Sniffer flights is spread over the year to maximise the enforcement efficiency and reduce redundant measurements, nevertheless as the conditions during winter are less favourable it is recommended to organise the sniffer flights from March until October.

For the flight planning of missions over the Belgian and neighbouring waters, one sniffer flight of up to maximum 3 hours per day is recommended, as an alternative two shorter flights may be organised as well, but in this case, it is advised to maximise the time between the 2 flights. The standard template (OO-MMM_FLIGHTPLANNING (Date).xls) should be used for compiling the Flight planning (available on seafile "11-SURV-Planning\01-Flight\YEAR\Flight"), after finalising the template a PDF should generated and send to the national contact points including PSC in Belgium (sulphur@mobilit.fgov.be) and Netherlands (psc@ilent.nl) and the maintenance company Styl Aviation (OO-MMM@stylaviation.com), make sure that "Pollution (Sniffer)" is selected at mission type (see Figure 10).

The official Bonn Agreement waypoints should be used for planning a flight routing, focusing on shipping lanes and other zones of interest (e.g. port entry zones). Flight routing for the MARPOL Annex VI monitoring is very susceptible for changes in flight as in practice the flight route depends on the presence of ships. Therefore, it is required to use dynamic flight routes (see example in Figure 9) based on predefined waypoints, but where the routing is adapted in flight to maximize the number of monitored ships.

To make sure no communication problems occur with the ATC's it is advised to include a larger area in the flight planning than the actual envisioned routing (e.g. including the complete NHTSS from NH to FB2). For the planning of flight routes over Dutch waters it is advised to focus on the shipping lanes to and from Rotterdam (waypoints: NN1-NL11-NL7 and Maas Center) (see Figure 11)

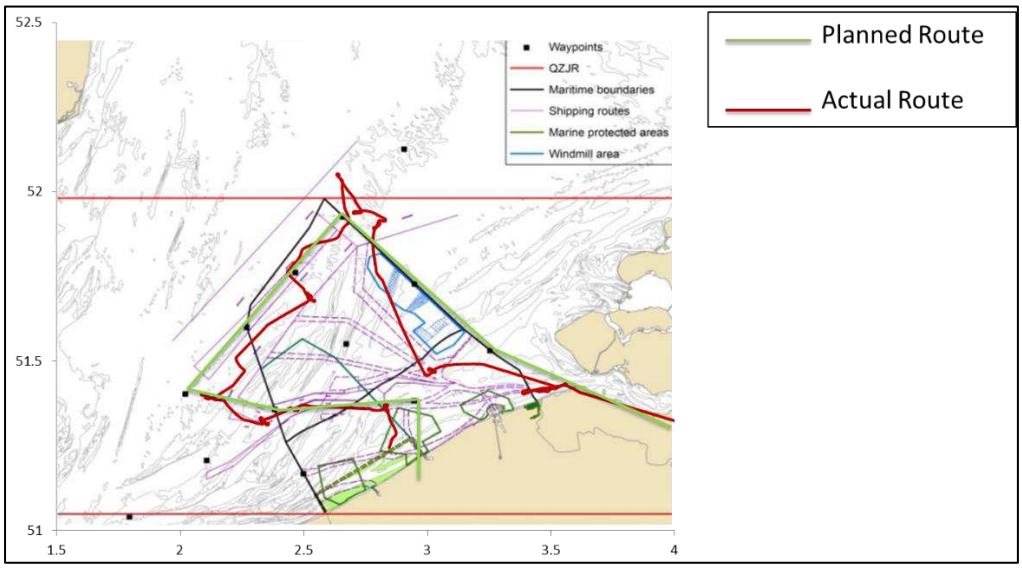
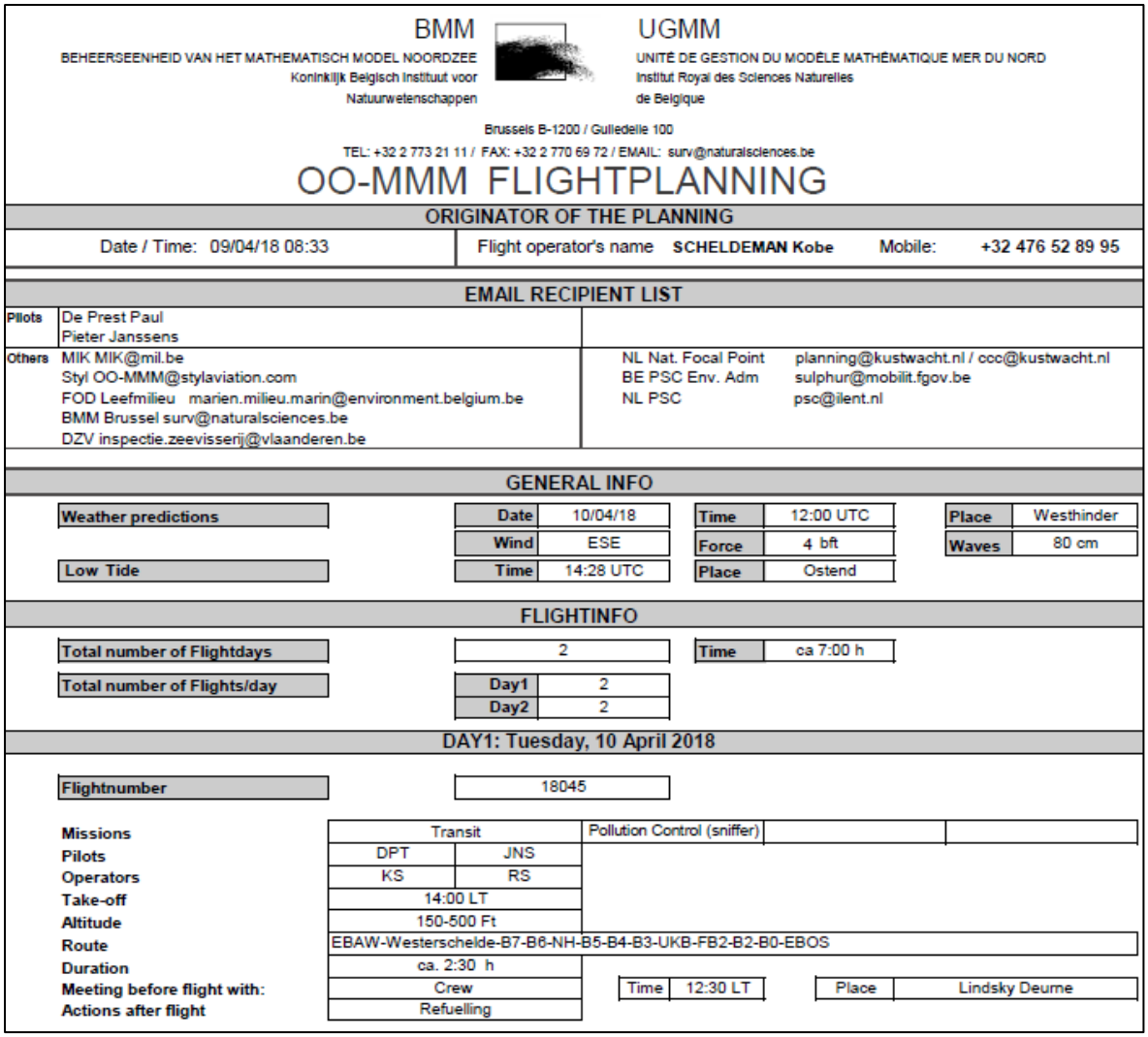


Figure 9 Example of planned and actual route of a MARPOL Annex VI monitoring flight in BE waters



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OO-MMM FLIGHTPLANNING

ORIGINATOR OF THE PLANNING

Date / Time: 09/04/18 08:33	Flight operator's name **SCHELDEMAN Kobe**	Mobile: +32 476 52 89 95

EMAIL RECIPIENT LIST

Pilots	De Prest Paul Pieter Janssens		
Others	MIK MIK@mil.be Styl OO-MMM@stylaviation.com FOD Leefmilieu marien.milieu.marin@environment.belgium.be BMM Brussel surv@naturalsciences.be DZV inspectie.zeevisserij@vlaanderen.be	NL Nat. Focal Point BE PSC Env. Adm NL PSC	planning@kustwacht.nl / ccc@kustwacht.nl sulphur@mobilit.fgov.be psc@ilent.nl

GENERAL INFO

Weather predictions	**Date**	10/04/18	**Time**	12:00 UTC	**Place**	Westhinder
	Wind	ESE	**Force**	4 bft	**Waves**	80 cm
Low Tide	**Time**	14:28 UTC	**Place**	Ostend		

FLIGHTINFO

Total number of Flightdays	2	**Time**	ca 7:00 h	
Total number of Flights/day	**Day1**	2		
	Day2	2		

DAY1: Tuesday, 10 April 2018

Flightnumber	18045					
Missions	Transit		Pollution Control (sniffer)			
Pilots	DPT	JNS				
Operators	KS	RS				
Take-off	14:00 LT					
Altitude	150-500 Ft					
Route	EBAW-Westerschelde-B7-B6-NH-B5-B4-B3-UKB-FB2-B2-B0-EBOS					
Duration	ca. 2:30 h					
Meeting before flight with:	Crew		**Time**	12:30 LT	**Place**	Lindsky Deurne
Actions after flight	Refuelling					

Figure 10 Example of Flight planning for Sniffer flight

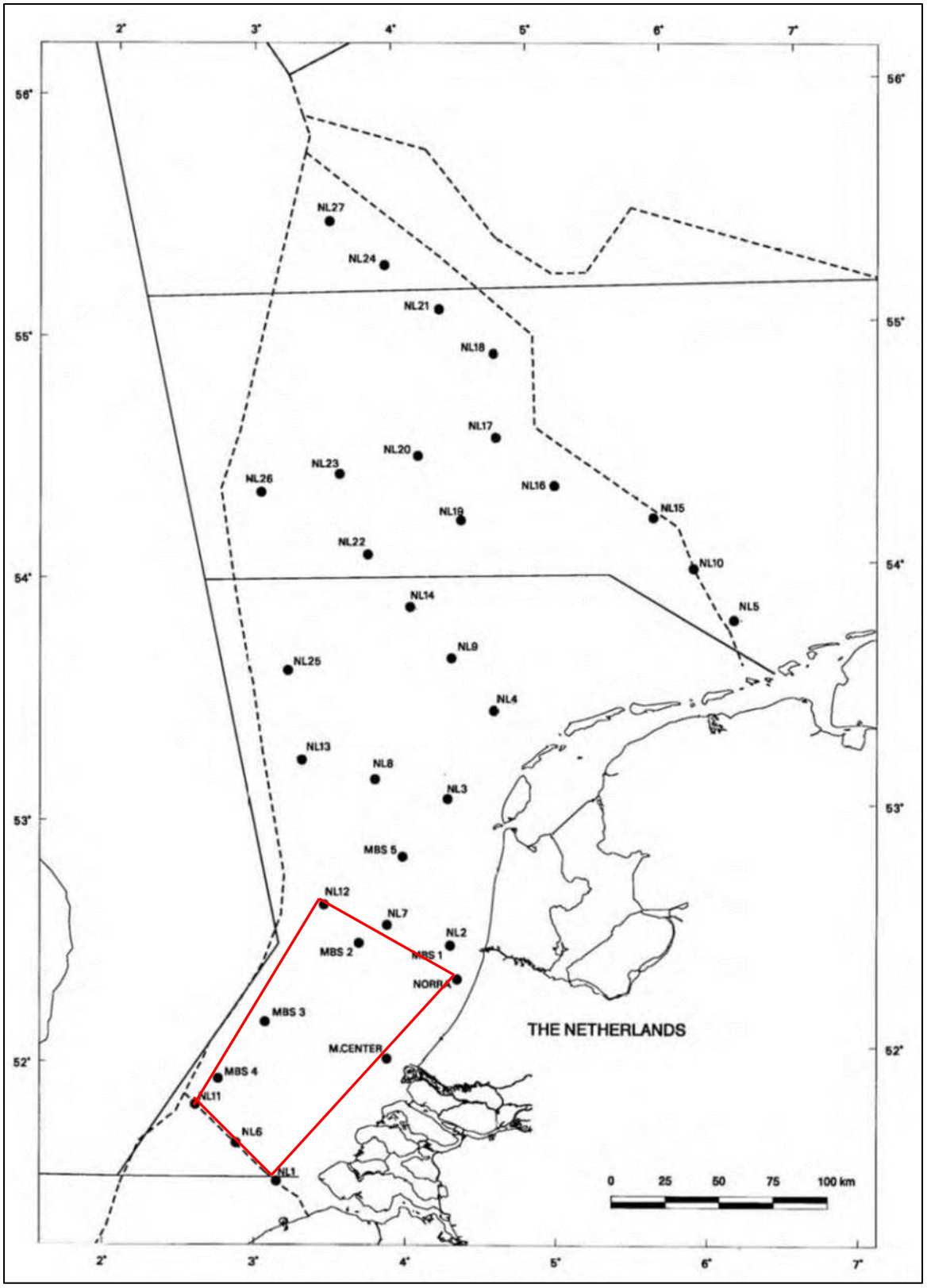


Figure 11 Dutch BA waypoints and main zone of interest (red)

2.3. On ground procedures before mission start (3hr before take-off)

The gas sensors used in the sniffer sensor systems are not stable in time and measurement results may vary according to environmental conditions (temperature, humidity, …), therefore detailed calibration and maintenance procedures have been described **Section 2 of the Sniffer Quality Management System**. Before every mission the sniffer software should be calibrated, therefore the basic procedures are provided in this section of the QMS. In case a hardware calibration is needed or in case the gas cylinders need to be calibrated, **Section 2 of the SQMS** should be consulted.

SOP 1.2. Power on Sniffer with GPU

1. Connect power extension cord (if operated in Ostend, place cable protector)
2. Connect GPU to external power input on sniffer battery, power on GPU,
3. Battery-switch must be turned in "External" mode towards the nose of the AC (LED light is ON)
4. Toggle the sniffer-switch at console operator seat (at intercom jacks)
5. Toggle the EPS switch of the sniffer pumps (right side of the console)
6. Check circuit breaker on emergency sniffer battery (must be pressed in)
7. Check the power use on the GPU (must be lower than 30amp at startup)

Note: when the sniffer battery is fully drained and/or the sniffer is powered through the AC circuit instead of the EXT circuit, leave the pumps off for 1 hour after system startup

SOP 1.3. Laptop installation

1. Install laptop in RAM mount and connect thunderbolt
2. Switch on laptop
3. Connect to MUMM_LOG_PC using Teamviewer (V12) use 192.168.1.9 (make sure Teamviewer accepts LAN connections) and pwd: "mumm"
4. On personal Laptop open SQMS-Follow-up.xlsx on Sniffer data>>Calibration, in the header of the different active gas components (CO2-1(#), CO2-2(#), SO2 (#), NO (#)) it is indicated if a software calibration, hardware calibration or Gas cylinder calibration is required.

Note: Sniffer has to be warmed up at least 60-120 minutes before every calibration and sniffer flight. For NOx: check the error log MAIN MENU>>Analyser State Menu>>Status Menu status>>show error list OR press on the orange light with a narrow pen. In case "Instrument warm-up" is indicated, the sensor is not yet ready- the sniffer should not be switched off from the moment the software calibration is done until the end of the mission (even if the mission is spread over several days).

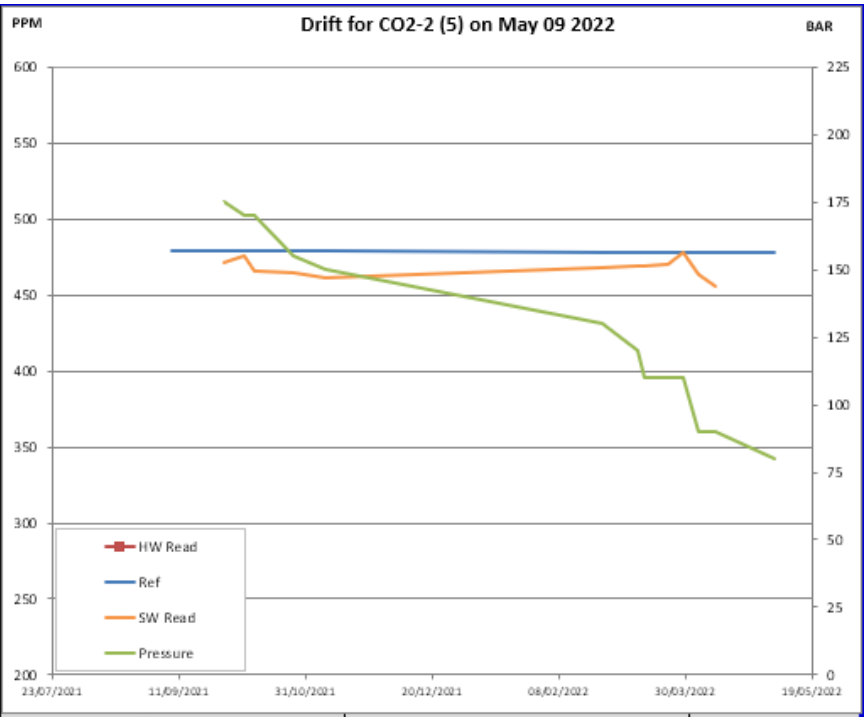
SOP 1.4. Software calibration

1. Put chart with cylinders next to aircraft (ca 3 m)
2. Connect flexible hose to pitot tube via Swagelok 3/8 with inner Nylon ferrule (tighten finger tight and use 3/4 wrench to tighten 1 quarter)
3. Set the carbon filter below the pilot seats from "Ground" to "Air" mode
4. Open SQMQ followup file 0. QMS\2. SNIFFER QA\QA_Follow-up
5. Open gas sheets (green tabs) and go to gas sheets
6. Enter date in first column, use Ctrl+; as shortcut
7. Check if the ref concentrations matches the reference gases (indicated in writing on cylinder)
8. Open IGPS Real (on MUMM_LOG_PC using Teamviewer)
9. Go to SNF in IGPS Software
10. Open calibration for CO2, if none present create new one (Figure 14)

   a. Select "Main component": CO2
   b. Check concentration and edit if necessary (300-450 **ppm**)
   c. Set "Time": 60 Sec

11. Open gas cylinder valve
12. Connect flexible hose to CO2 reference gas cylinder via Swagelok 1/4" (tighten fingertight and turn 1 quarter with a 7/16 wrench)
   a. Check pressure of the gas bottle on first manometer (min 10 bar)
   b. Check pressure of the output on second manometer (must be 2 bar)
   c. Check if over flow is 0.6-0.08 l/min, if necessary adjust volume (ca 9-11 l/min)
   d. Check reading of CO2 on IGPS software (check also if SO2 is zero)
   e. Check reading on IGPS, wait (60 sec) until stable
13. On IGPS software start calibration (green light appears)
14. After calibration (60 seconds) a comment will be shown in comment log
15. Disconnect the flexible tube
16. Close cylinder valve and fill in end pressure in active CO2-sheet in SQMS-Follow-up.xlsx
17. Repeat steps 11-16 for the second CO2 gas mixture
18. Open SO2 (#) sheet and enter date (use Ctrl+;)
19. Check if the ref concentration matches the SO2 reference gas
20. Go to SNF in IGPS software
21. Open calibration for SO2, if none present create new one (see Figure 14)
   a. Select "Main component": SO2
   b. Check concentration and edit if necessary (300-400 ppb)
   c. Set "Time": 120 Sec
22. Open gas cylinder valve
   a. Connect flexible tube with the SO2 reference gas cylinder via Swagelok 1/4" (tighten finger tight and turn 1 quarter with a 7/16 wrench)
   b. Check pressure of the gas bottle on first manometer (min 10 bar)
   c. Check pressure of the output on second manometer (must be 1.5 bar)
   d. Check if overflow is 0.8 l/min, if necessary adjust volume (ca 9-11 l/min)
   e. Check reading of SO2 on IGPS software
   f. Check reading on IGPS, wait (60 sec) until stable (check also if CO2 is zero)
23. Select "Start calibration"
   a. green light appears
   b. message appears: merge with old calibration: click "yes"
24. After calibration (120 seconds) a comment will be shown in comment log
25. Disconnect the flexible tube
26. Close cylinder valve and fill in end pressure in SO2-sheet in SQMS-Follow-up.xlsx
27. go to Settings>>Utilities and check "k" and "o" for SO2 stream and Licor 7200 - CO2 and copy these calibration factors to the SQMS-Follow-up.xlsx sheets (see Figure 15)

Manufacturer	Airplus
Gas botle ref	JA95ND8
MUMM reference	CO2-2 (5)
Purchase date	
Delivery date	
Start date	06/08/2021
End Date	
Duration	276 Days
Requested concentration	470.0 PPM
Commercial concentration	479.4 PPM
Warranty	22/05/2026
Error absolute	
Error percentage	0.500%
Actual error	0%
Traces of SO2	0.0 PPB
Traces of NO	0.4 PPB
Traces of NO2	0.0 PPB
Nr of calibrations for 50 bar	
Pressure for GAS calibrati	7.3
Date of last HW calibration	04/05/2022
Date of last gas calibration	21/02/2022
Date of last HW Check	27/01/2020
SW calibration needed	Yes
HW calibration needed	No
Referene Gas Drift	0.15%
Software drift	1.32%
Sensor drift	Data Missing
Gas calibration warning	Yes
Gas +1 calibration warning	
HW check needed	Yes



Date of calibration	REF	Software		Hardware		Pressure
		SW k-factor	SW Offset (o)	HW Read	HW Zero	
14/03/2022	478.0 PPM	1.010	4.500			110 Bar
23/03/2022	478.0 PPM	1.006	5.100			110 Bar
29/03/2022	478.0 PPM	1.000	0.000	477.0 PPM	0.5 PPM	110 Bar
04/04/2022	478.0 PPM	1.020	5.300			90 Bar
11/04/2022	478.0 PPM	1.028	9.586			90 Bar
04/05/2022	478.0 PPM			478.0 PPM	-0.4 PPM	80 Bar

Figure 12 Print screen from the SQMS-Follow-up.xlsx file



Figure 13 During calibration the aircraft is powered with the GPU connected to the Power input (A) and the Switch (C) set to "EXT", the led indicator will light up when the battery is receiving power (B)

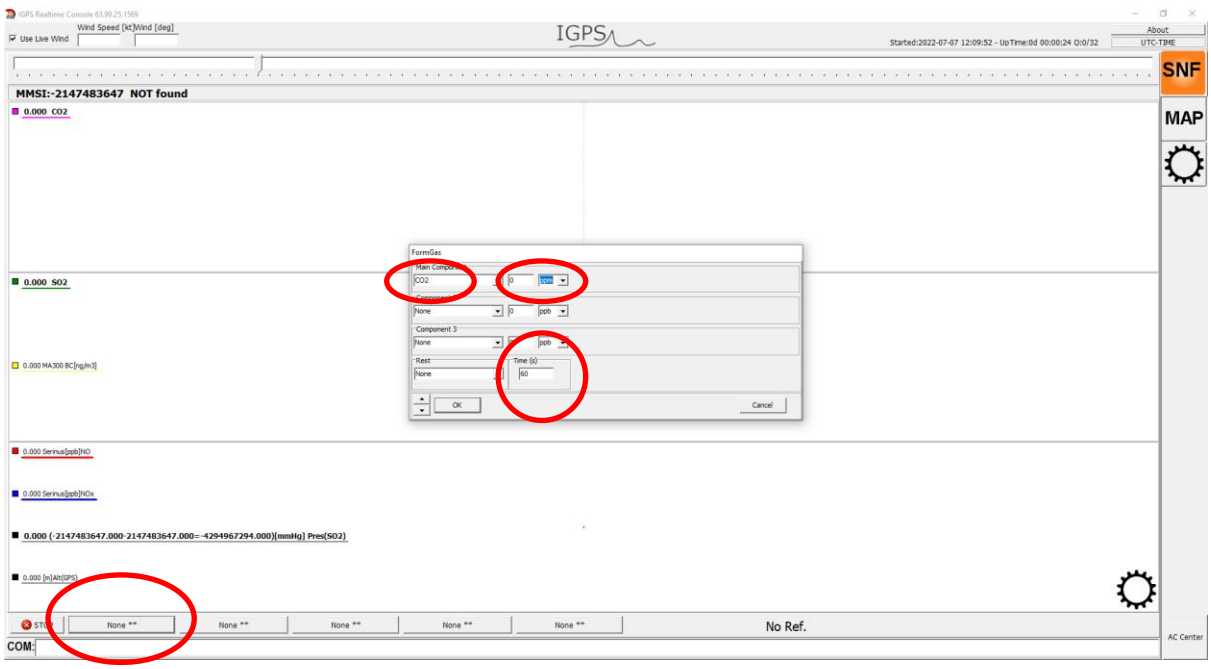


Figure 14 To start new calibration setting, select "None" in "SNF" view, a pop-up window will open, select the component (SO2 or CO2) enter concentration (in ppb or ppm) and select time (120 sec for SO2; 6O sec for CO2)**

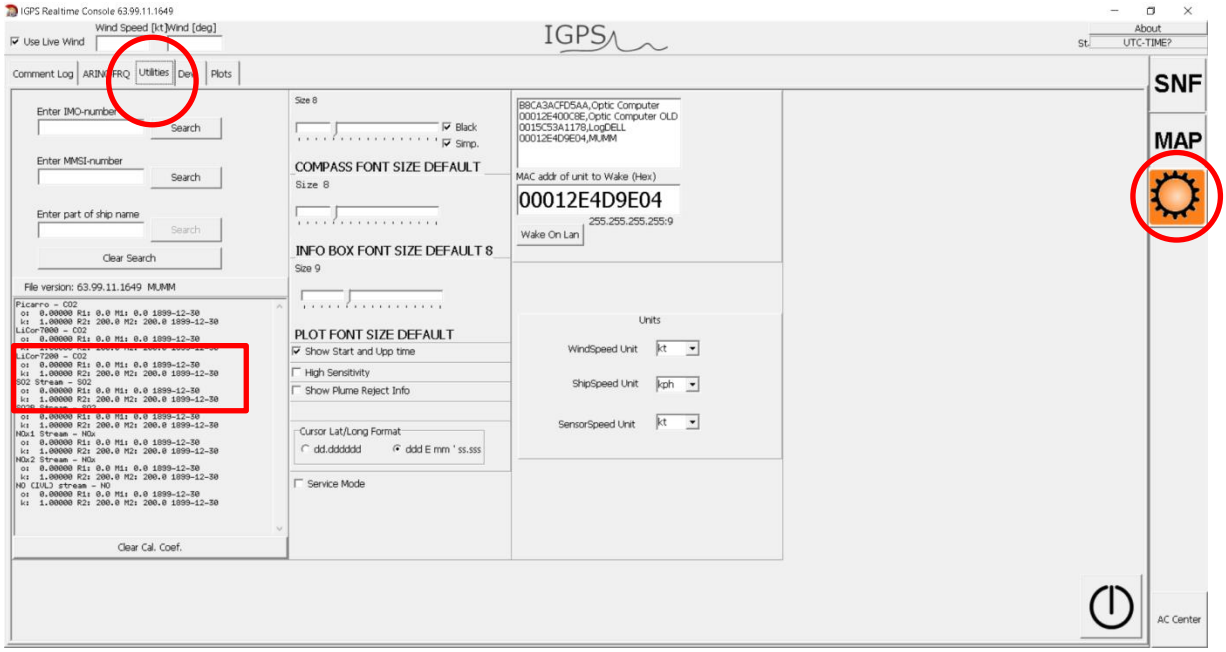


Figure 15 After (complete) calibration the new calibration factors (k and o) are visible under settings view (cog wheel) under "Utilities" tab

The NOx sensor requires a hardware calibration. The calibration gas mixture is NO in nitrogen, this mixture is used for both the NO as the NOx calibration.

SOP 1.5. NO hardware calibration

1. For the NO calibration connect the smartphone to the Serinus
    a. Open Serinus application
    b. Click connect
    c. To improve the connection keep the device close to the sensor
2. Set the sensor to "all mode"
    a. Quick menu
    b. Gas to measure
    c. Set to "All"
3. Set Sensor to 30 second averaging time
    a. Go to Main Menu>>Measurement menu
    b. Go to Filter
    c. Set to 30 s filter
4. Open synthetic air gas cylinder
5. Connect flexible tubing to the Synthetic air gas supply
6. Write down the concentration of NO (zero)
7. Go to Calibration menu
    a. Main Menu >> Calibration menu
    b. Scroll down to zero NO
    c. Click select >> if an error message appears click "confirm"
    d. Scroll down to Zero NO2
    e. Click select >> if an error message appears click "confirm"
8. On the IGPS SNF graph look at the NO and NOx signal, If both NO and NOx stay within +/- 5 ppb continue otherwise repeat step 33
9. Disconnect synthetic air from flexible hosing, close the cylinder valve

10. Open NO gas cylinder
11. Connect flexible tubing to the NO gas supply
12. Write down the NO concentration (span)
13. Go to Calibration menu
    a. Main Menu >> Calibration menu
    b. Scroll down to Span NO
    c. Check if the concentration matches with the concentration on the cylinder and SQMS-followup.xls file
    d. Wait 1 minute
    e. Click select
    f. Scroll down to Span NOx
    g. Check if the concentration matches with the concentration on the cylinder and SQMS-followup.xls file (NO+NO2 concentration)
    h. Wait 1 minute
    i. Click select

Note: NOx signal must always be (slightly) higher than NO

14. On the IGPS SNF graph look at the NO and NOx signal, If both NO and NOx stay within +/- 5 ppb of the reference and NOx>NO, continue otherwise repeat step 39
15. Disconnect NO from flexible hosing, close cylinder valve
16. Set the filter back to none
    a. Go to Main Menu>>Measurement menu
    b. Go to Filter
    c. Set to “none “
17. Set the sensor back to NOx
    a. Quick menu
    b. Gas to measure
    c. Set to “NOx”
18. Write down the span and zero concentration in the SQMS-Follow-up.xlsx file

At the end of the calibration procedure the sniffer sensor is tested with two gas mixture of CO2 and SO2 in synthetic air simulation a low (ca 0.1-0.5% FSC) and a high FSC plume (ca. 1-2.5% FSC).

SOP 1.6. Plume simulation mixture check

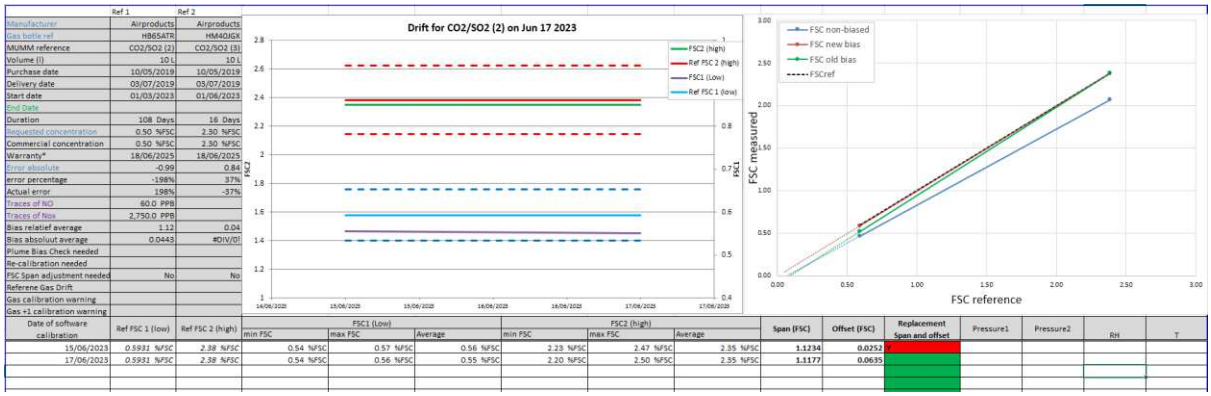
1. Open IGPS present on personal laptop (**do not use** MUMM_LOG_PC)!!
2. Make sure the background values are stable for 1 min
3. Keep the opening of the tubing upwind, avoid breathing out close to the tubing end
4. Start with the low FSC mixture
5. Place the plume simulation mixture cylinder with the opening downwind
6. Open the cylinder valve, check the pressure
7. Release a few sudden bursts of gas to purge the regulator
8. Hold the opening of the tubing a few cm in front of the regulator
9. Open the toggle valve for <1 sec
10. Check if the values for SO2 and CO2 are within limits
    a. CO2 should be below 2000 ppm

   b. SO2 should be below 2000 ppb
   c. Clear peaks no background

11. Conduct a FSC measurement (see 3.3.1) and link the measurement to the emulated AIS detection in the equator
12. Wait 1 min
13. Repeat steps 7-11 two more times
14. Write down the min and max FSC in xls file sheet CO2+SO2 under FSC1
15. Continue with the high FSC mixture
16. Open the cylinder valve, check the pressure
17. Release a few sudden bursts of gas to purge the regulator
18. Hold the opening of the tubing a few cm in front of the regulator
19. Open the toggle valve for <1 sec
20. Check if the values for SO2 and CO2 are within limits
   a. CO2 should be below 2000 ppm
   b. SO2 should be below 2000 ppb
   c. Clear peaks no background
21. Conduct a FSC measurement (see 3.3.1) and link the measurement to the emulated AIS detection in the equator
22. Wait 1 min
23. Repeat steps 17-21 two more times
24. Write down the min and max FSC in xls file sheet CO2+SO2 under FSC2
25. The updated FSC span and offset are displayed in column O and P
26. Check if the measured FSC falls within the acceptable limits
   a. On graph the average FSC (Red line) must fall withing the dotted lines
   b. The FSC values that fall outside the limit will be highlighted in red
27. In case the average values falls outside the limits, the new span and offset must be entered in the ini file for all IGPS stations used for the measurements (on 1) operator laptop and 2) MUMM-LOG-PC)
   a. Close IGPS present
   b. On MUMM-LOG-PC only: close watchdog and close IGPS present again
   c. Open C:\IGPS\AISPresent.ini
   d. Scroll down to:

      ….
      FSC_Span = 1.2571
      FSC_Offset = 0.0007
      ….

   e. Replace the old span and offset values with the new offset and span values
   f. Save the AISPresent.ini file
   g. On MUMM-LOG-PC reopen watchdog from C:\IGPS\WatchdogIGPSpresent
   h. Set the value in column K to “Y”
   i. Open C:\IGPS\Thresholds, BIAS and SFOC-2022.xls go to sheet “FSC→Bias correctie”
   j. Enter flight number and date
   k. Copy the new FSC span and offset values
28. In case the average FSC value does not fall outside the limits
   a. Set the value in column K to “N”



	Ref 1	Ref 2
Manufacturer	Airproducts	Airproducts
Gas bottle ref	HB65ATR	HM40JGK
MUMM reference	CO2/SO2 (2)	CO2/SO2 (3)
Volume (l)	10 L	10 L
Purchase date	10/05/2019	10/05/2019
Delivery date	03/07/2019	03/07/2019
Start date	01/03/2023	01/06/2023
End Date		
Duration	108 Days	16 Days
Requested concentration	0.50 %FSC	2.30 %FSC
Commercial concentration	0.50 %FSC	2.30 %FSC
Warranty*	18/06/2025	18/06/2025
Error absolute	-0.99	0.84
error percentage	-198%	37%
Actual error	198%	-37%
Traces of NO	60.0 PPB	
Traces of Nox	2,750.0 PPB	
Bias relatief average	1.12	0.04
Bias absoluut average	0.0443	#DIV/0!
Plume Bias Check needed		
Re-calibration needed		
FSC Span adjustment needed	No	No
Referene Gas Drift		
Gas calibration warning		
Gas +1 calibration warning		

Date of software calibration	Ref FSC 1 (low)	Ref FSC 2 (high)	FSC1 (Low)			FSC2 (high)			Span (FSC)	Offset (FSC)	Replacement Span and offset	Pressure1	Pressure2	RH	T
			min FSC	max FSC	Average	min FSC	max FSC	Average							
15/06/2023	0.5931 %FSC	2.38 %FSC	0.54 %FSC	0.57 %FSC	0.56 %FSC	2.23 %FSC	2.47 %FSC	2.35 %FSC	1.1234	0.0252					
17/06/2023	0.5931 %FSC	2.38 %FSC	0.54 %FSC	0.56 %FSC	0.55 %FSC	2.20 %FSC	2.50 %FSC	2.35 %FSC	1.1177	0.0635					

Figure 16 SQMS-follow up file with CO2+SO2 sheet

2.4. Before take-off

SOP 1.7. Power switch before take off

1. Keep GPU power up to 5 min before starting of the engines
2. Check power on GPU (must be lower than 25 Amp)
3. Request pilots to switch on Survey Power
4. Set battery switch to “AC” (check if green led indicator is on)
5. Disconnect power cable of GPU
6. Disconnect cabling from GPU to Battery
7. Check if external sniffer battery takes-over power supply without interruption

2.5. Mission preparation after engine start

After the starting up of the engines, but (optimally) before take-off the final preparations need to be performed to be able to check for eventual malfunctioning. This can be done during taxiing

SOP 1.8. Mission startup.

1. Check power, this can be confirmed by checking the EPS light on the console, in case the survey power is online this light should be white.
2. Start-up console and enter “Mission login” information
3. Start VM on console (GUI>>Control >>FLIRA615) (see)
4. Disconnect VGA converter (VM toolbar Devices>>USB>> Magic Air>>Disconnect USB Device) (see)
5. Reconnect VGA converter (VM toolbar Devices>>USB>> Magic Air>>Connect USB Device)
6. Activate extended view (In Windows XP Task bar>> right click orange symbol>>select extended view) (see)
7. Open DVR video signal one (GUI>>DVR>>Matrix click on the block under video 1) a new black window will be opened (see)
8. Check with Pilots if Video 2 is selected on the Avalex cockpit display
9. Open “AIS-Present” on VM
10. Switch to SNF, zoom in on chart and activate Y-bar scale
11. Restore the AIS present window
12. Move the AIS-present window right (should become visible on the DVR window)
13. Maximize AIS-present (right click on window and select maximize)
14. Open Teamviewer V12, connect to MUMM_LOG_PC (IP: 192.168.1.9, pwd: “mumm”)

15. Adjust the AIS present on the MUMM_LOG_PC to optimize the map for the pilots

16. All other aspects of the general flight preparation on the console can now be committed

- **a.** Enter Flight routing
- **b.** Enter weather information
- **c.** Enter mission times in Time Manager
- **d.** Adjust ECS (activate AIS track and vector)
- **e.** Open the event manager
- **f.** Open the AIS info window

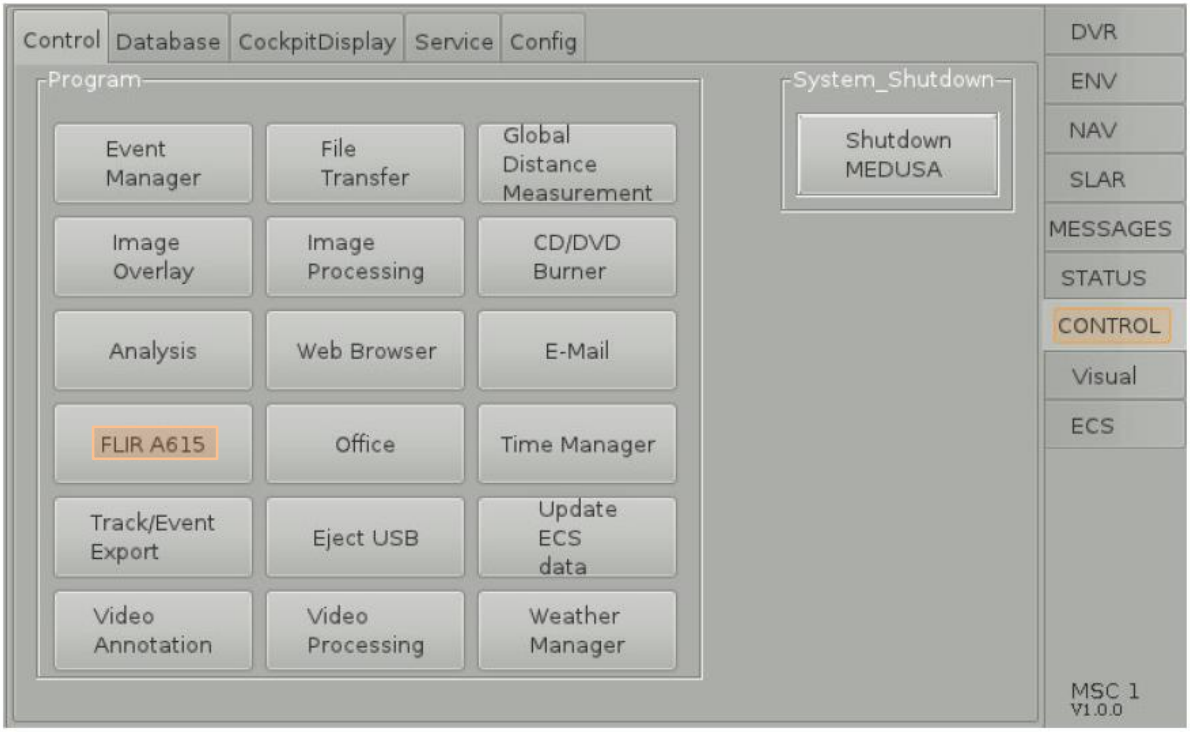


Figure 17 GUI window to launch VM

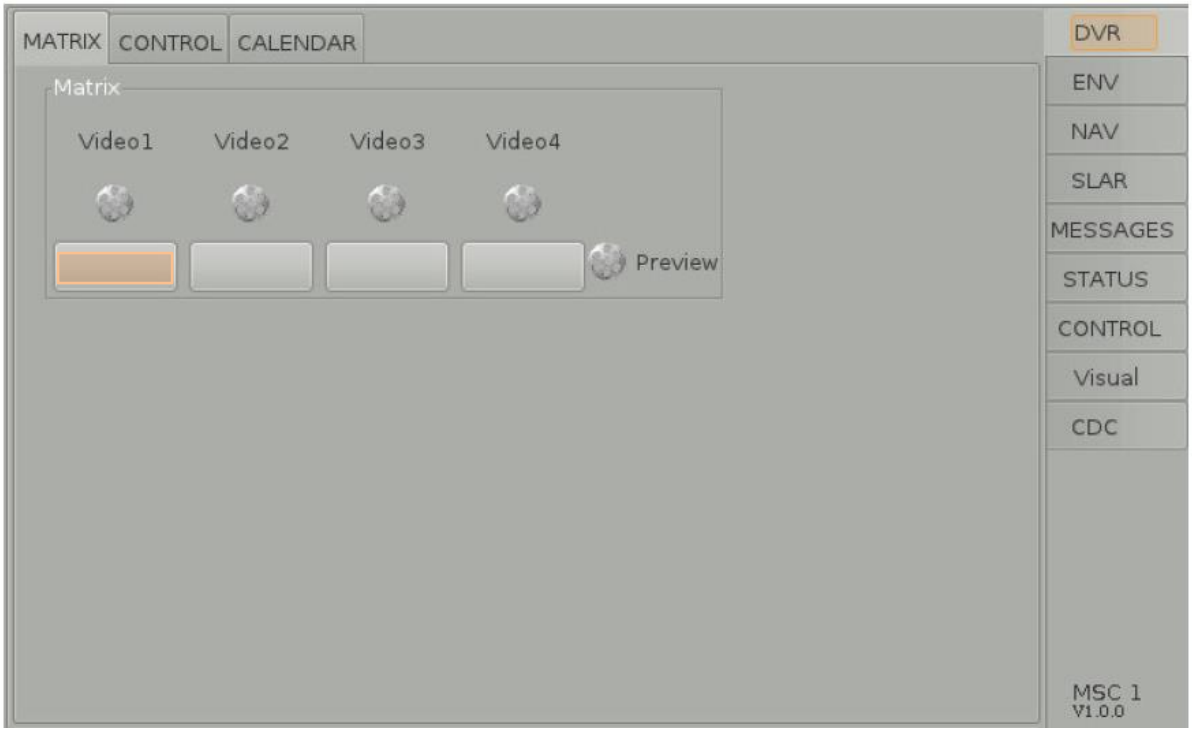


Figure 18 GUI window to activate the DVR window

CHAPTER 3. IN-FLIGHT OPERATION

To optimally conduct sniffer flights the flights needs to be performed by 2 pilots and 2 operators. The whole crew will need to work closely together during flight and a proper and efficient communication protocol needs to be established for this purpose .

3.1. Flight Approach

The monitoring of ship plumes with a sniffer sensor is not without risk and a well-considered flight approach is recommendable. For fixed-wing aircraft with sniffer sensors, 5 different scenarios for flight approaches can be defined according to the wind vector (Vw = direction and force) and the ship vector (Vs = course and speed).

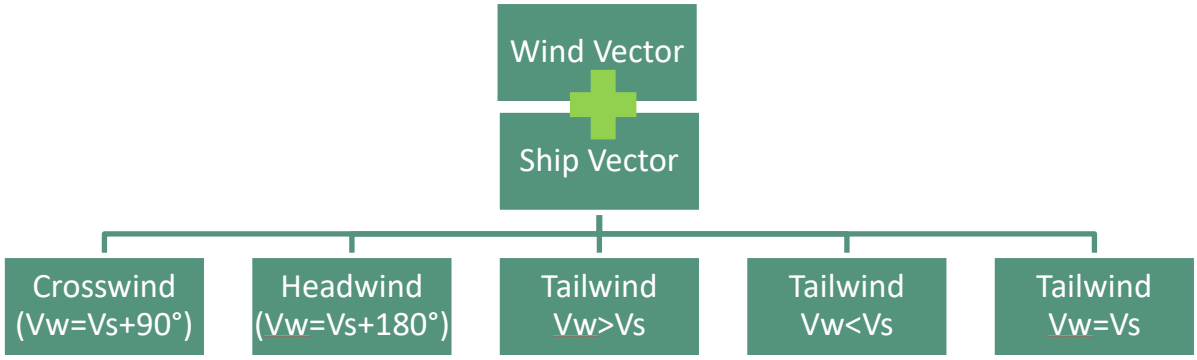


Figure 19 Flight pattern: 5 scenarios

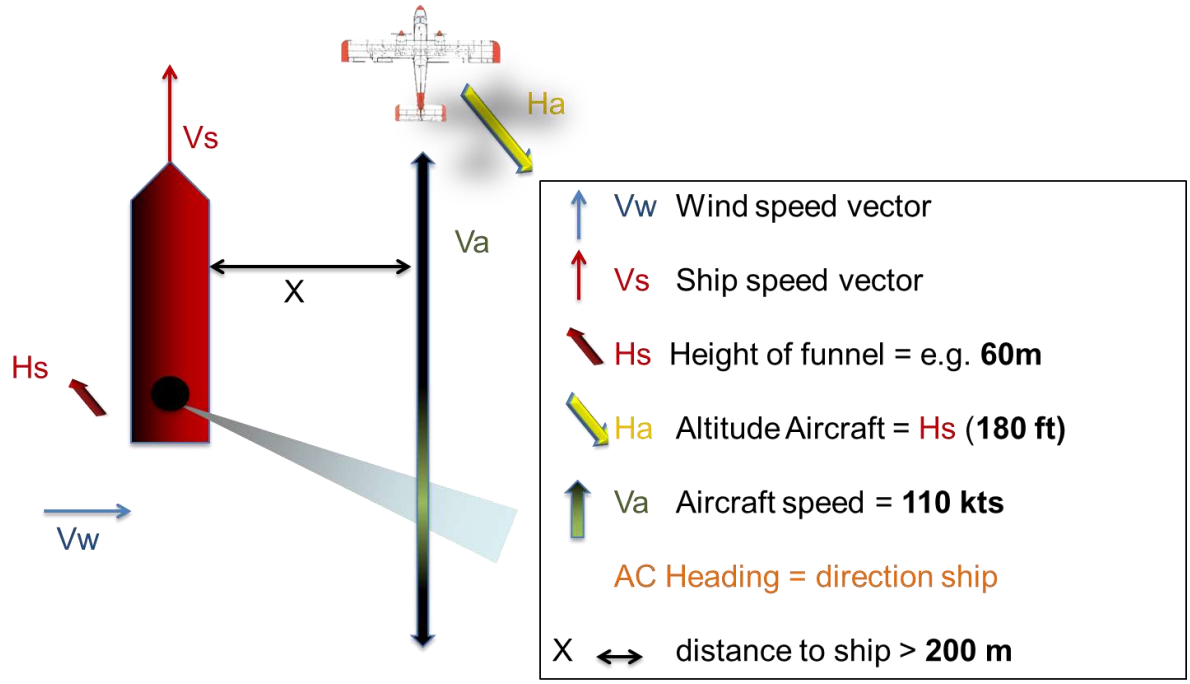


Figure 20 Crosswind Scenario (Vw = Vs +90°)

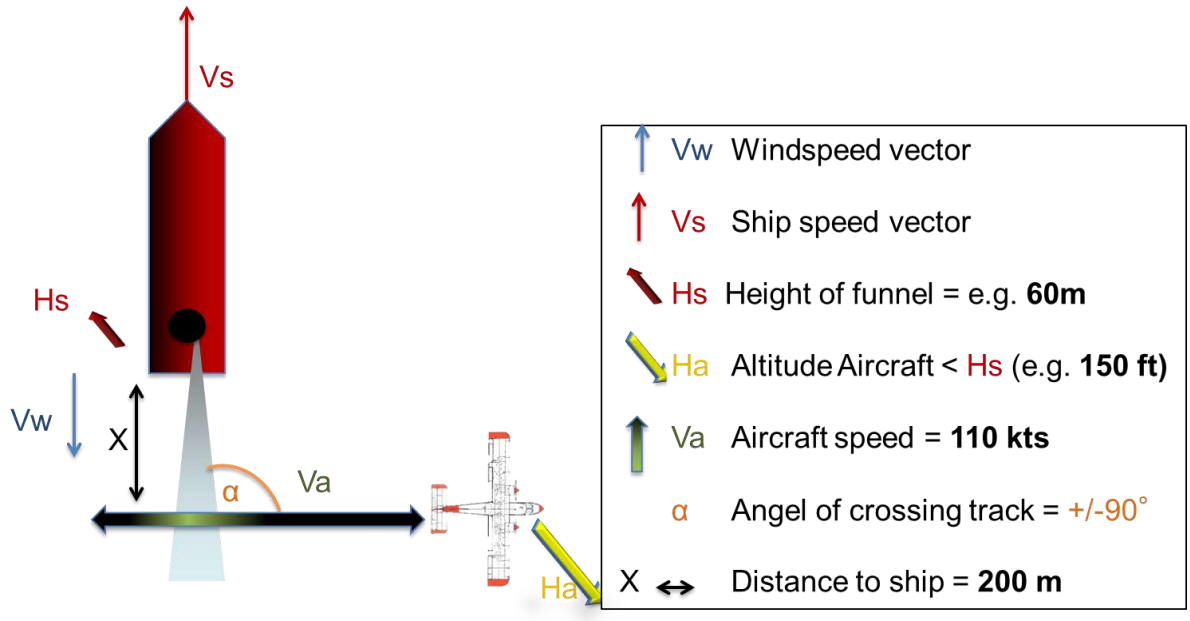


Figure 21 Headwind Scenario (Vw = Vs + 180°)

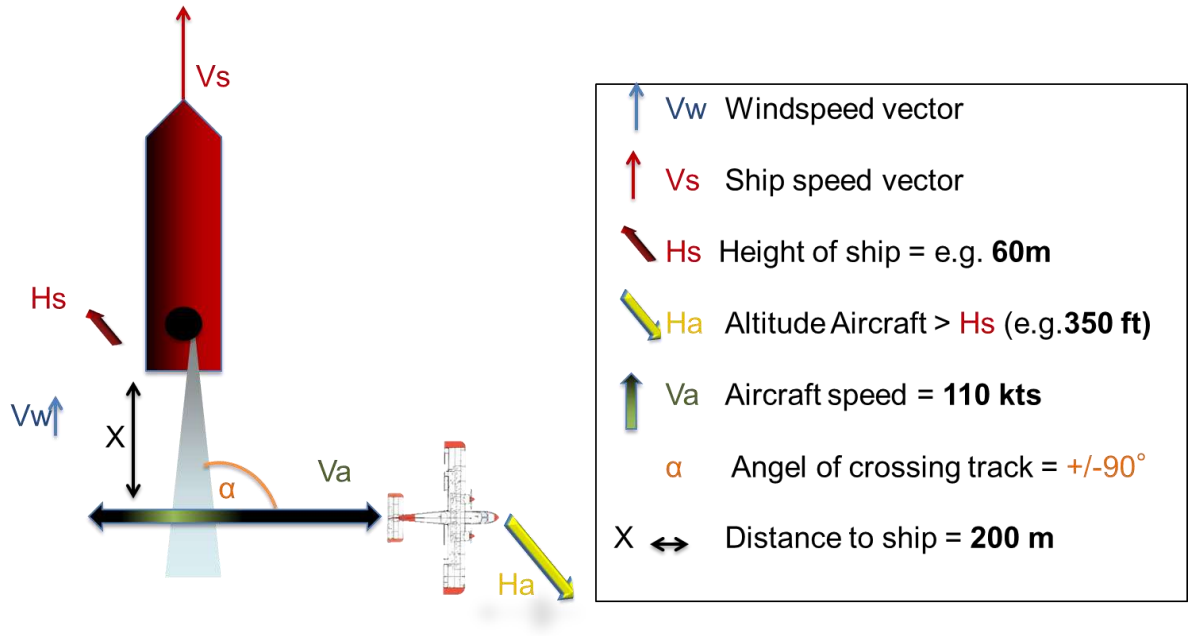


Figure 22 Limited tailwind Scenario (Vw<Vs)

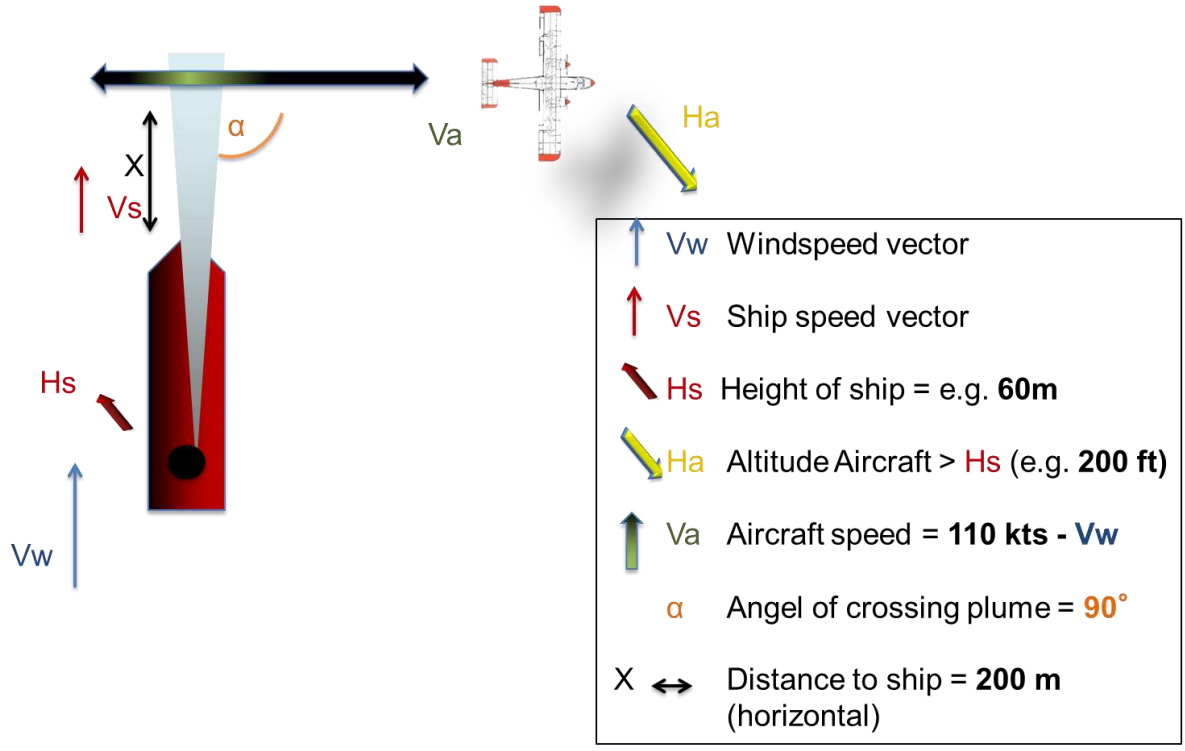


Figure 23 Strong tailwind Scenario (VS<VW)

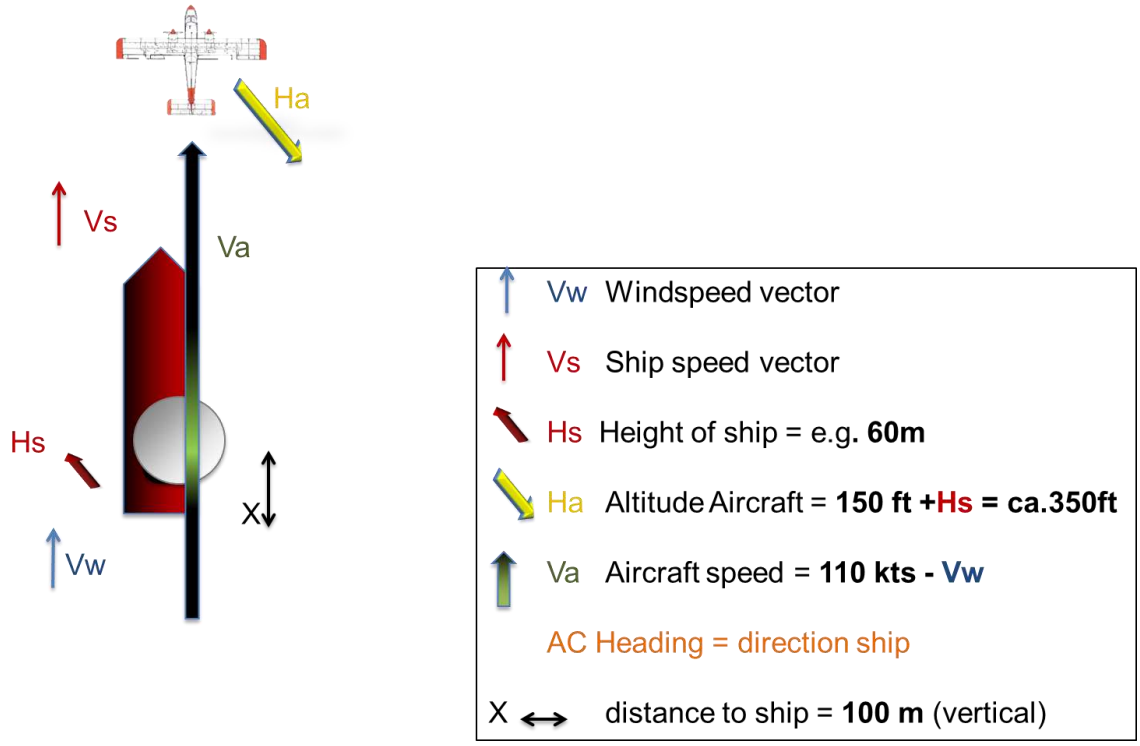


Figure 24 Vertical plume scenario (Vw=Vs)

The main principle is that the exhaust plume is sampled in a straight line with a heading never directly towards the ship, against the apparent wind direction with an angle of ca. 90° relative to the direction of the exhaust plume. Depending on the angle of the wind, the plume may be found higher or lower than the funnel height. In 4 out 5 scenarios the plume is sampled downward wind (wind will move the aircraft away from the ship), only in case of a soft tailwind, the wind may be blowing the aircraft towards the ship but at negligible force (<10 kts). To optimally plan the approach, it is important that the pilots have a good understanding on the location of the plume, therefore the use of well-developed navigation software and communication with the pilots is vital (see 3.5).

In 4 out of 5 scenarios, the aircraft never has to fly directly over the ship. Only in the (rare) scenario with tailwind where Vw = Vs giving a vertical smoke plume, the aircraft has to fly over the ship. In all other cases, a minimum distance of 200m from the ships is recommended.

3.1.1 Altitude

For safety reasons a minimum altitude of 150ft is recommended for MARPOL Annex VI monitoring For the time between sniffer measurements it is advised to fly at 500ft (or more, depending on the time between 2 measurements) for safety reasons and communication with air traffic control authorities.

3.1.2 Distance to ships

For safety reasons, the ship plumes should not be monitored closer than 150m from the ship with fixed-wing aircraft with sniffer sensor, the maximum distance that an efficient measurement can be executed is ca. 2000m but this is strongly depending on the prevailing wind conditions, the ship characteristics and the exhaust plume.

3.1.3 Speed

The recommended indicated air speed (IAS) to execute sniffer measurements is 100–120 kts. The stall speed of the Belgian coast guard aircraft is 35 kts, but for sniffer flights the operational speed is 110 kts with engine power settings of 59%.

3.1.4 Plume localisation

The localisation of a ship's exhaust plume can sometimes be challenging, even with (2D) software models and an experienced aircrew. The current IGPS Real software is providing the estimated direction of the exhaust plume and is able to visualize the plume location on a nautical chart together with the AIS information. The software is not able to estimate the height of the centre of the plume. As a result several measurement attempts might be required before a successful measurement can be made.

In case there is no visual indication of the height of the plume, it is recommended to do the first measurement at funnel height, if needed followed by a second and/or third measurement attempt which can be done 25-50 ft higher or lower than the funnel height. Depending on the wind conditions it might be necessary to make a full 360° turn (in case of strong wind) or only a 180° turn (in case of moderate wind) for a consecutive measurement attempt. The information of the relative plume height (compared to the funnel) can be used for following measurements for ships with same heading and speed.

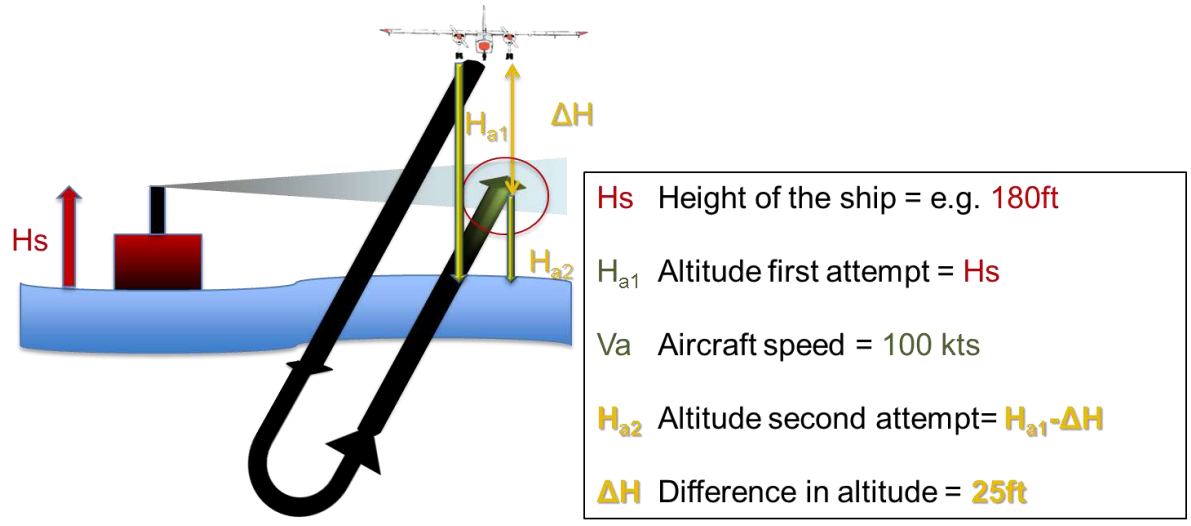


Figure 25 Sampling procedure in case the first attempt was not successful (low to moderate wind conditions).

3.2. Console operator

The console operator is responsible for the following tasks in flight:

- Selecting the ships for inspection (3.2.1)
- Communicating the position and the smoke plume location to the pilots (3.2.2)
- Evaluate measurement quality (3.2.3)
- setting the mode of the NOx sensor (3.2.4)
- conducting the radio communication (for NOx) (3.2.5, **Annex C** - Radio communication checklist),
- taking notes (FSC, NOx, Number of attempts and engine parameters)
- creating the reports of non-compliant ships (Reporting to PSC).

3.2.1 Ship selection

The main purpose of airborne MARPOL Annex VI monitoring is currently still on the effective targeting of ships for port state inspection, and therefore as many different ships as possible must be monitored at sea at various locations. Some limitations apply:

- Only ships on-route should be monitored
- Only ships with length larger than 100m should be monitored, this differs according to the wind conditions and ship type, in most conditions a minimum of 130m is more adequate

In case certain ships or companies are repeatedly observed to be non-compliant, these ships or companies can be inspected priory. On the other hand, if certain ships are repeatedly observed to be compliant, these ships can sometime be skipped to reduce flight time (see Figure 26).

SOP 1.9. To select a ship for inspection

1. make sure that “only moving” ships is enabled
    a. Go to MAP (a)
    b. Select settings tab in bottom right (h)
    c. Activate “only moving ships”
    d. Ships are displayed according to size (d)
2. Move with the cursor over the different ships, AIS info is displayed in top left corner, to select useful ships
    a. Look at the size (>100m)
    b. Look at the speed (slow moving ships are still displayed but should not be selected)
    c. Look at the age to identify Tier
3. Double click on ship (will get a red circle)
4. When other users select ships, the ships will get a magenta circle

LNG ships

Gas tankers running on boil off gasses emit almost no SO2, these ships can be monitored although the often generate zero or even negative FSC values. However some gas tankers have permission to use high sulphur fuel oil for emergency purposes, this should be evaluated by the PSC inspector.

EGCS or scrubber ships

Ships equipped with emission abating methods (Exhaust Gas Cleaning Systems or scrubbers) are running on high sulphur fuel oil, but the exhaust gasses are threaded resulting in emissions with lower SO2/CO2 ratio (calculated FSC) than regular 0.1% LSFO ships. Scrubber ships should be inspected regularly to evaluate the proper working of the scrubber system.

3.2.2 Communication with pilots

When ships are selected they are visible to the pilots on the MAP 2 screen. The zoom levels needs to be set by the operators (this can be done by connecting to the MUMM-PC using TeamViewer). Once the ships are selected, the operator decides which ship to inspect first. The compass (b) together with the white heading line (c) is used to give the heading to the next ship, the distance spheres (g) give the relative flight time (1,2,5,10min). For the selected ships, the software will provide an indication of the smoke plume position relative to the ship (f) using the 12hr direction system this position can be shared quickly to the pilots. Following information should be provided to the (co)pilot:

- Heading to the next ship (b+c): in English xxx° (pronounce all digits individually)
- Time to the next ship (g): x min
- Position of the smoke plume (f): xx o'clock
- E.g.: Target at three zero zero; 1 minute; smoke at three o'clock

When getting closer to the next target should be provided so that pilots can orientate and optimize the flight pattern. When the ship is measured the graphs will show this to the pilot (Video 2) and the console operator (DVR-1) when the measurement is successful this should be communicated.

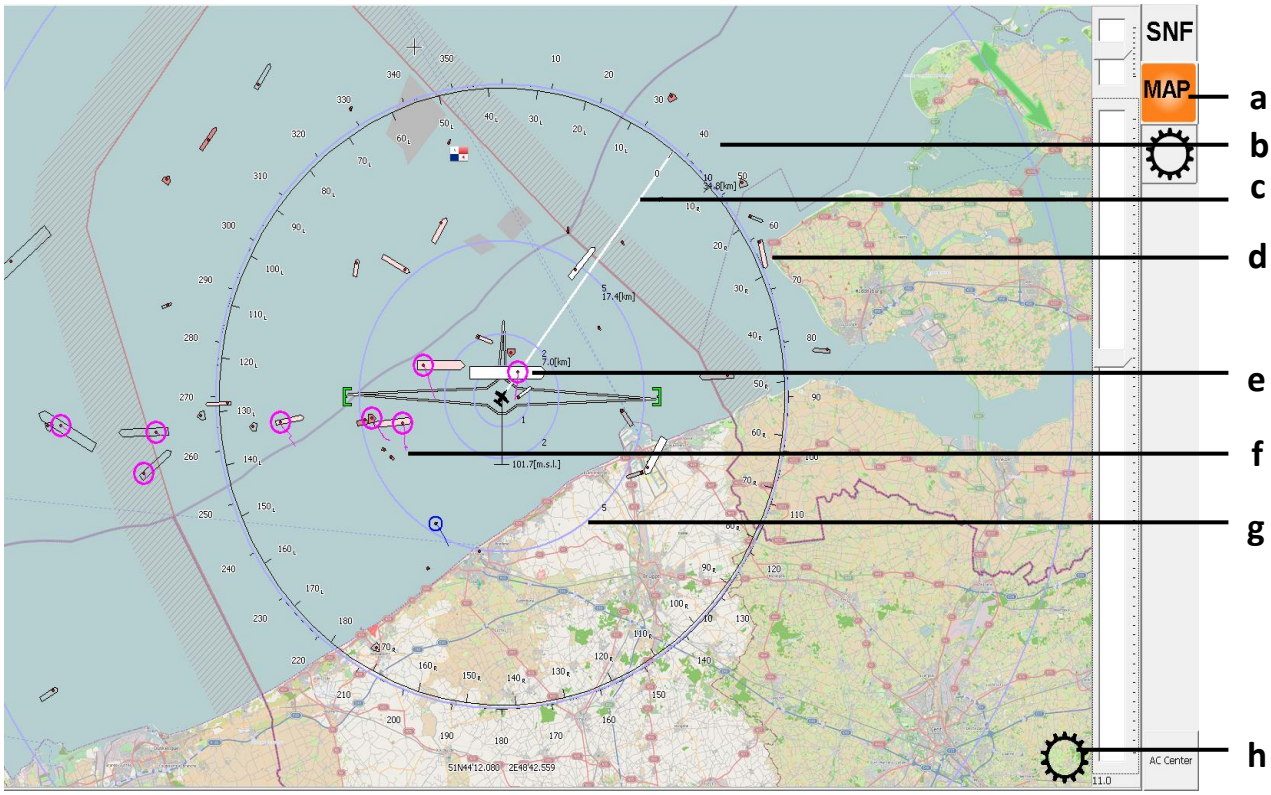


Figure 26 MAP view of IGPS software

3.2.3 Measurement Quality

Both operators should asses the quality of the measurements, in most cases a quick glance at the graph on the DVR-1 graph is sufficient to establish if the quality is enough, in case of doubt the quality should be checked by the laptop operator. Following conditions must be met:

- Stable background before and after the peak
- Sufficient peak height compared to background noise (min 5 ppm CO2)
- Sufficient time between peaks
- Good singular peaks and no interference from other ships or other sources

In case the measurement quality is not good enough, a second measurement should be performed.

3.2.4 NOx sensor mode

In case a too high FSC is observed during (one of the) first attempt(s) (10% of the cases). The NOx sensor should be set to NO and 2 measurement confirmation should be performed.

SOP 1.10. Switching to NO after FSC alert

1. Set the sensor to “NO mode”
    a. Quick menu
    b. Gas to measure
    c. Set to “NO”
2. Take 2 more measurements
3. Set the sensor back to “NOx mode”
    a. Quick menu
    b. Gas to measure
    c. Set to “NOx”

3.2.5 Radio communication to get SFC (NOx alerts)

For ships outside the piloted areas. In case an initial measurement shows a potential violation, contact should be made with the ship (CH 16→67), using the special radio communication checklist from (see **Annex C - Radio communication checklist)**, to request engine parameters that laptop operator will use to calculated the SFC. Following information must be requested from the chief engineer:

- Fuel consumption main engines(s) (m^3/hr)
- Current power of the main engine(s) (kW)
- Total power of the main engine(s) (kW)
- Maximum RPM of main engine(s)

3.2.6 Sampling attempts

Monitoring campaigns have shown that most vessels are compliant (estimate of 90-95% based on BE and SE monitoring results), and therefore in many cases 1 FSC measurement (= 1 low pass for fixed-wing aircraft with sniffer sensor) per vessel will be sufficient to verify compliancy, in most cases (80%) the first measurement attempt is successful. As mentioned above however, it may sometimes be required to perform several additional measurement attempts before a successful FSC measurement can be made. To limit the flight safety risks and optimise the aerial monitoring efficiency it is recommended to limit the number of measurement attempts. In case a first measurement attempt is

unsuccessful it is recommended to perform not more than 2 additional attempts, after which the ship should be abandoned.

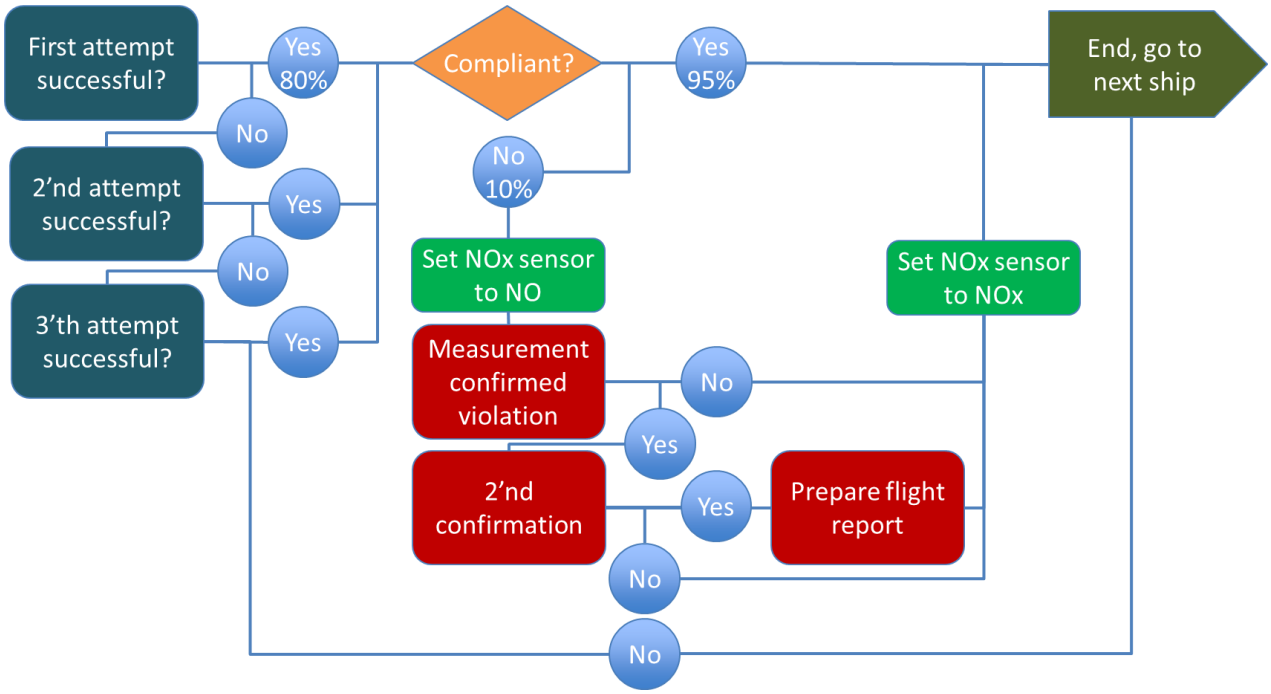


Figure 27 Schematic overview sampling attempts for fixed-wing aircraft with sniffer sensor for FSC monitoring.

3.2.7 Taking notes

The laptop operator should write down following information:

- time and end of sniffer mission type,
- name of the ship,
- measurement results (FSC+NOx),
- number of measurements,
- engine parameters.

3.3. Laptop operator

The laptop operator is responsible for conducting the measurements and in case of radio communication to enter the engine parameters in the SFC calculation file. In case a non-compliant ship is observed, the console operator will create the report and in the meanwhile the laptop operator may take over the guiding of the pilots to allow the console operator to collect the data for the reporting (3.2.1 and 3.2.2).

3.3.1 Conducting measurements

The laptop operator works mainly in the SNF mode, by sliding the zoom level (top) to the right the peaks are optimally visualised. To enable the scale click on the “CO2”, “SO2”, “NOx” legend (left side). When flying through the plumes the concentrations will give peaks on the chart. To conduct a measurement:

SOP 1.11. To conduct measurements

1. Click on the CO2 graph in the area of the peak
2. A second view opens, this is the plume measurement window
3. Move the red box start and end in line with the start and end of the peak
4. Move the left line of the first black arched box “start” to a stable area in front of the peak
5. Move the right line of the second black arched box “end” to a stable area behind the peak
6. The measurement of FSC and NOx is displayed in the top together with the Keel Laying Year and possible source
7. Click on “ok”
8. MAP view will be opened automatically
9. Assign ship
    a. go to the source (ship) with cursor,
    b. click right,
    c. Select “use xxx ship xxx…”
10. Mark ship
    a. go to ship with cursor
    b. click right and select either “HIGH”, “LOW” or “NOT DETECTED”
11. Set map back with “AC centre” (bottom right side)

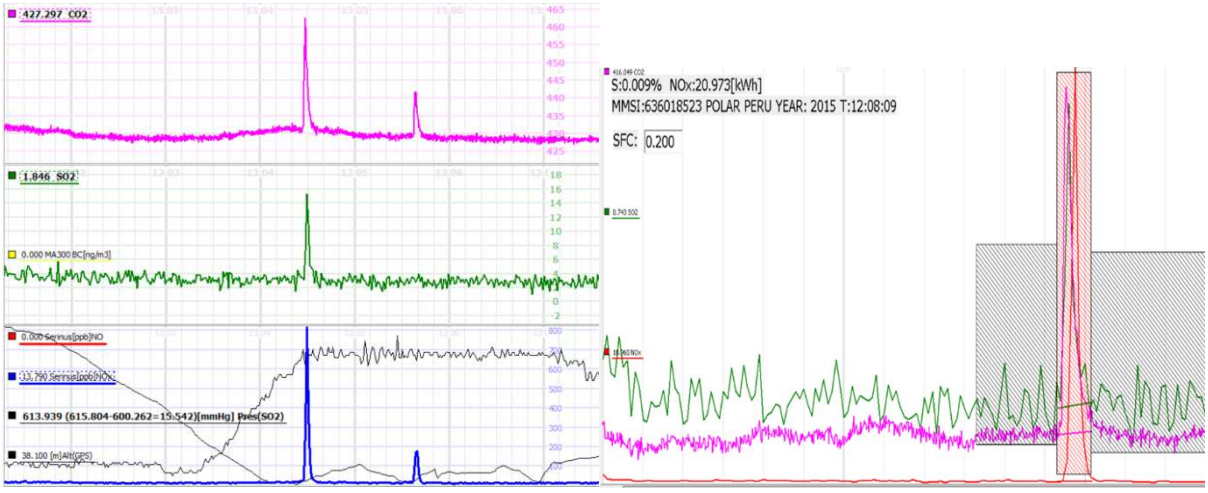


Figure 28 Figure 27 SNF view with the basic graphs on the left side (CO2, SO2 and NOx) and the plume measurement window on the right side

The laptop operator should also check if the measurement quality is sufficient (3.2.3), special attention should be given to non-compliant ships.

- **Min 5ppm CO2** (for compliant ships)
- **Min 3ppb SO2** (for non-compliant ships)
- **Min 15ppb NOx** (for non-compliant ships)
- **Stable background before and after passage** (no inversion layers)
- **No SO2 tail** (cut off at CO2 peak)
- **No other plume peaks** (from ships or land) **within 30 sec before or after measurement**

3.3.2 NOx

For the compliance monitoring of NOx, the laptop operator should look at the following information prior to the measurement:

- Keel laying date (IGPS)
- Ship type (visual)
- Ship length (AIS)
- Ship speed (AIS)
- Ship location

The thresholds for reporting will depend on this information.

Keel laying date

Different thresholds were defined based on the keel laying date. The dates is displayed on the AIS info box when selecting a ship on the IGPS MAP. Tier I starts from 2000, Tier II from 2011 and Tier III from 2021 (Table 3).

Ship type

The thresholds for ships with RPM>500 rpm should be used (Table 4) for following ship types: ROROs, Passenger vessels, cruise ships.

Ship length

For ships <160 m the threshold for ships with ERS > 500 rpm need to be used for the initial evaluation (Table 4).

Ship speed

For containers and tankers possible violation should only be reported from the orange flag when their speed is <12 kts. Roros and bulk carriers sailing slower than 8 kts should only be reported from the orange flag (Table 4).

Ship location

In case the ship is close to port (Westerscheld, Zeebrugge), the vessel has a pilot on board and is most likely in communication with VTS, therefore no VHF radio-communication should be established. For these ships an SFC of 160 g/kWh will be used. There is no need to adjust the SFC in the software. In case a potential violation is observed with the standard SFC of 200g/kWh, the measurement should be recalculated using the "Threholds, Bias and SFC.xls" file (sheet NOX→SFC correction) if with the lower SFC the ship is still in violation one additional measurement should be taken.

3.3.3 Colour flags (thresholds) FSC

FSC measurement can be categorized according to a threshold or colour flags based on the FSC value, the measurement-uncertainty and level of quality. The colour flags can always be consulted in flight in the "Threholds, Bias and SFC.xls" file (sheet FSC).

Table 2. Threshold colour flags for categorizing the emission measurement and reporting to PSC

Thresholds	FSC	CI
Yellow	0.13	68%
Orange	0.2	95%
Red	0.3	99%

3.3.4 Colour flag (thresholds) NOx

The thresholds for NOx are much more complex than for FSC, for NOx, 2 tables with colour flags are composed, the first set is for ships with an RPM smaller than 500 and is based on the limit for an RPM < 130 (Table 3), the second set is for ships with an RPM > 500 (Table 4).

In addition to the RPM also the Keel Laying date (Tier) will determine the threshold, a colour flag list is provided for every Tier level. The values are based on the uncertainty and a confidence level. The values are rounded to provide more operational values that can be easily memories by the operators. Both tables are also available in "Threholds, Bias and SFC.xls" file (sheet NOx) and should be consulted when in doubt.

Table 3 Threholds for ships with RPM <500

Threholds	Tier I ('01-'10)	Tier II ('11-'20)	Tier III (≥2021)	Tier I+II	Tier III	CI
Limit (130xRPM)	17	14.4	3.4	NTE (BE)	NTE (IMO)	
Yellow	25	20	7	15%	50%	68%
Orange	35	30	9	20%	60%	95%
Red	55	45	12	50%	65%	99%

Table 4 Thresholds for ships with RPM >500

Threholds	Tier I ('01-'10)	Tier II ('11-'20)	Tier III (≥2021)	Tier I+II	Tier III	CI
Limit (500xRPM)	13	10.5	2.6	NTE (BE)	NTE (IMO)	
Yellow	20	15	5	10%	50%	68%
Orange	25	20	6	20%	50%	95%
Red	45	35	7	50%	50%	99%

3.3.5 SFC

When a potential NOx violation is observed the console operator will perform radio communication with the ship to obtain following engine parameters:

- Fuel consumption main engine (m^3/hr)
- Current power of the main engine (kW)
- Total power of the main engine (kW)
- Maximum RPM

The parameters A-C can be entered in the "NOx" sheet (Figure 29). The SFC is calculated automatically. This SFC can be entered in the IGPS to conduct a second measurement.

SOP 1.12. Change SFC valued on IGPS

1. Click on the CO2 graph in the SNF window
2. The plume measurement window will be opened
3. The SFC values is indicated in the left side of the window
4. Enter the new value for SFC
5. Double left mouse click to finish
6. The next measurements will be taken with the new FSC

As in most occasions the engine parameters will be received after the second measurement was taken, the NOx measurements can also be converted using the sheet "NOX→ SFC correction". The SFC is already updated based on the entered data in the NOx sheet, the two first measurements only need to be entered to get the converted NOx values.

3.3.6 Engine load

The engine load is calculated together with the SFC in the NOx sheet when the engine parameters are entered. Ships sailing at an engine load less than 25% (rounded to 5%) should be reported from the orange colour flag only and should be reported as "off cycle"

SFC calculation			Threholds	Tier I ('01-'10)	Tier II ('11-'20)	Tier III (>2021)	Tier I+II	Tier III	CI	Threholds	Tier I ('01-'10)	Tier II ('11-'20)	Tier III (>2021)	Tier I+II	Tier III	CI
SFOC	Fill in data below	kg/kWh	Limit (130xRPM)	17	14.4	3.4	NTE (BE)	NTE (IMO)		Limit (500xRPM)	13	10.5	2.6	NTE (BE)	NTE (IMO)	
Fuel consumption	Fill in data below	kg/hr	Yellow	25	20	7	15%	50%	68%	Yellow	20	15	5	10%	50%	68%
Fuel Density	Default of 0.9 is used		Orange	35	30	9	20%	60%	95%	Orange	25	20	6	20%	50%	95%
Current power use	Fill in data below	kWh	Red	55	45	12	50%	65%	99%	Red	45	35	7	50%	50%	99%
			Threshold = Limit.NTE + σ.U + b													

Fill in fuel effieciency data in this table		
Fuel Consumption (main engine) *(choose one of the following parameters)*		*Example*
kg/hr		*7500*
m^3 / hr		*7.5*
m^3 / Day		*180*
l/hr		*8000*
cubic ton/hr		*8*
cubic ton/day		*200*
Density (0.8-1 kg/l) *(choose one of the following parameters, if left empty default of 0.9 will be used)*		
kg/l		*0.98*
kg/cubic ton		*980*
Power use (main engine) *(choose one of the following parameters, when using parameters in red, both parameters need to be provided)*		
kW		*37500*
mW		*37.5*
engine capcity (kWh)		*50000*
engine load (%)		*75*

Figure 29 SFC calculation with the Thresholds and Bias Excel file (NOx sheet)

CHAPTER 4. POST-FLIGHT MISSION OPERATION

To avoid time loss and issues with the power supply the post flight operations must be briefly discussed between operators and pilots before the shutdown of the engines and survey power supply. The operations after flight include the reporting, import of mission data and ground powering or shutdown of the sniffer system. The different post flight operation do not necessarily have to be committed successively but can be initiated on the same time by different operators/pilots.

4.1. Reporting to PSC

The sniffer measurement results of non-compliant vessels have to be reported to PSC and the vessels will then be marked in the Thetis-EU database. Therefore the aerial monitoring results on non-compliant vessels should be reported in near real time. For a non-compliant vessel, this means that reporting time is limited to 15 min after landing in order to provide sufficient time for the planning and prioritisation of port inspections. The flight report is send to the national 24/7 coastguard station (MIK), who forwards the flight report to PSC. Measurement results of both non-compliant as compliant vessels are also shared throughout Thetis-EU, this data-export and upload process is largely automated, but some data still needs to be validated manually.

Table 2 PSC-Communication matrix

	Compliant	**Non Compliance**
Reporting Time	<1hr after flight	Near real time (<15 min after landing)
Reporting Means	Thetis-EU web database	Thetis-EU + Flight report

See Section 3 of the Sniffer Quality Management System, Chapter 4 for more information on the reporting of non-compliant ships using the Belgian Flight Report.

4.2. Import of ship monitoring data

After all sniffer measurements are done, but **before the sniffer is shut down** the emission file and log files from the MUMM LOG PC need to be backed-up by the laptop operator:

SOP 1.13. To backup TCP log files

1. Copy logs
    - **a.** On laptop go to MUMM-LOG-PC on TeamViewer
    - **b.** Go to C:/IGPS/TCP LOG
    - **c.** Copy recent TCP logfiles (from same day)
    - **d.** On Laptop go to seafile folder 0.QMS\Sniffer DM\Logs\YEAR
    - **e.** Paste the files, in case error message pops up, select “Don’t copy” + “do this for all other x files”
2. Copy the emission file
    - **a.** On laptop go to MUMM-LOG-PC on TeamViewer
    - **b.** Go to C:/IGPS
    - **c.** Copy Emissionsdata_MUMM_LOG_PC.txt
    - **d.** On laptop go to C:/IGPS/

e. Paste the emission file, select "replace"

Once the date is backed up, all IGPS data needs to be imported via following procedure.

SOP 1.14. Import IGPS data

1. Open personal file "IMPORTV22_operatorinitials.xlsm" in "Seafile >> 11-Instrumentatie >> 05-Fluxsense_Sniffer >> SNIFFER DATA >> IMPORT IGPS DATA
2. Import the raw data
    a. The first button will import all data from the C:\IGPS directory
    b. The second button will allow you to import data from a dedicated directory (eg. IGPS POST FLIGHT)
3. Click third button "Calculate Results", the Results sheet will be opened,
4. Check if all ships are present
    a. If all ships are present continue with 5
    b. (if not close import and add measurements, see 5.2 and restart at 1)
5. Edit data in Results sheet
6. Delete double lines
7. Add the number of attempts
8. Check for unknown Keel Laying Years (e.g. use Thetis-EU or Marine traffic);
9. Check the colour flags for FSC
    a. Check if the sequence is correct for NO/NOx
    b. Check the sequence of the emissions measurements
    c. In case a ship has 2 different colour flags use lowest flag
    d. Ungroup the columns right from the emission measurement (blue numbers) change from 1,2,3 to 2,1,3 or accordingly
10. Check the colour flags for NOx
    a. Check the Gross Tonnage for TIER 0 ships with length <150m
    b. check the sequence of the emissions measurements, in case a ship has 2 different colour flags use lowest flag
    c. Ungroup the columns right from the emission measurement (blue numbers) change from 1,2,3 to 2,1,3 or accordingly
11. Recalculate sheet, and check if all adjustments are made correctly
12. Go back to "guidelines" and add start date (if different from the present day) add start/end times in case of multiple flights
13. Add flight number
14. Click apply filter
15. Check the Full data, ILT and EMSA sheets (sheets are read only)
16. Click on all 3 Export buttons
    a. Full data will be exported in the standard YEAR directory,
    b. ILT sheet will be exported in the EXTERN directory
    c. The EMSA file will be exported in the EMSA input files data directory)

Note: For violations check if after 15 min the EMSA file is moved from the "input files" directory to the "imported" directory and the alert is available on Thetis-EU,

In case of errors, or for more information on login in to Thetis-EU follow the steps as described in Section 3 of the SQMS, Chapter 5.

4.3. System shut down with power on sniffer (see SOP 1.2)

SOP 1.15. Shutting down with power to sniffer

1. At tarmac in EBOS: GPU, cable and cable protector are in the orange box (code: 213)
2. Guide cable through camera opening (use dedicated connector to split the cable from the reel)
3. Connect GPU to external AC power bus with dedicated cable (see Figure 13)
4. Plug in GPU to reel
5. Plug in the power extension cable to the 230V socket (on the lighting pole)
6. Switch on sniffer battery must be in “EXT” position

4.4. System full shut down

SOP 1.16. Full shut downs

1. Shut down sniffer sensor on the VM by First operator:
    a. Go to the utilities tab
    b. Press the power button in the right bottom
2. MUMM-LOG PC will shut down, together with the IGPS software on the VM.
3. After IGPS software is off, switch off sniffer switch at intercom jacks
4. Put Sniffer battery switch in off mode (middle)
5. Set carbon filter to ground

CHAPTER 5. POST FLIGHT ANALYSIS

This chapter describes the re-analysis of mission data for operational purposes, this can be done at any time after the flight. For more detailed data analysis see Section 3 of the Sniffer Quality Management System, Sniffer Data Management Manual, Chapter 5.

5.1. Copy TCP-log files

Make a backup of the program files, log files and emission files from the IGPS folder from the LOG_PC (see Chapter 4)

5.2. Reloading mission using IGPS-Present

IGPS present can be used to reload old mission data (from log files), a special IGPS Post flight folder has been installed on the C:\ and shared through Seafile, this contains the same software and folders as the IGPS folder, but the advantage is that the data may be deleted.

SOP 1.17. To reload mission

1. Copy Emissiondata_ODN_XXX.rbins.be.txt from C:\IGPS to C:\IGPS POST FLIGHT folder
2. Open IGPS POST FLIGHT and open LOG file (SNF>>Setting>>load data file>>Select LOG with flight hour)
3. Flight will be loaded (slow) to go faster to the correct time click on the SNF graph (look at timer)
4. When time is right, go to MAP to identify ship and when AC passes through ship plume go to SNF
5. Do measurement and assign measurement to correct ship
6. Data is now added to the emission data under the IGPS post flight folder and be either copied back to the IGPS folder or can be imported from the IGPS Post flight folder in the Import.xls file

5.2.1 Missing Data

In case ships are missing from the import file or in case the ships are present but the measurements are missing, the import needs to be ceased and the data needs to be extracted first by reloading the missing, For more information on how to retrieve this information see Section 3 of the Sniffer Quality Management System, Sniffer Data Management Manual, Chapter 5.

5.3. Detailed analysis of mission data with IGPS extract and IGPS analysis

SOP 1.18. Analysis with IGPS ANA

1. Open IGPS Extract (AIS_Ex8)
2. Press start
3. Select log file (from Sniffer_Data/Logs)
4. Select Temp folder, this folder will be used as temporary working folder
5. After extraction is completed, close AIS_Ex8
6. Open IGPS_Ana44
7. Press start

8. Select Temp Folder
9. Select emission file (C/IGPS/Emsissiondata_ODN-name)
10. Use green arrows to scroll in flight to look for the required peak/ship
11. Adjust background and peak brackets where necessary
12. Go to map, Right mouse click, link to ship
13. Save (the Emissiondata file will be updated)

For more information on IGPS EXTR and IGPS Ana see Section 3 of the Sniffer Quality Management System, Sniffer Data Management Manual, Chapter 1.

CHAPTER 6. REFERENCES

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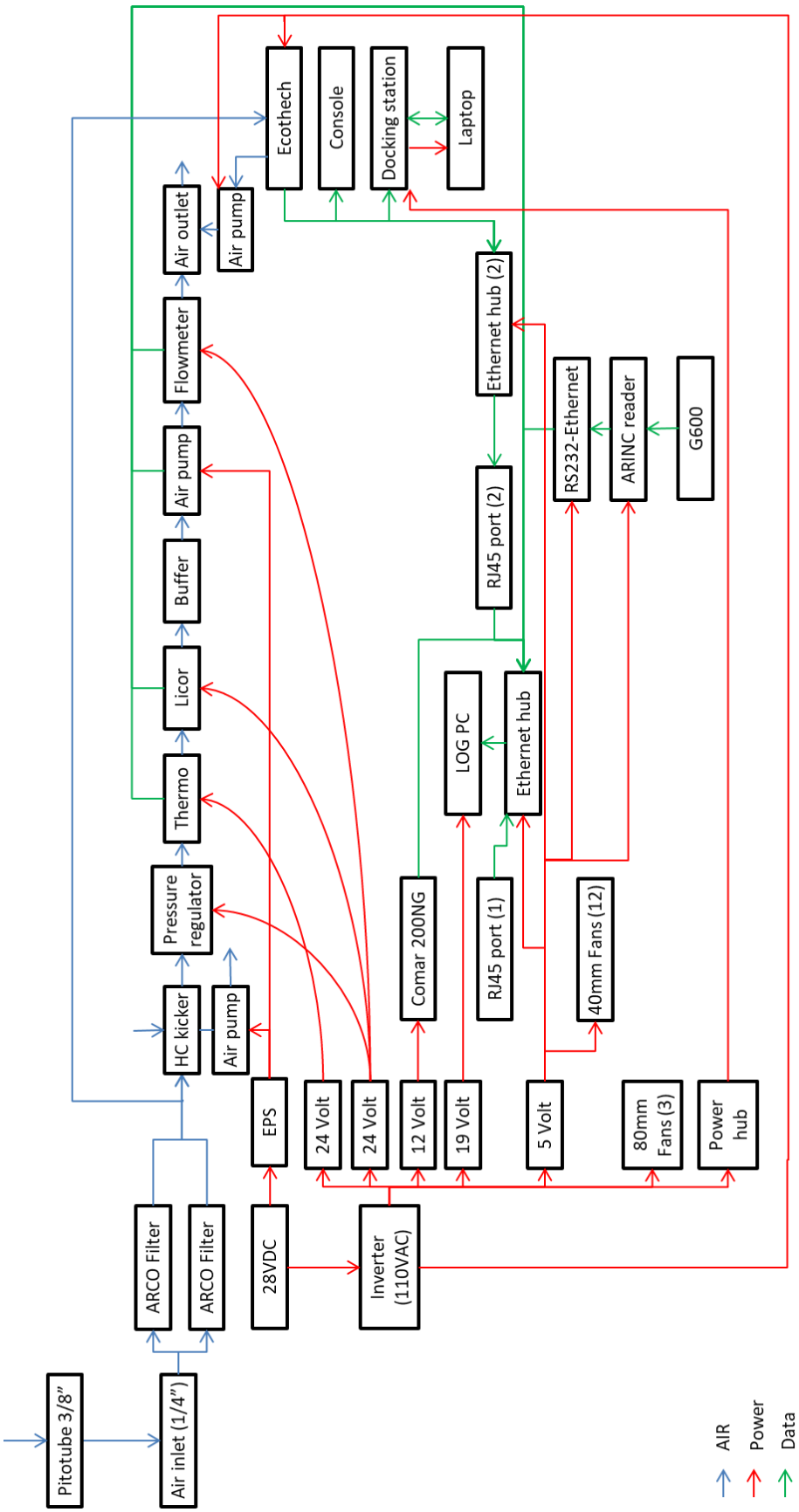
RAM mount Installation instructions, https://www.rammount.com/part/RAM-VBD-128-SW1#

ANNEX A – TECHNICAL FICHE OO-MMM

1. Airborne platform	
Type	Britten Norman Islander
Call sign	OO-MMM
Length	10.9
Wingspan	14.02m
Height	3.77m
Engines	2 Lycoming engines (300 hp)
Autonomy	5 hrs
2. SLAR	
Model	Terma SLAR 9000
Range	20/20 nm (standard operations) up to 40/40 nm
Resolution on ground	35m (20nm range); 75m (40 nm range)
Note:	With pixel per pixel georeferencing from Flight Management System (FMS)
3. IR sensor	
Model	FLIR A645
Resolution	650x480
FOV	45°
F-value	1
Thermal sensitivity	50 mK
4. Video camcorder	
Model	Sony FDR-FX7
Resolution	1080i
Focal length	37,4 -748 mm (16/9) 45,7-914mm (4/3)
Optical zoom	x20
5. GPS Positioning en Flight Management System	
Model GPS	Garmin GTN650 (x2)
Model FMS	Garmin G600
Notes	Data-export of coordinates, course, airspeed, groundspeed, windspeed and direction, time, date, altitude (barometric), roll and pitch angle to control-unit Built in Airband VHF radio-communication 1m accuracy
6. Still camera's	
Model 1	Nikon D850
Lens 1	VR 16-35mm
Model 2	Nikon D800

Lens 2	VR 70-300 mm
Note	Image overlay on console Georeferenced from Garmin 18x PC GPS receiver
7. Control-unit	
Model	OPTIMARE MEDUSA System
Note	Integration and control van sensors and sensor-images equipped with ECDIS and Comar SLR200 AIS receiver
8. Radar altimeter	
Model	Bendix King KRA405B
Note	Data-export from barometric altitude to control unit Accuracy: 1m
9. VHF/FM Airborne transceiver	
Model	Technisonic TFM-138B
Note	Installed in control unit Voice recording on video images
10. Satcom	
Model	Garmin GSR 56
Note	Control is Integrated in Garmin G600 Flight Management System Voice communication, weather updates and Text messages (SMS)
11.Transponder	
Model	Garmin GTX335 Mode ES
Registration	10036
Transponder n	44B5AD
Serial Nr	C468

ANNEX B - BLOCK DIAGRAM



ANNEX C - RADIO COMMUNICATION CHECKLIST

On channel 16

Shipname- shipename- shipname this is the Belgian coastguard aircraft

on channel 16. How do you read me Over

Shipname please reading you …by 5, please switch to channel **7-3**. Over

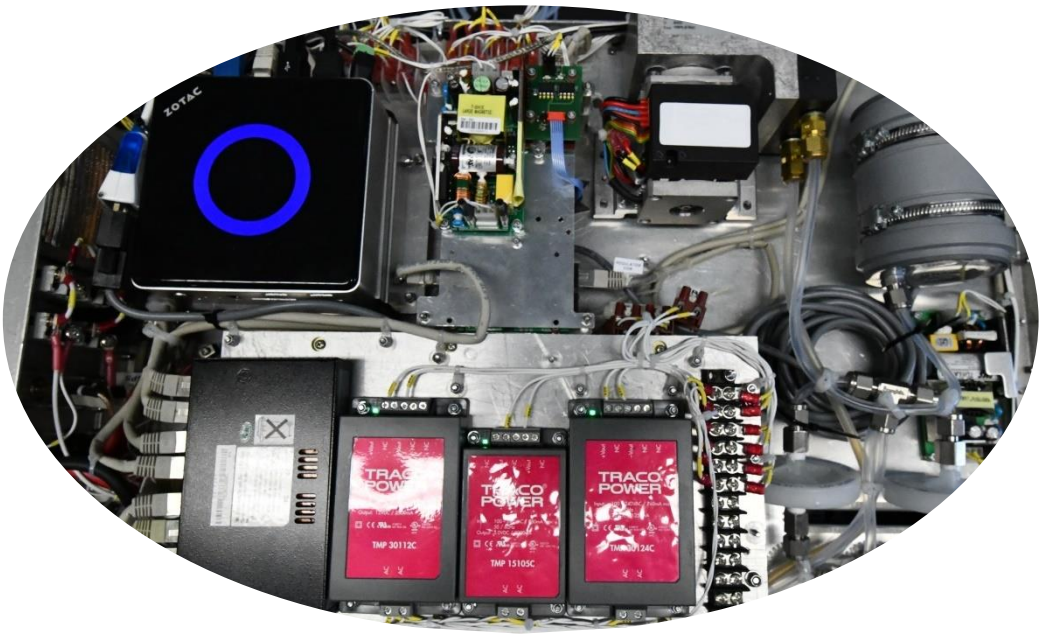
On Channel 67

1. We are conducting air pollution surveillance and I have to inform you that we measured some high NOx values in the smoke plume of your vessel. We would like to ask your chief engineer to provide us with some information, please note:.....
2. What is your fuel consumption of your main engine(s) at this moment in **metric ton/hr**? ..
3. What is the current power use of your main engine(s) in kWh? .....
4. What is the total power of your main engine(s)
5. What is your maximum RPM .....

SNIFFER QUALITY MANAGEMENT SYSTEM

SECTION 2.

SNIFFER QUALITY ASSURANCE MANUAL



REVISIONS

Revision Date	Chapter - section	Page	Description
27/06/2018	Chapter 4 4.2	4-6	Modification of SO2 hardware calibration with J251 connector (option 1)
23/06/2022	All		Adding of NOx sensor, NOx pump, hydrocarbon kicker and update of the air pump
25/07/2022	Chapter 1 and Chapter 6 1.1, 1.1.8, 1.1.10 and 6.1.10		Adding of Hydrocarbon kicker
25/07/2022	Chapter 3 and Chapter 5 5.1, 5.2		Adding of plume simulation mixture

ABOUT THIS MANUAL

The Sniffer Quality Assurance Manual was developed by MUMM to be used with the sniffer installation on board of the Belgian Coastguard Aircraft, a BN Islander (BN2A) with call sign OO-MMM. The Quality Assurance System constitutes to Section 2 of the Sniffer Quality Management System (QMS). The Sniffer Quality Management System was specifically designed for the Belgian Marpol Annex VI monitoring program entailing the proper functioning of the sniffer system on board of the Belgian Coastguard Aircraft and the provision of accurate and consistent data collection. The Quality Management System consists of in total 3 Sections, Section 1 describes the operational aspects of the airborne monitoring. Section 3 consists of the data management aspects (see Figure 1). For every section a detailed manual is developed and available on the Seafile folder 1. SNIFFER QMS under the Seafile library 05-Instrumentation/05-FluxSense_Sniffer

In this manual, detailed information and step to step instructions are provided about the installation, calibration, and servicing of the sniffer sensor system. The manual is organized in different chapters and annexes to provide direct access to specific information, chapters can be toggled directly. The chapter can also be used as stand-alone guides during the different interventions in the field.

- **"Chapter 1 Sniffer sensor "** describes the installation on board of the OO-MMM aircraft and the main components of the Sniffer sensor system.
- **"Chapter 2 Intervention and servicing scheme"** provides a detailed overview and schedule of the required maintenance interventions and preventive service.
- "**Chapter 3 Software calibrations**" provide all information to perform software calibrations.
- "**Chapter 4 Hardware calibrations**" provide all information to perform hardware calibrations.
- "**Chapter 5 Management reference gasses**" describes all practical aspects of the management and calibration of the reference gasses.
- "**Chapter 6 Preventive servicing**" provides detailed maintenance instructions for preventive servicing of the sniffer sensor system.
- "**Chapter 7 Troubleshooting**" presents guidelines to provide solutions for combating failures.
- **"Annex A – ",** provides an extensive but exhaustive list of the different components of the sniffer sensor system.
- **"Annex B - Interface Connection Documentation",** provides details on the different connectors and wiring of the sniffer sensor system.
- **"Annex C - Block Diagrams",** provides different diagrams that may help with the understanding of the sniffer sensor concept.
- "**Annex D - SCHEMES**" provides schemes of the parts of the sniffer system concept.



Figure 30 Sniffer QMS Structure

The sniffer sensor system manufactured by FluxSense (Sweden), consists of a compilation of components from different soft and hardware providers. This manual was composed by the scientific Service MUMM of the Royal Belgian Institute based on the different maintenance provisions of the components, applied on the specification of the sniffer sensor system on board of the Belgian Coastguard Aircraft and the nature of the Belgian North Sea Aerial Surveillance Program, as a result this manual may possibly not fully reflect the official opinion of the manufacturers.

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CHAPTER 1. SNIFFER SENSOR SYSTEM INSTALLATION

The sniffer sensor system is the complete equipment setup used for airborne Marpol Annex VI monitoring. The sniffer sensor system is installed in a BN Islander type B2-A with immatriculation OO-MMM. The sniffer sensor installation is EASA certified by Airplus (Part 21 Design organisation). The certification is done with a minor change modification of the existing Surveillance system on board of the aircraft that was provided by Optimare and was EASA certified by Airplus in 2011. The EASA certification for the sniffer installation can be found in Annex E. The sniffer installation consists of following parts (a detailed part inventory list is available in "**Annex A – "):**

- Sniffer sensor
- Client stations
- Tubing
- Signal wiring
- Power distribution
- Sniffer equipment rack

1.1. Sniffer sensor

- The main component of the sniffer sensor installation is the sniffer sensor. The sniffer sensor was developed by Chalmers University and commercialized by FluxSense (Sweden). The sniffer sensor is a collection of different components and sensors that are installed in a custom-made casing (see also Figure 2). The sensors consist of certified equipment used for ambient air quality monitoring that has been disassembled from its original case and reassembled in the sniffer sensor. The different components have been specially adapted for the purpose of airborne monitoring of ship exhausts. Therefore, some components were either reduced in size or removed, also the sample rate of the sensors has been increased to allow high speed continuous air quality measurements on board of fixed wing aircraft. The main components of the sniffer sensor are:
- Located in the upper part (see Figure 34Figure 34 Internal components of the sniffer system (lower part) (Note, the filters have been moved outside the sniffer to a filter box)):

  1. CO2 sensor
  2. SO2 sensor
  3. Hydrocarbon kicker
  4. Pressure and flow regulators
  5. Air pump (NOx)

- Located in the bottom part (see Figure 34):

  6. Log Computer
  7. AIS/GPS receiver
  8. ARINC reader
  9. Air pumps (2)

- Located in both compartments:

  10. Internal Tubing
  11. Internal power distribution

12. Internal signal wiring
13. Fans
14. Casing

- Located outside the sniffer housing:

15. NOx sensor
16. Particle filter box
17. BC sensor and Serial-Ethernet converter

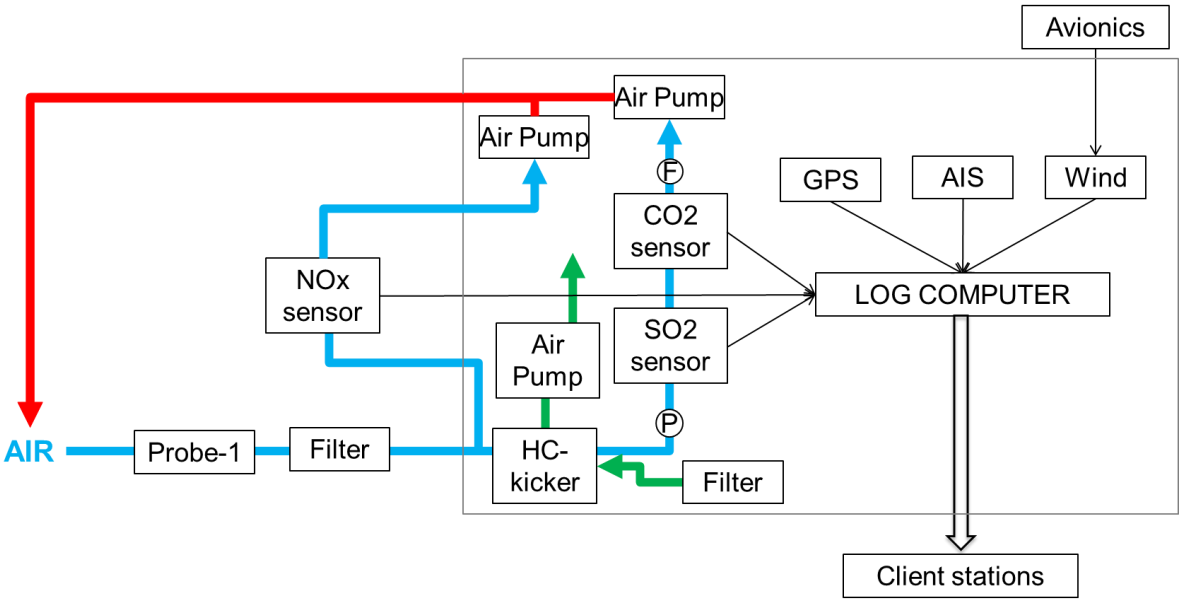


Figure 31 Block diagram of component of the Sniffer sensor

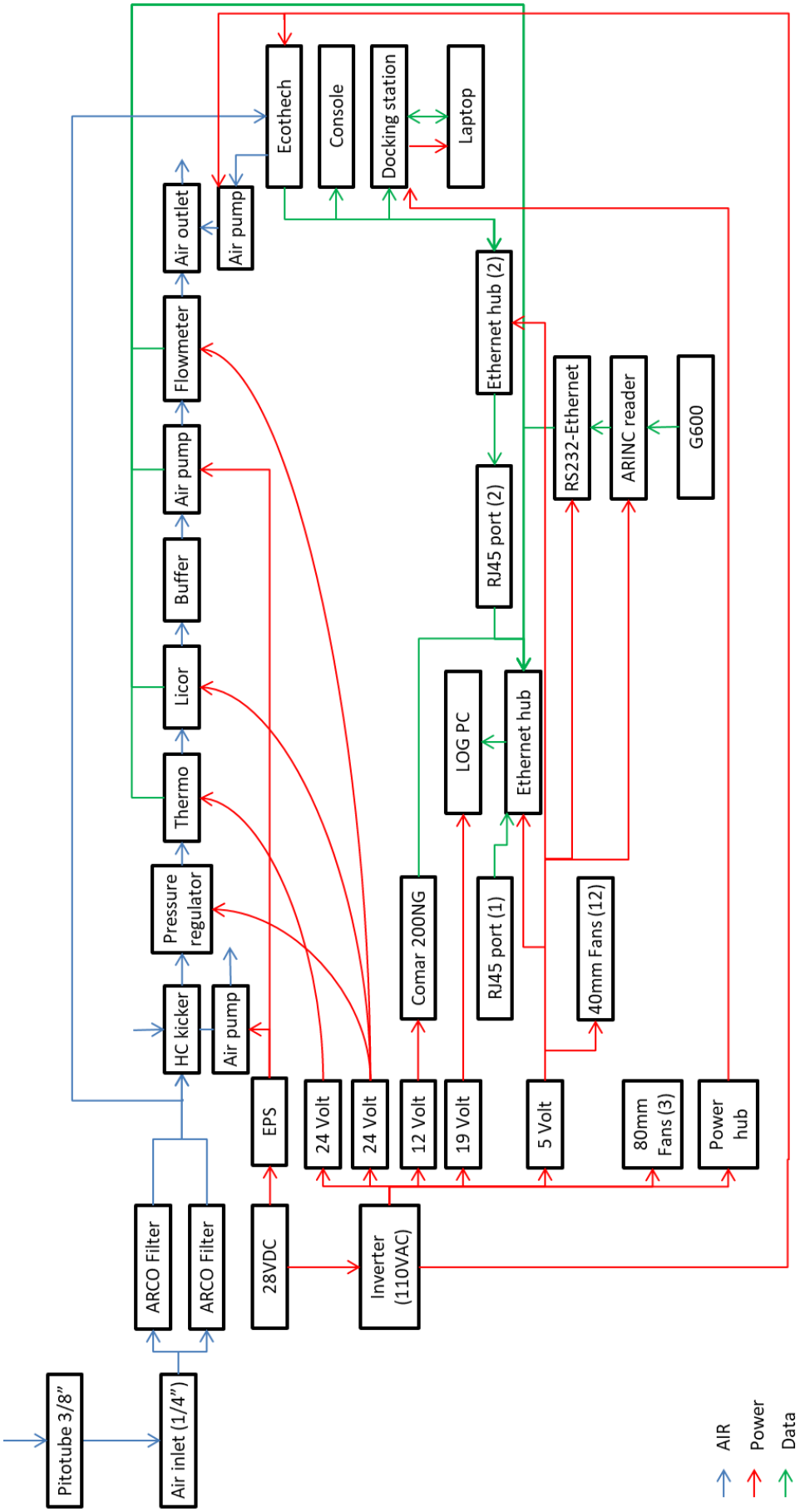


Figure 32 Schematic view of the internal component of the Sniffer sensor

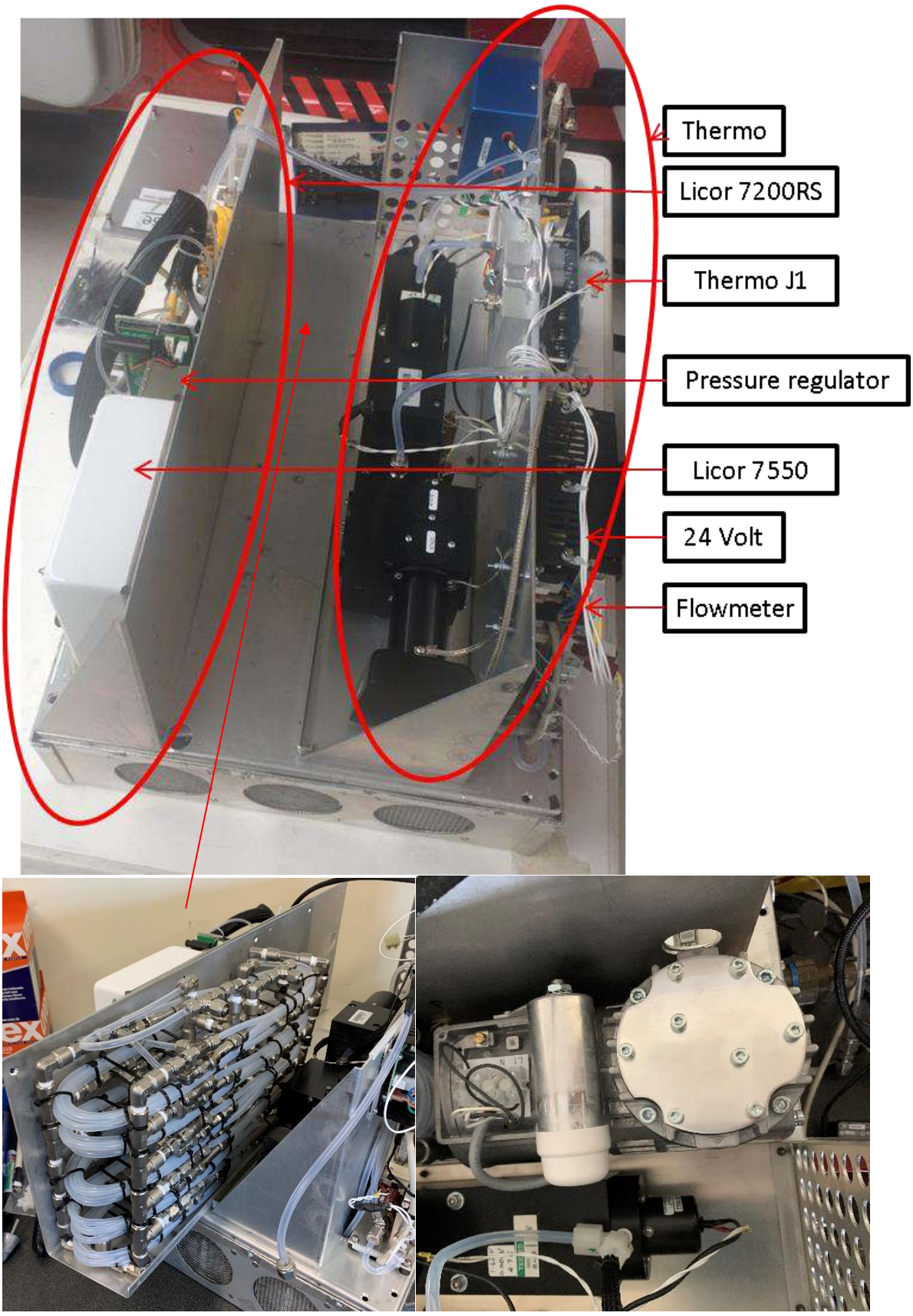


Figure 33 Internal Components of the sniffer system (upper part), (note the hydrocarbon kicker and NOx pump are installed on a removable tray in the empty part between the LICOR and the Thermo sensor).

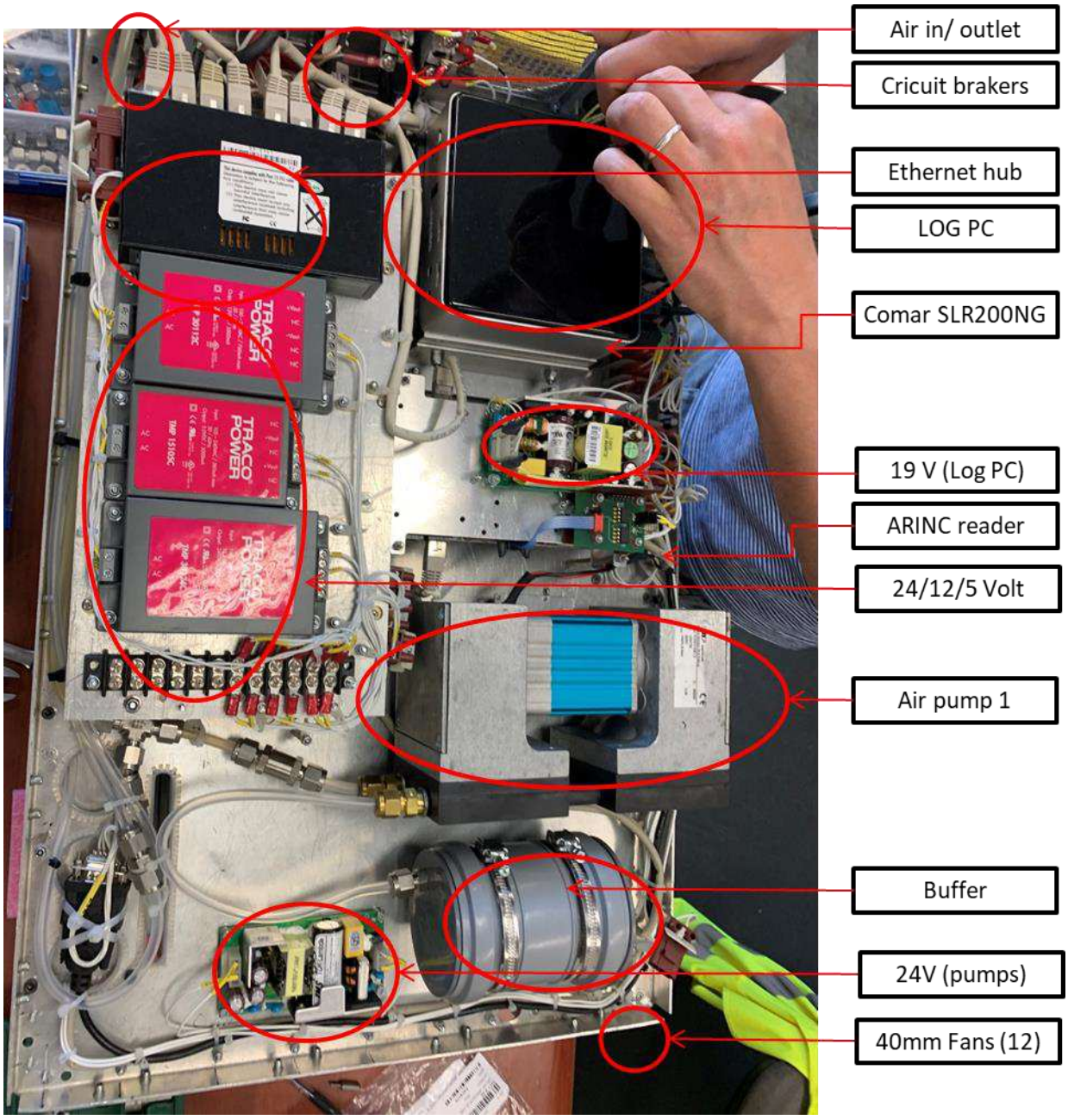


Figure 34 Internal components of the sniffer system (lower part) (Note, the filters have been moved outside the sniffer to a filter box)

1.1.1 CO2 sensor

The CO2 sensor that is used is the Biosciences Licor LI-7200RS combined with the Bioscience Licor LI-7550 analyser interface unit (see Figure 35). The LI-7200RS uses non-dispersive infrared spectroscopy to measure CO_2 and water vapour densities in air. It transmits infrared radiation through temperature-controlled optical filters, then through the closed sample path to a thermally regulated lead selenide detector. Some of the infrared radiation is absorbed by CO_2 and water vapour in the sample path. Gas densities are computed from the ratio of absorbed radiation to a reference. Only the CO2 concentration is used in the sniffer sensor system. The RS model is an improvement of the optical hardware resulting in a lower cleaning frequency of the optical components and lower drift. The LI-7200RS has following specifications:

- Ruggedized
- High speed measurement (5, 10 or 20 Hz)
- Calibration Range: 0 to 3000 µmol mol-1
- Accuracy: Within 1% of reading
- Zero Drift (per °C): ±0.1 ppm typical; ±0.3 ppm maximum
- RMS Noise (typical @ 370 ppm CO2): max 0.16 ppm (at 20 hz)
- Gain Drift (% of reading per °C @ 370 ppm): ±0.02% typical; ±0.1% maximum
- Direct Sensitivity to H2O (mol CO2 mol-1 H20): ±2.00E-05 typical; ±4.00E-05 maximum
- Data-output: RS232 and Ethernet

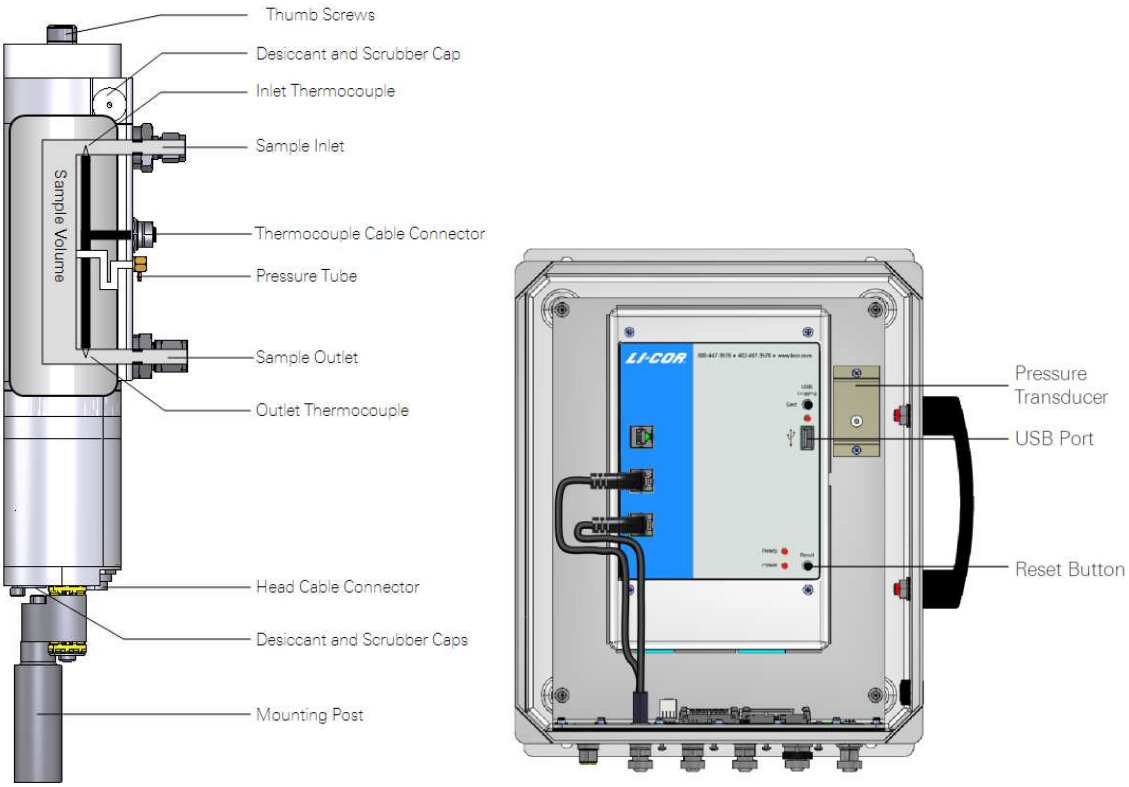


Figure 35 Schematic overview of the Licor7200RS (Biosciences 2015)

1.1.2 SO2 sensor

The SO2 sensor involves a Thermo Fischer Scientific 43i Trace Level Enhanced SO2 Analyser (see Figure 36). The sensor is based on the pulsed fluorescence technique for the measurement of SO2 concentration in ambient air, this technique operates on the principle that SO2 molecules absorb ultraviolet (UV) light and become excited at one wavelength, then decay to a lower energy state emitting UV light at a different wavelength.

The sensor is a Trace Level Enhanced (TLE) analyser, meaning it is a high sensitivity for analysing SO2. The sensing principle is linear and therefore only 1 span gas is required for its calibration. As the measurement of SO2 in exhaust gas is of the magnitude of 30 or more PPB no special zero calibration gas is necessary (CO2 reference gas in synthetic air is acceptable)

Specifications Thermo 43i TLE:

- High sensitivity (0.2 ppb)

- Fast response time
- Linearity through all ranges
- Totally self-contained
- Insensitive to changes in flow and ambient temperature
- User-selectable digital input/output capabilities
- Standard communications features include RS232/485 and Ethernet
- Limited drift (zero drift: <0.2 ppb / 24h – Span drift: 1% per week)

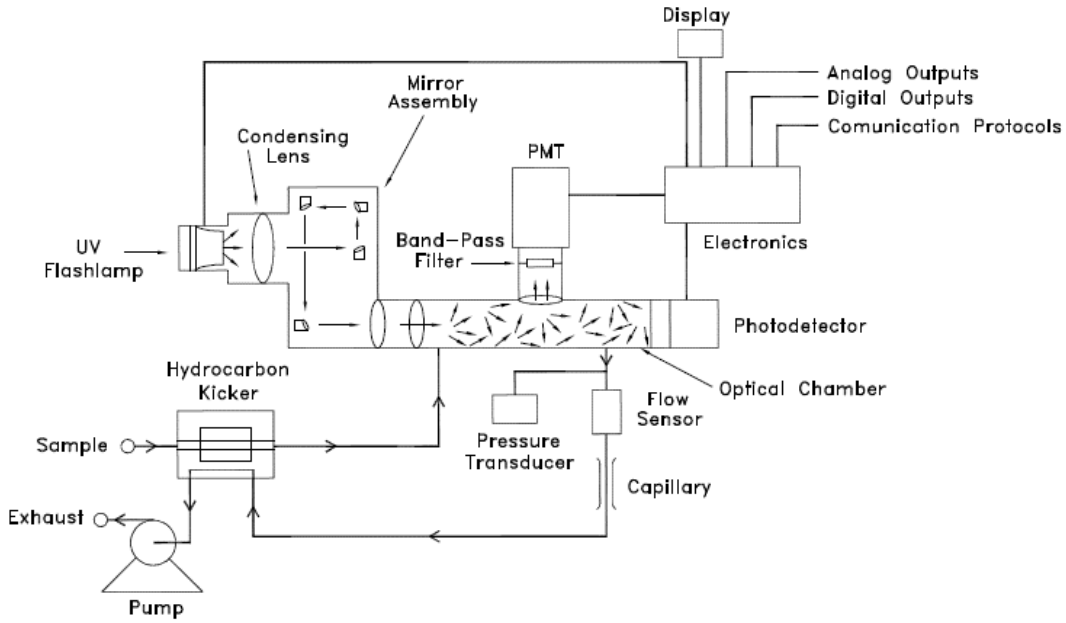


Figure 36 Schematic flow of the Thermo 43i TLE, the hydrocarbon kicker is not used in the sniffer sensor setup

1.1.3 NOx sensor

De NOx sensor used in the sniffer sensor system is a Ecotech Serinus 40 NOx analyser. The instrument uses gas-phase chemiluminescence detection to perform continuous analysis of nitric oxide (NO), total oxides of nitrogen (NOX), and nitrogen dioxide (NO2). This is achieved by using one primary reaction cell and drawing the sample through two separate paths controlled by the main controller PCA. The instrument consists of a pneumatic system, an NO2 to NO converter, a reaction cell, a measurement cell (PMT), an ozone generator and a main controller PCA.

The analysis of nitrogen oxides by chemiluminescence is based on the luminescence from an activated molecular NO2 species produced by the reaction between NO and O3 in an evacuated chamber. The NO molecules react with ozone to form the activated species NO2* according to the reaction mechanism:

$NO + O3 \rightarrow NO2^* + O2$

Equation 1 – Chemiluminescence Reaction for NO

As the activated species NO2* reverts to a lower energy state, it emits broad-band radiation from 500 to 3000 nm, with a maximum intensity at approximately 1100 nm. Since one NO molecule is required to form one NO2* molecule, the intensity of the Chemiluminescent reaction is directly proportional

to the NO concentration within the sample. The PMT current is then directly proportional to the chemiluminescence intensity.

Any NO present in the sample, when drawn through the NO path, reacts with ozone in the reaction cell resulting in the NO measurement. Any NO or NO_2 present in the sample when drawn through the NO_x path, first passes through the NO to NO_2 converter. This process allows the NO to pass through unaffected but converts any NO_2 in the sample into NO. Thus the total NO (NO + converted NO_2) in the NO_x path reacts with ozone in the reaction cell resulting in the NO_x measurement.
In the reaction cell energy is released in the form of chemiluminescent radiation, which is filtered by an optical bandpass filter and detected by the photomultiplier tube (PMT). The level of chemiluminescence detected is directly proportionally to the concentration of NO in the sample.
The concentration of NO_2 is calculated by subtracting the NO measurement from NO_x measurement.

$NO_x = NO + NO_2$ Or $NO_2 = NO_x - NO$

The system can be remotely access by using the serinus application on android devices, this application copies the display and control buttons of the NOx sensor display



Figure 37 Ecothech Serinus 40 NOx analyser (lef) and remote Serinus application for Android devices

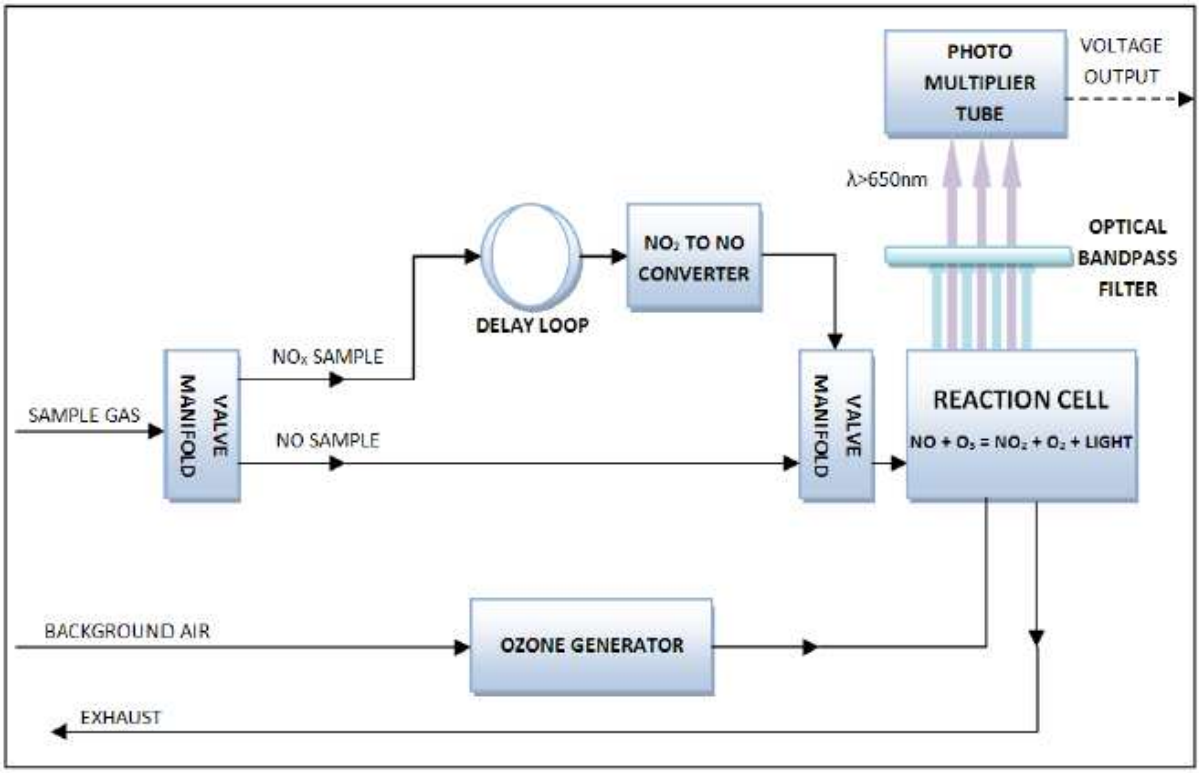


Figure 38 Schematic flow of the Ecotech Serinus 40 NOx sensor, the Delay loop is not used in the sniffer sensor system as this would provide different result time for NO and NOx measurement

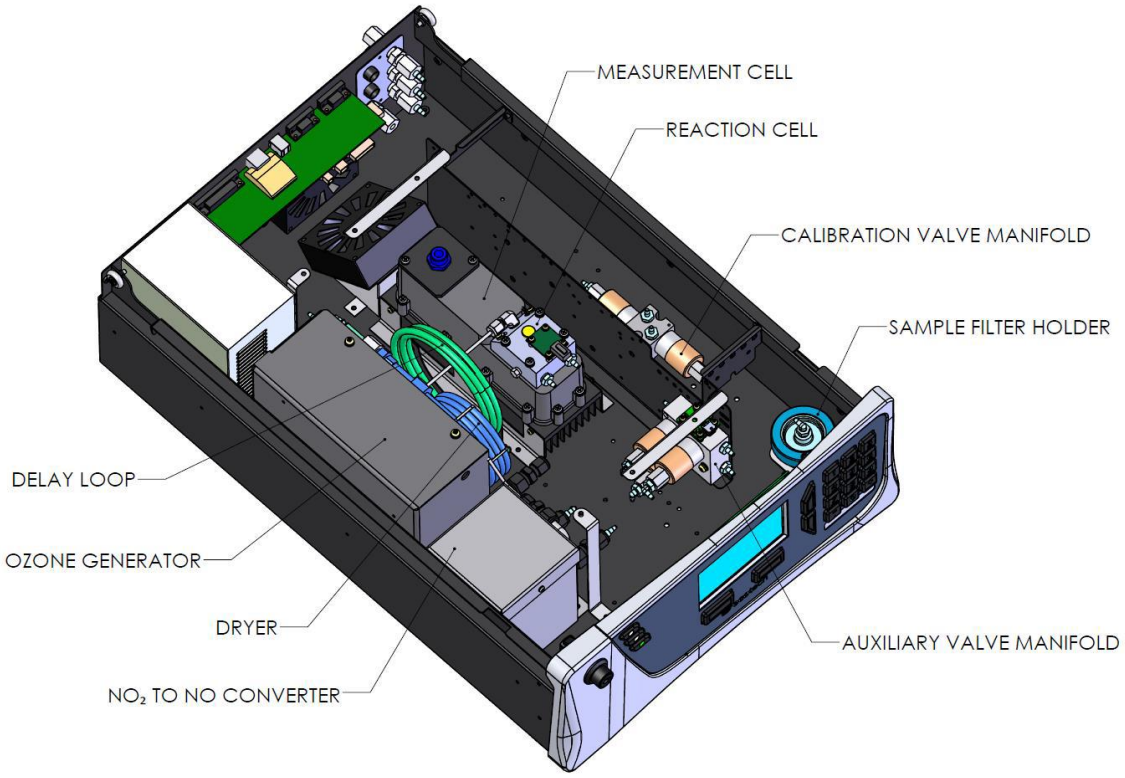


Figure 39 Schematic overview of Ecothech Serinus 40 NOx sensor system (note that the delay loop and sample filter are not used)

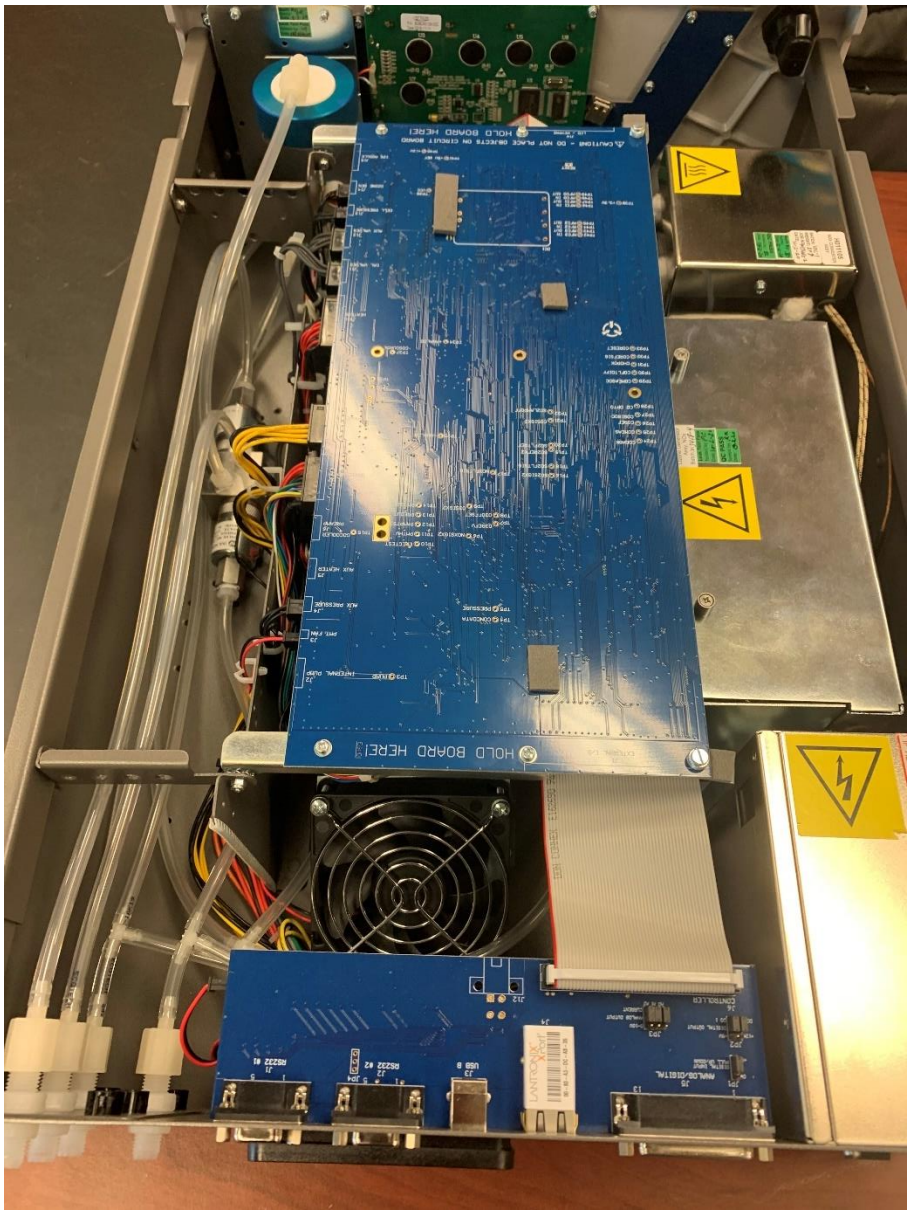


Figure 40 internal parts of the NOx sensor

Note: The “Delay loop” is bypassed from the NOx sensor to reduce the time between measurement and display in NOx mode. If for some reason the sensor needs to be operating back in the “All” mode (to measure the NO2), this delay loop must be re-installed.

1.1.4 Pressure and flow regulators

A flow controller (EL-FLOW F-201CV Mass Flow Controller (MFC)) and pressure meter (EL-PRESS P-502C Pressure Meter with F-004AC valve for low ΔP applications) from Bronkhorst are installed inside the sniffer sensor to ensure a constant and stable airflow through the sniffer sensor system (see Figure 41).

The control valve of the EL-FLOW F-201CV Mass Flow Controller (MFC) forms a closed loop pressure control system with the EL-PRESS P-502C Pressure Transducer, the Mass Flow Meter of the MFC measures the required flow rate to maintain a pressure level 70-80% of the atmospheric pressure. The setpoint voltage divider enables to adjust the maximum flow to build up the required pressure level.

The Bronkhorst regulators are connected to the Ethernet network with both a Flowbus and a RS232 to Ethernet connection.

Specifications (combined):

- Accuracy: ±0.5% FS
- Repeatability: <0.1% RD
- Pressure range: 1:50
- Response time: 2msec
- Control stability: < ±0.05%FS
- Operating temp: -10-70°C
- Temperature sensitivity: 0.1% FS/°C
- Attitude sensitivity: <0.3 mbar
- Max Kv value $6.6x10^{-2}$ (F-201CV)
- Warmup time: 30 secs (F-201CV)
- Power: 15-24Vdc <300mA
- Communication: RS232

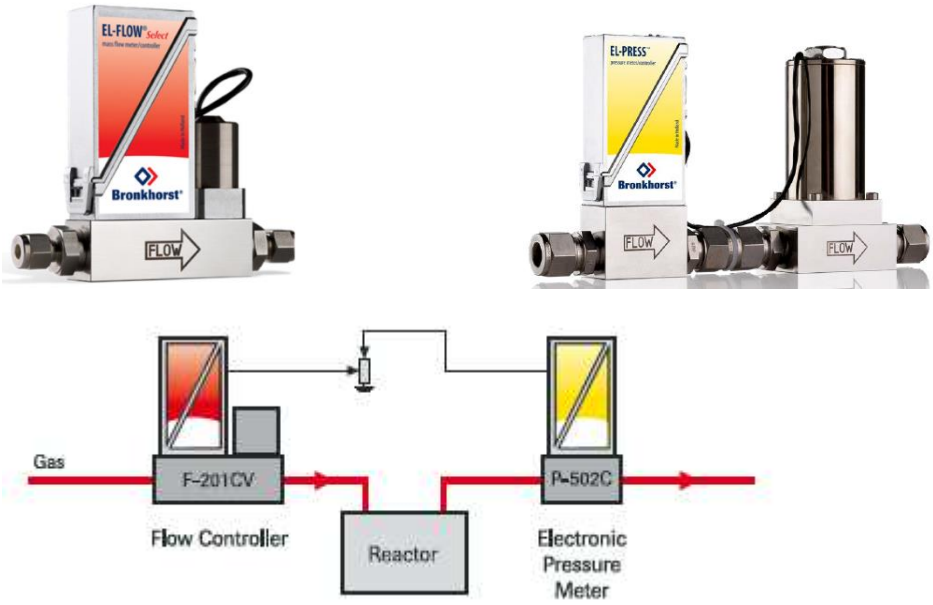


Figure 41 Setup of the flow controller and pressure meter

1.1.5 MUMM_LOG_PC

A Zotac Zbox Nano ID64 mini pc is installed in the sniffer (see Figure 42), this mini pc is further referred as the MUMM_LOG_PC. The MUMM_LOG_PC centralizes the data acquisition and data output to the different client users via Ethernet. One USB port is connected to the external USB connector, this can be used to connect external devices (keyboard, mouse, drives, …) or for troubleshooting. The HDMI output of this PC is connected to an external HDMI connector and used for the visualisation of the IGPS navigation charts to the cockpitdisplay (VGA2 on Avalex AVM 4095) via an HDMI to VGA converter which is installed outside the sniffer sensor. The BIOS has been modified to startup after connecting to power supply. Wake-On LAN has been activated (based on Mac Address).

The basic characteristics of the MUMM_LOG_PC are

- Manufacturer: Zotac
- Model: Zbox Nano ID64
- Operating system: Microsoft Windows 7 professional (64 bit) version 6.1.7601 SP 1
- Processor: Intel(R) Core(TM) i5-3337U CPU @ 1.80GHz, 1801 Mhz, 2 Core(s), 4 Logical Processor(s)
- Memory: 8GB RAM
- Hard Drive: Samsung EVO 850 2.5" of 1 TB (original: WD 10JFCX HDD of 1TB)
- Mac Address: 00012E4D9E04

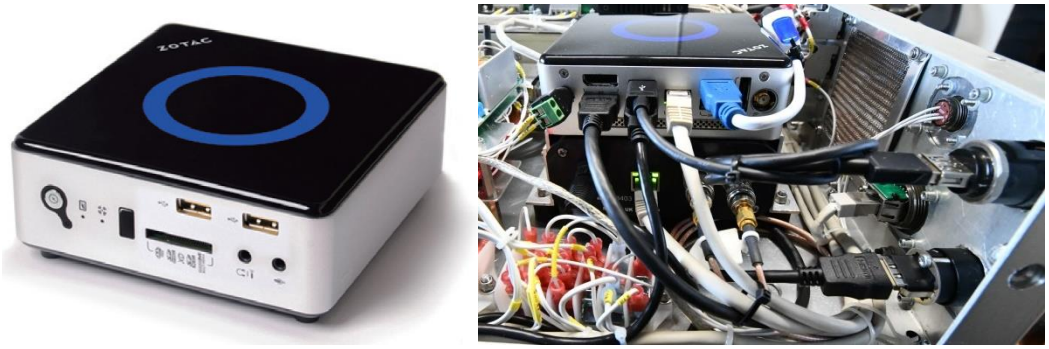


Figure 42 Zotac Zbox Nano ID64 unit with different connections

To access the internal MUMM_LOG_PC, a remote connection can be realized using TeamViewer (V12) or Windows remote desktop. The IP address of the MUMM_LOG_PC is 192.168.1.9 with login name “MUMM” and password “mumm”. To enable this connection the IP configuration of the client stations have to be adjusted (see 1.6 External signal wiring)

1.1.6 AIS+GPS receiver

The network NMEA AIS+GPS receiver used in the sniffer sensor consist of a Comar SLR200NG receiver (see Figure 43). A VHF antenna is installed on the belly of the aircraft and connected to the ASP connector panel (TNC), a GPS receiver is installed on the top of the aircraft and connected to the ASP connector panel (TNC). The receiver is located in the bottom compartment of the sniffer under the LOG PC (see Figure 42) and is attached to the frame with M7 and M8 locknuts.

Specifications AIS+GPS

- Manufacturer: Comar
- Type: SLAR200NG
- Connectors: VHF Antenna BNC; GPS Antenna TNC
- Output Port: RJ45 Ethernet port
- Power Supply Range: 9 – 30 Volts dc
- Power Consumption: 400 mW
- Output Baud Rate: 38,400 Baud

Specifications GPS antenna

- Manufacturer: Cobham
- Type: CI 401-220
- LNA
- Frequency: 1575.42 +/-3 MHz
- VSWR: 1.5:1 Maximum
- Polarization: RHCP

- Radiation Pattern Hemispherical
- Output Impedance: 50 Ohms
- Gain @ 1575.42 MHz 26.5-31.5 dB
- DC Voltage 4 to 24 Volts
- DC Current Min/Max 25mA / 40 mA
- Noise Figure 3.8 dB
- Selectivity: -40 dB Min. @ Satcom 1626.5 MHz

Specifications VHF antenna

- Manufacturer: Cobham
- Type: CI 292-3
- Frequency : 136-174 & 138-174 MH
- Gain: 2.5 dB Minimum
- Impedance: 50 Ω
- Polarization: Vertical
- Patter: Omnidirectional
- Power: 50 Watts



Figure 43 Comar SLR200NG receiver, Cobham VHF antenna and Cobham GPS antenna

1.1.7 Arinc

An Arinc converter is installed in the sniffer (Olimex ARINC ADC 20160815) and connected with a 5 volt RS232-Ethernet converter. This device translates the navigation information coming from the aircraft avionics (Garmin G6TN650) ASP-CON-06 (Pin1-3), the Arinc data stream contains a great number of navigation data, but currently only the wind information is used by the sniffer sensor system (labels 315 and 316).

2018-08-2210:51:39.720100,from,192.168.1.121:9760,ADC,-1,-1,348,482,609,-1,715,682,686,688,691,686,-1,-1,-1,-1

Table 5 ASP-CON-06 specifications

	Description	Manufacturer
Connector Type Chasis	D38999/20FE35PN-LC	Amphenol
Contact Type Chasis	55x Male	Amphenol
Shell Size Chasis	17	Amphenol
Connector Type Cable end	D3899/26FE35PN-LC	Amphenol
Contact Type Cable end	55x Female	Amphenol
Shell Size Cable end	17	Amphenol

PIN	Conductor Type	Signal Name	Signal Logic / Load (A)
1	AWG 22 Double shielded	Arinc 429 TX A (from GTN 650 nr 1)	
2	AWG 22 Double shielded	Arinc 429 TX B (from GTN 650 nr 1)	
3	AWG 22 Return	Arinc 429 Return (from GTN 650 nr 1)	

Table 6 Available data labels on the Arinc signal from the Garmin GTN650 (100 Hz)

Label	Parameter	Range	Sig bits	Resolution	Update interval
150	Greenwich Mean Time	0-23 h 0-59 m 0-59 s		1 s	1 Hz
204	Baro altitude	±131072 ft		1 ft	1 Hz
260	Date			1 day	1 Hz
310	Latitude	±180°		0.00017°	10 Hz
311	Longitude	±180°		0.00017°	10 Hz
312	Ground Speed	4096 kn		0.1 kn	1 Hz
313	True Track	±180°		0.1°	1 Hz
314	True Heading	±180°		0.1°	10 Hz
315	Wind Speed	255 kn		1 kn	1 Hz
316	True Wind Direction	±180°		1°	1 Hz
(317)	(Magnetic Track)	(±180°)		(0.1 °)	(1 Hz)
321	Drift Angle	±180°		0.1°	10 Hz
324	Pitch Angle	±180°		0.1°	10 Hz
325	Roll Angle	±180°		0.1°	10 Hz

1.1.8 Air pumps

There are in total 3 pumps used in the sniffer sensor system, the first pump is used for the CO_2 and SO_2 sensors, the second pump is used for the hydrocarbon Kicker and the third pump is used for the NO_x sensor. The pump used for the SO_2 and CO_2 sensor, is the main pump in the sniffer sensor (838.1.2 KNDC-B), this is a two headed pump (replaced the former one headed main pump in 2021):

- Manufacturer: KNF
- TYPE: PJ33413-838.1.2
- NO: 15207799
- U: 24 VDC (3.7 A)
- Pmax: +50kPa (0.5bar)
- Flow at barometric pressure: 60l /min
- Weight: 3 kg

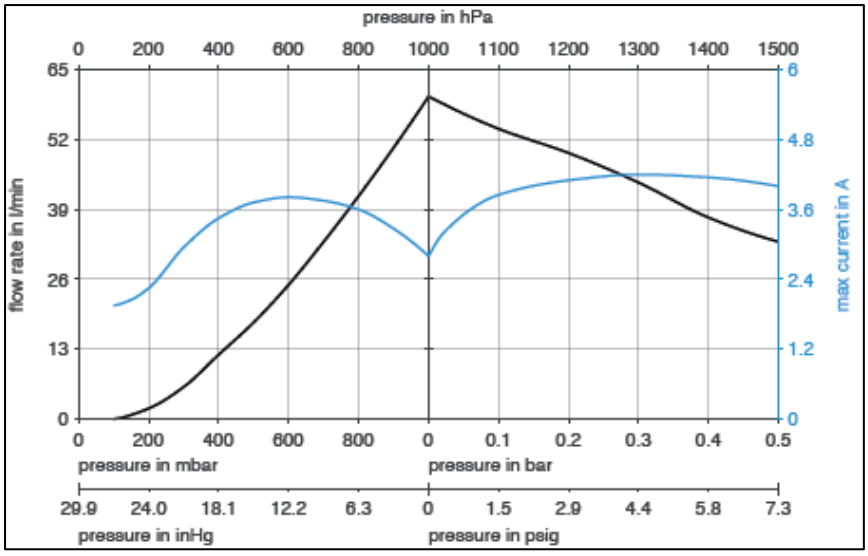


Figure 44 Pressure diagram KNF N_838.1.2 KNDC-B

A buffer (PVC tube of 10 cm diameter and ca. 15 cm long) is installed just before the pump-inlet. The pressure in the sniffer system is ca 600 mm Hg (800mbar), the actual airflow is ca 15 l/min. This circuit is pressure and flow controlled by the Bronkhorst regulators (see further). The pump used for the hydrocarbon kicker is the former main pump (838.1 KNDC-B), this pump provides an under pressure for the removal of the VOC particles in the hydrocarbon kicker.

- Manufacturer: KNF
- TYPE: PM26726-838
- NO: 9315084
- U: 24 VDC (3.7 A)
- Pmax: +50kPa (0.5bar)
- Flow at barometric pressure: 32l /min
- Weight: 2.2 kg

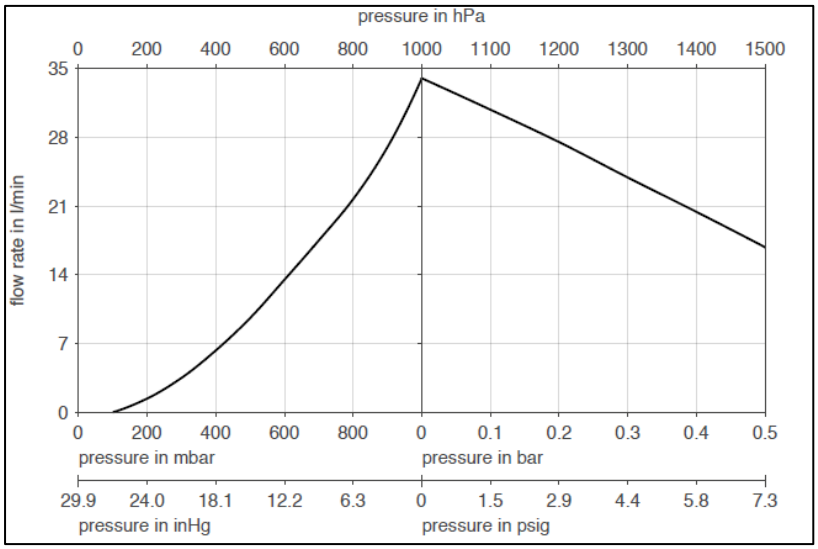


Figure 45 Pressure diagram KNF N_838.1 KNDC-B

The third pump (N 026 ATE) is used in the NO_x circuit, the airflow is split between the particle filter and the pressure regulator, this circuit goes to the NOx sensor and comes back to the sniffer sensor where it is connected to the following pump

- Manufacturer: KNF
- TYPE: N 022 ATE
- NO: PM32615-N022
- U: 110 VAC (2 A)
- Pmax: 2.5bar
- Ultimate vacuum pressure: 100mbar
- Flow at barometric pressure: 17l /min
- Weight: 5 kg

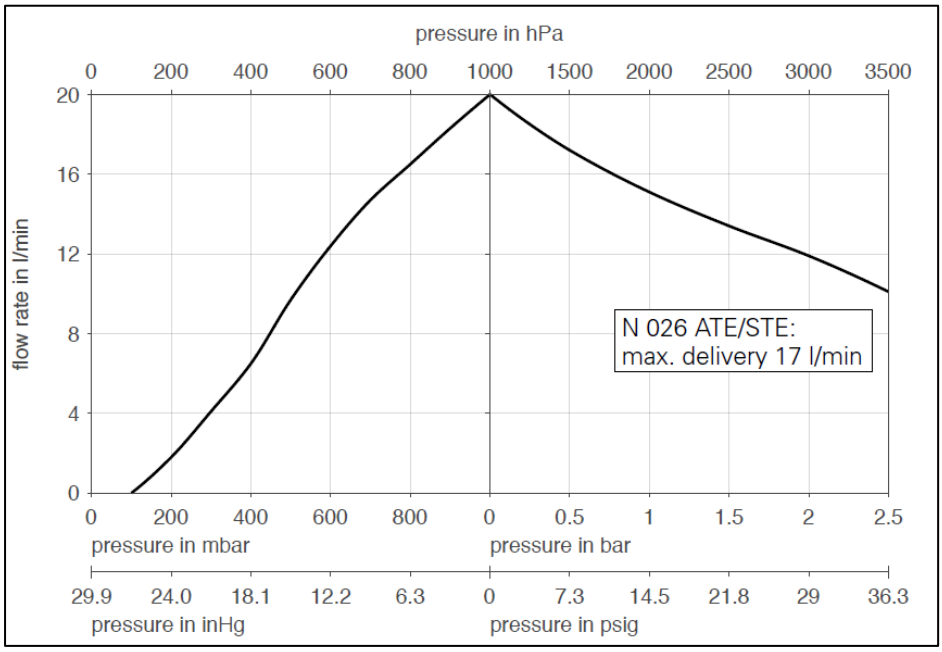


Figure 46 Pressure diagram N 026 ATE

1.1.9 Internal tubing

Almost all tubing inside the sniffer sensor is done with 1/4” Swagelok stainless steel fittings and 1/4" Teflon tubing (see 1.2.3 Connecting to the sniffer for more information), except from the exhaust tubing (from the confluence of 2 outgoing pumps 1 and 3), this section is done in 3/8 tubing to allow for an optimal release. As the NOx sensor emits ozone, an exhaust was added and one-way check valves are installed at the outlet of the pumps.

1.1.10 Hydrocarbon kicker

A special hydrocarbon kicker has been developed to remove hydrocarbons from the airflow to the SO2 sensor. This hydrocarbon kicker consists of 10 parallel installed standard Thermo 43i hydrocarbon kickers from decommissioned Thermo 43i sensors (Figure 47).

The working mechanism is based on semipermeable tubing in an inner compartment. Air flows inside this tubing towards the SO2 sensor. A dedicated pump creates an airflow in the outer compartment. Due to capillaries that are the start of this outer compartment an under pressure is created. This under pressure draws hydrocarbons through the semipermeable wall (Figure 48)

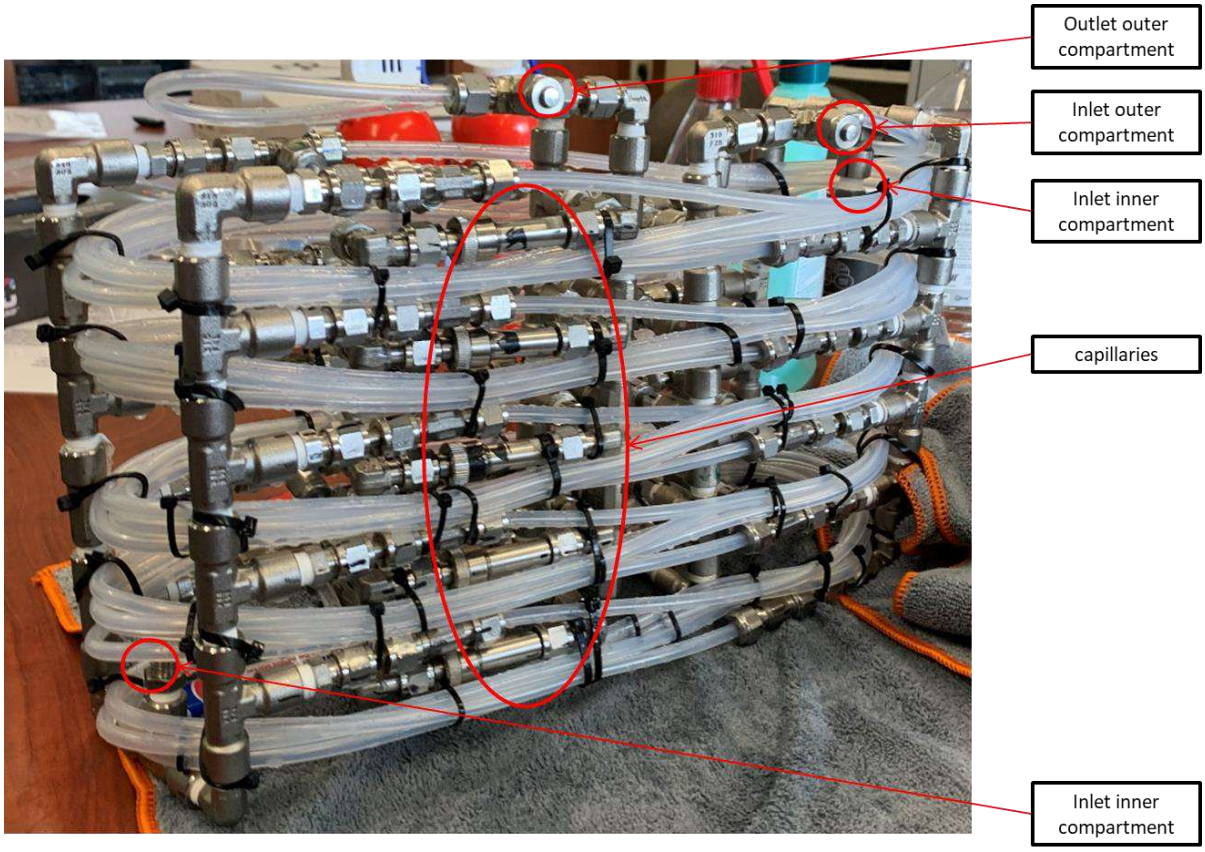


Figure 47 Custom designed hydrocarbon kicker

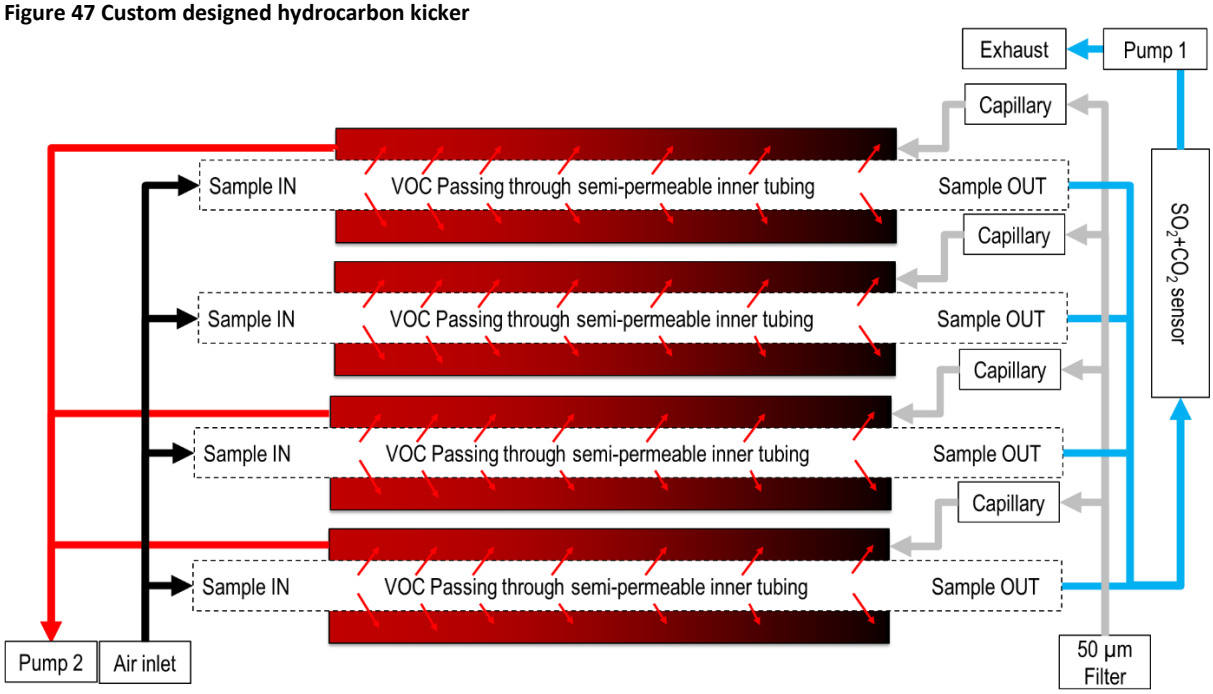


Figure 48 Schematic drawing of the hydrocarbon kicker

1.1.11 Internal signal wiring

The Sniffer sensor setup is based on a network environment, all data is logged on the sniffer sensor internal computer MUMM_LOG_PC, this data can be accessed from different client stations following client stations are used during operations:

- MUMM_LOG_PC: for visualisation of the MAP to the cockpitdisplay (on MAP2)
- Operator Laptop: for manual calculation of the FSC
- Console: for strategic overview, guiding pilots and plotting graphs on VIDEO 2 on cockpitdisplay

To connect different client stations to the sniffer sensor a set of predefined IP addresses need to be used (Table 1), for more information on how to set the IP address see Section 3 of the SQMS.

Table 1 IP addresses for external connection to the sniffer sensor

IP addresses	User
192.168.1.230 -239	available
192.168.1.240	Console via VM
192.168.1.241	PC Ward via Thunderbolt dock
192.168.1.242	PC Kobe via Thunderbolt dock
192.168.1.243	PC Annelore via Thunderbolt dock
192.168.1.244	PC Benjamin via Thunderbolt dock
192.168.1.245	PC Ward via cable
192.168.1.246	PC Kobe via cable
192.168.1.247	PC Annelore via cable
192.168.1.249	PC Benjamin via cable

1.1.12 Internal power distribution

The sniffer system uses an inverter (KGS SS120) to the 28VDC (20A CB) of the aircraft to 115VAC, this is necessary for the external components and the Thermo 43i TLE sensor. For the different components other power conversions are necessary (115VAC to 24, 19, 12, 5 VAC). The total theoretic power consumption of the sniffer system and the external components (Laptop + Thunderbolt Dock) is 18 A. The actual power consumption of the sniffer system is 8-11 A, this means that there is still a potential of 8 A available for future modifications. An overview of the internal power distribution is displayed in Figure 6. Following power converters are installed:

- Inverter KGS SS120 (28 VDC to 115 VAC 60 Hz) to power converters and 80 mm fans (10.3A ~50A@28V)
- Traco Power TMP 15105C 100-240VAC to 5 VDC (3 A ~0.5A@28VAC)
  18. Ethernet hub
  19. RS232 to Ethernet
  20. 40mm fans
- Traco Power TMP 30112C 100-240VAC to 12 VDC (2.5 A ~1.1A@28VAC)
  21. AIS+GPS
  22. ARINC board
- Traco Power TMP 30124C 100-240VAC to 24 VDC (1.25 A ~1.1A@28VAC)
  23. Licor
  24. Bronkhorst regulators
- Unknown manufacturer 115-19V (3.4 A ~2.3A@24VAC), located next to the LOG PC
  25. Log Computer
- Thermo power converter 115-24 V (166 watt – 7 A ~6A@28VAC) located beside the motherboard
  26. Thermo
- EPC power supply (26V)
  27. Air pump 1 (KNF 838.1-2)
  28. Air pump 2 (KNF 838.1

4 circuit breakers are available on the casing of the sniffer:

- CB 1 (5A): External 115V connector (J211) for NO_x sensor
- CB 2 (5A): Traco power converters, air pump (1&2) and MUMM_LOG_PC
- CB 3 (5A): NO_x air pump (KNF N 022 ATE)
- CB 4 (5A): Thermo 43i TLE

Following internal fuses are included:

- Fuse 1: Inverter 50 A
- Fuse 2: LICOR 2.5A

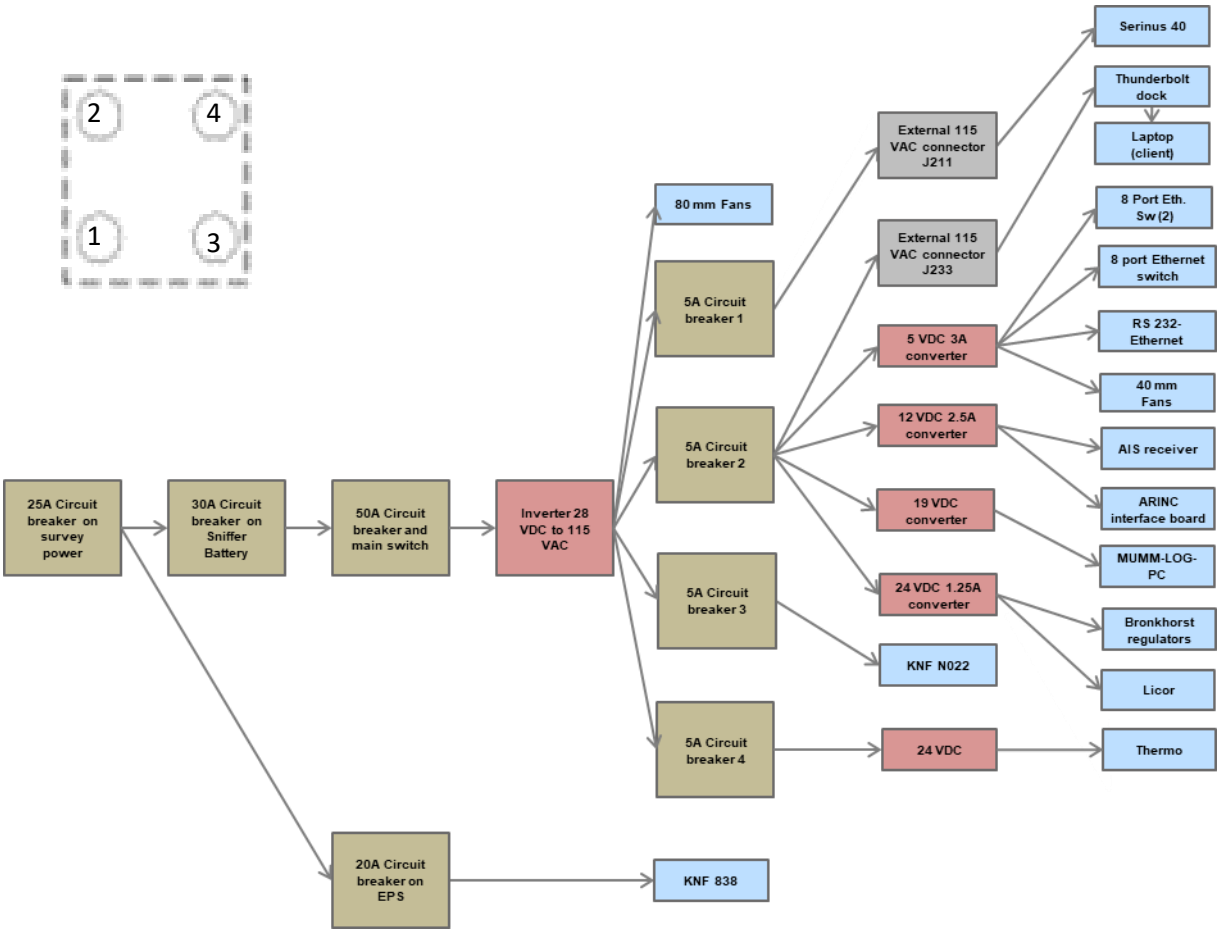


Figure 49 Overview power distribution and circuit breakers inside the sniffer sensor system

1.1.13 Fans

2 types of fans are used, 3 x 80 mm fans (NMB) running on 115 VAC on the backside and 12 x 40 mm fans (Sunon) running on 5 VDC on the front side (installed in 3 blocks of 4 fans).

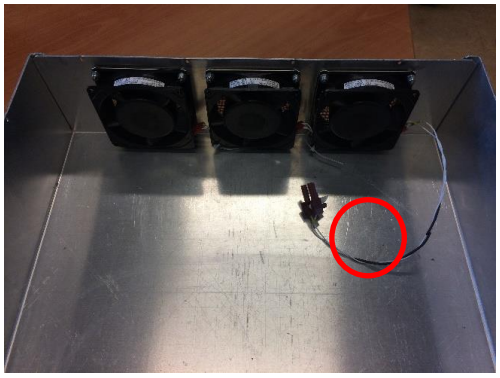


Figure 50 Cooling fans (115 VAC) with power connector (red)

1.1.14 Casing

The sniffer sensor is divided in 2 main parts, a bottom part and top part that are separated by an aluminium inner frame. All components and wiring are attached to this inner frame. Different openings are made in the internal frame to connect components between the top and bottom part. The bottom and top part are closed from the outside with large aluminium covers, that contain almost the full exterior of the sniffer sensor (except the connector panel). The fans are the only sensor components attached to the covers, all fans are covered with fine aluminium mesh to avoid EM interference. The top and bottom covers are attached to the internal frame with M3x10 TX10 screws. Most components and wiring are attached to the internal frame with M5 locknuts. The available space in the sensor for future sensors is 60x12x25 (LxWxH). All connectors used on the sniffer are MIL standard connectors (EMC shielded) and are attached to the sniffer casing using Allen hex screws size M2.5x10

1.2. NOx sensor

A NOx sensor was added to the sniffer sensor system. The sensor is an Ecothech Serinus 40. The sensor is installed in the back of the aircraft. A protection plate is installed in the front of the sensor protecting it from accidental touches on the control buttons. All commands go through a smartphone with the Serinus application connected through Bluetooth.



Figure 7 NOx sensor installed in the rear luggage compartment (here displayed without the protective front panel)

1.3. Client station

The sniffer sensor system is a network based system. This means that all sensor data is gathered on the internal LOG-PC and made available for different IGPS software installations on client stations. In theory a vast amount of client stations can be connected to the Sniffer by using ethernet. For operational use, only 2 client stations are connected to the sniffer. 2 clients are used in the aircraft. One on the Mission Management Unit from Optimare on a Virtual Machine and on each of the operator laptops. This means that together with the MUMM_LOG_PC constantly 3 computers are receiving the sensor data and can be used for navigation and analysing the measurements.

1.3.1 Console (MMU)

The MMU is the main console in the aircraft used for the Medusa system. The MMU runs on a tailored Open Suse Linux Platform and is therefore not suited for the installation of the IGPS software. A Virtual Machine (VM Player) with a Windows XP installation is installed on the MMU to allow to run IGPS on the console.

To enable direct Ethernet connection from the VM to the Sniffer sensor an additional Ethernet cable was installed (from J221 to an Ethernet hub inside the console). The IGPS software is installed on the "C:" drive of this VM XP distribution. The firewall has been deactivated for the IGPS software.

The VM main settings are: 2GB RAM, 2 Processors, 60 GB virtual Hard Drive and 3 virtual Ethernet Network Adapters (bridged to host).

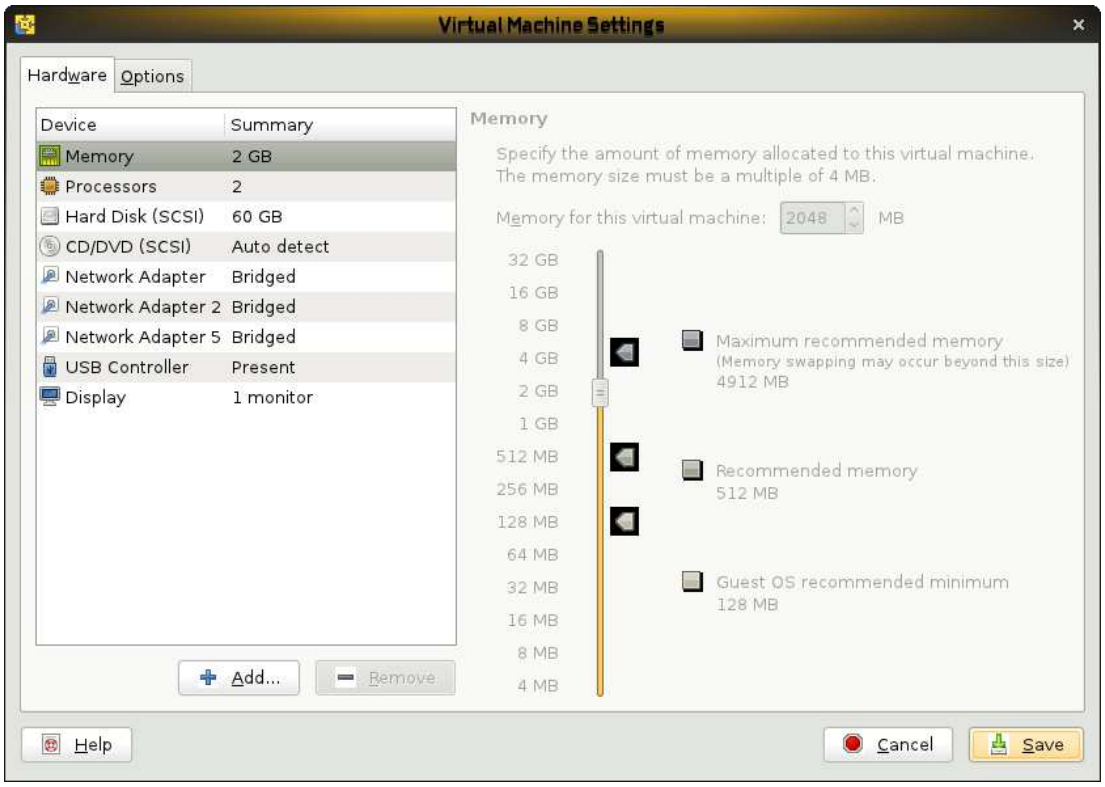
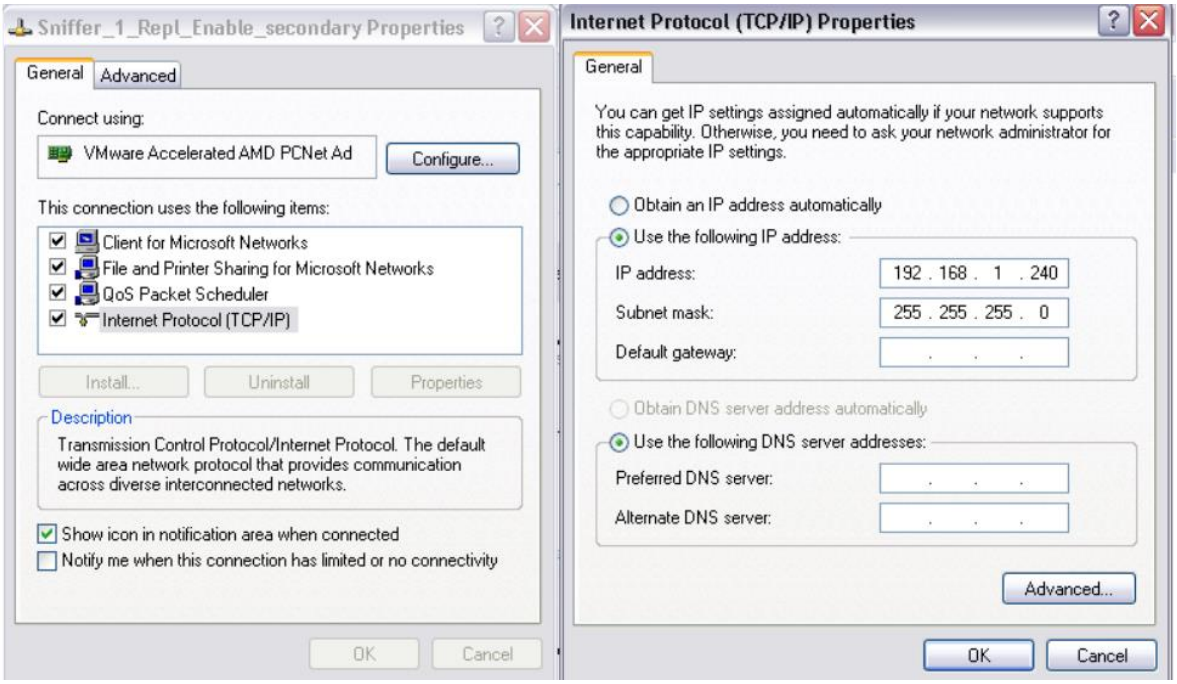


Figure 51 VM settings on the MMU

The network adaptors are used for the Wifi connection, the FLIR camera and the Sniffer sensor. The IP addresses for these 3 virtual Network adapters can be changed via the Network settings in Windows XP on the VM (see). Use following IP addresses for the network adapters:

- FLIR Camera:
- Wifi: Automatic
- Sniffer: 192.168.1.240 (Subnetmask 255.255.255.1)





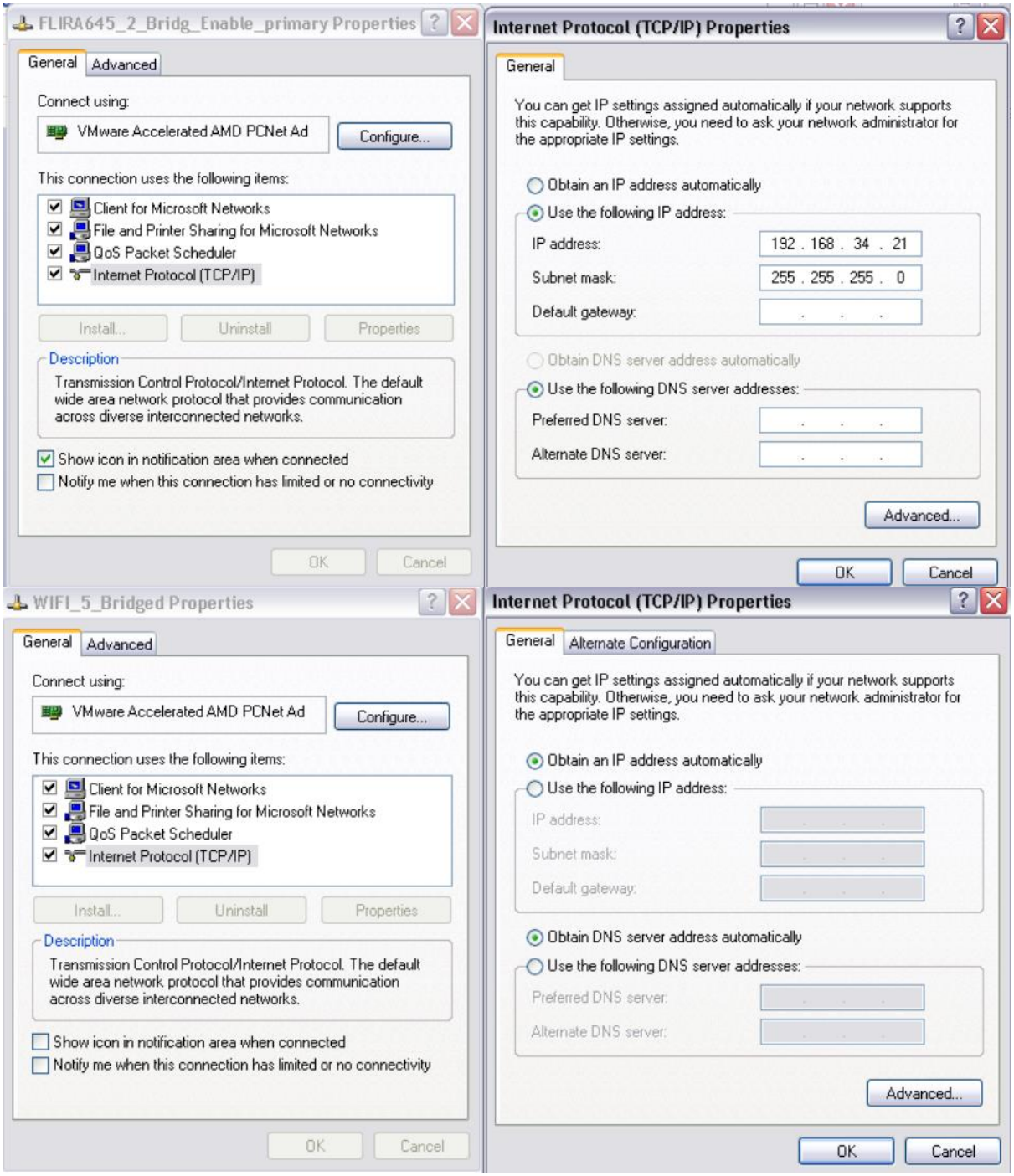


Figure 52 Network settings VM for Ethernet adapters 1 (Sniffer), 2 (FLIR) and 5 (WIFI)

Note: Because of an IP address conflict with the Sniffer, the WiFi connection can currently not be used together with the sniffer sensor (network adapter for WiFi must be disabled when operating the sniffer), in case the FLIR camera is required the sniffer network adapter must be disabled first After connecting the FLIR camera, the sniffer network adapter can be re-enabled.

The IGPS software is installed on the "C:" drive of this VM XP distribution. The firewall has been deactivated for the IGPS software. TeamViewer V12 has been installed on the VM to enable a remote desktop connection to the MUMM_LOG_PC. To allow sharing of folders with the console the shared folders must be activated in the Virtual Machine Settings and VMWare tools must be installed.

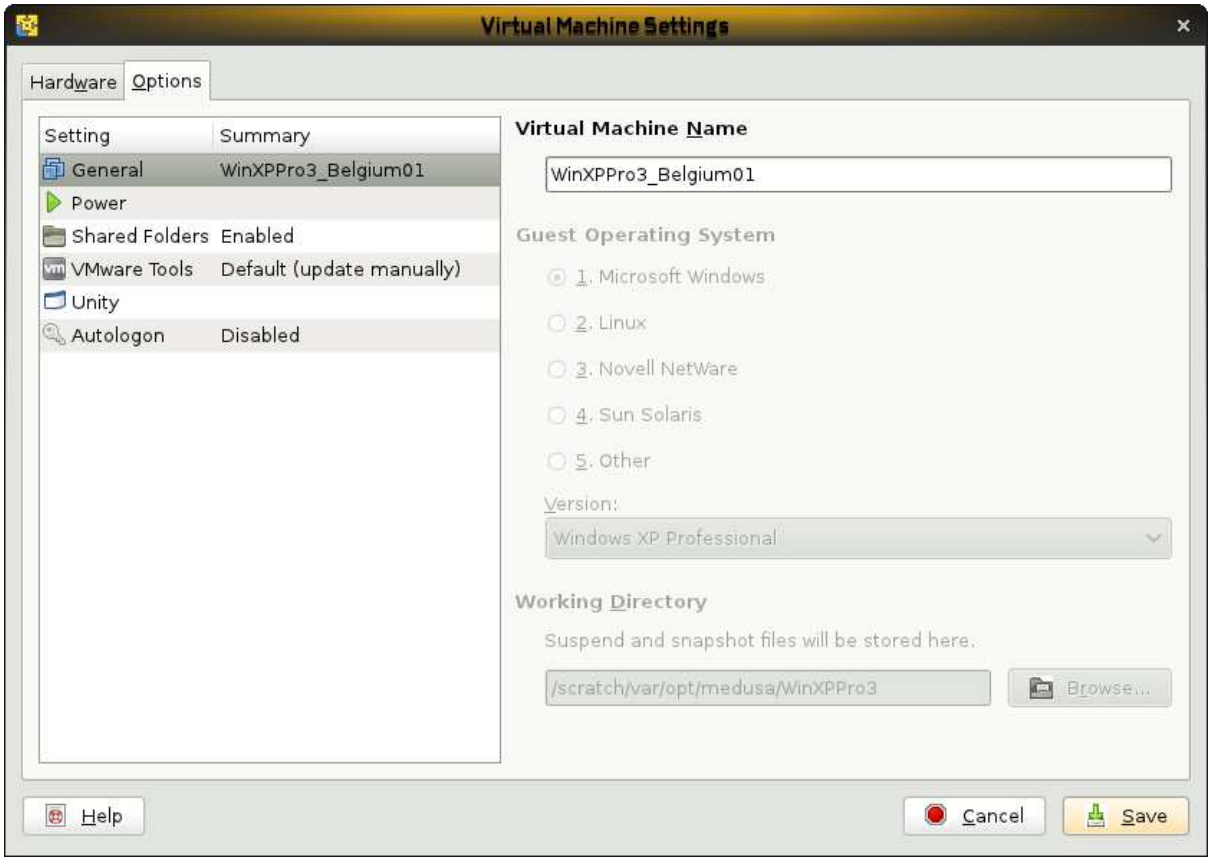


Figure 53 VM settings on the MMU shared folders and VMware tool

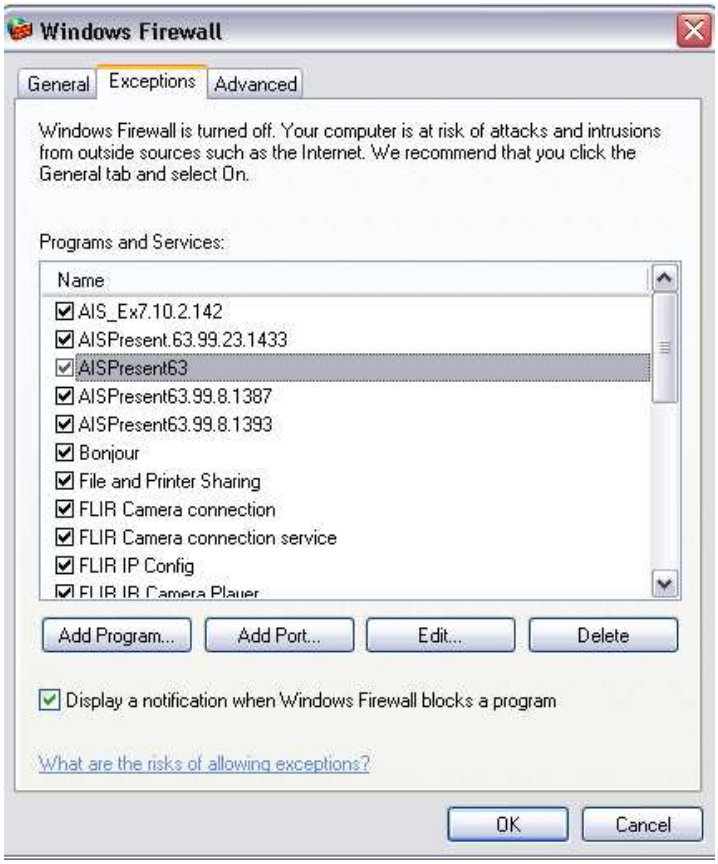


Figure 54 Firewall settings on VM

An additional USB to VGA adapter is installed on the VM (Startech USB to VGA External Video Card). This allows the presentation of the VM display (SNF view of the AISPresent.exe) to the cockpit display and G600 (Video 2). To connect the VGA adapter to the VM player, this device needs to be connected thorough Removable Devices>>Magic air. The remote monitor can be activated via the Magic Air button in the task bar.



Figure 55 USB to VGA converter

1.3.2 Operator laptop client stations

4 Dell Latitude 5420 stations have been acquired to be used during sniffer flight with following general specifications:

- Processor: i7-1165G7 CPU @ 2.8 GHz
- RAM: 32GB
- System: 64bit Windows 10Pro

In principle most off the shelves laptops would be suitable to run the IGPS software, but some requirements improve significantly operational efficiency.

- A touchscreen makes it easy to manipulate the software during flight.
- A 1TB Solid State Drive is more reliable in harsh environments (vibration).
- A fast processor and video card provide fast visualization and calculations of ship plumes and FSC.
- An illuminated keyboard allows to use the Laptops during low light conditions.
- A Thunderbolt connection use both power and Ethernet over 1 cable.
- A powerful battery to last during the whole flight.

To enable the connection from the Laptop to the sniffer sensor the firewall settings have been adjusted. This is generally requested during first opening of the IGPS software (AISPresent.exe) but in a few situations it was needed to do this manual, by adding a new in-bound and a new out-bound rule for the AISPresent.exe program in the firewall advanced settings (all connections are allowed).

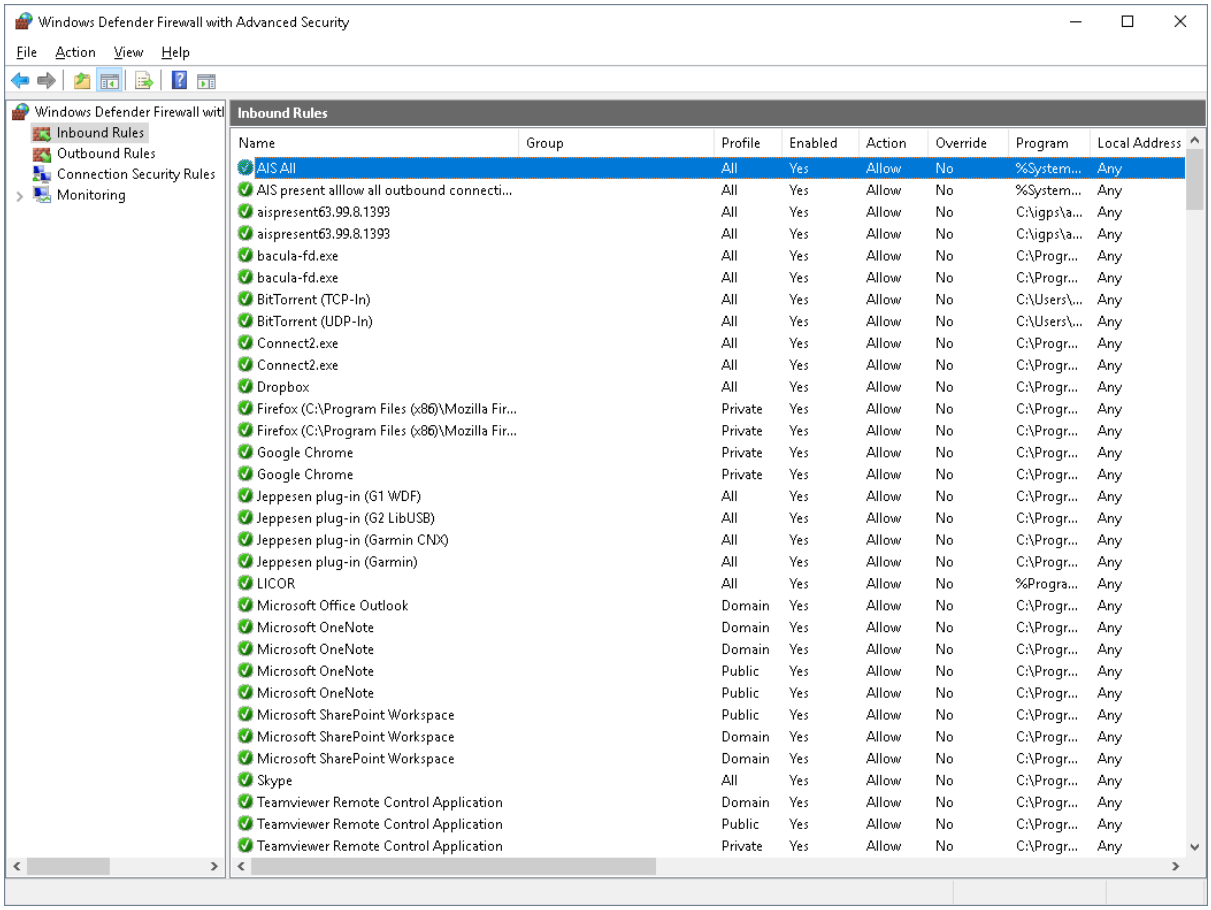


Figure 56 Advanced firewall settings

1.3.3 Laptop RAM mount and thunderbolt dock

To avoid issues with multiple cables a Startech thunderbolt docking station has been installed on the front side of the console, the laptop is connected to a 2 m thunderbolt cable providing, data (ethernet, USB, HDMI) and power. The thunderbolt dock and laptops are powered by 115V power connector on the Sniffer (J233). For operational and safety related reasons the operator laptops are mounted inside the aircraft using a laptop mount (Ram Mount Model: RAM-VBD-128-SW1).



Figure 57 RAM mount for installation operator laptop

1.3.4 IP addresses

A standard 5VDC 8 port RJ45 Ethernet hub (MXU85A0001) is used to connect all the different Ethernet connectors from the components to the MUMM_LOG_PC and client station. The internal main IP addresses in the sniffer sensor are displayed in Table 7.

Table 7 IP addresses used in the sniffer sensor

IP address	Component	Port
192.168.1.19	Co.Pilot Present	
192.168.1.9	Logger internal computer	
192.168.1. 95	Licor7200	7200
192.168.1.201	Thermo TLE 43i	Command: 9880 Stream: 9881
192.168.1.110	Comar AIS+GPS	10001
192.168.1.102	Bronkhorst Flowbus	1471
192.168.1.130 (CPC-3787) 192.168.1.106 (CPC-3787-RS232)	Bronkhorst pressure control: Ethernet to RS232	23 1470
192.168.1.121	ARINC receiver	9760
192.168.1.213	Ecotech Serinus 4.0	Serial port 97

1.3.5 IGPS software

The IGPS folder is installed on the "C:" drives of the operator laptops and are synched by Seafile. This way all operators use the same software version. The different software directories and files are:

- "Charts" Directory: folder with Open source charts of the world
- "Missions-Data" Directory: folder with generated reports of observations
- "MAIL" Directory: not used by SURV
- "AIS_EX8.exe" program: tool used for extraction of TCP-LOG files
- "AISPresent.exe" program: main software program used in flight and during calibrations
- "IPGSAna44.exe" program: software for post flight analysis (extraction required)
- "AISPresent.ini": this is the settings file for AIS present (can be read and edited using Notepad)
- "IP-configuration-SURV.txt" file: this document contains the used IP addresses for the different clients
- "Emissiondata_xxx.txt" files: are generated by the different clients (ODN-WVR, ODN-KS, ..) and contain the FSC measurements
- "Mail_Sniffer_SO2_Man_Meas.csv" file: contains the evaluation (High/Low/Not detected) of the manually marked ships
- "Comments _xxx.txt" contain the stored comments (old comment files are stored in "Comments" directory
- "wakeuplan.txt" file: contains the Mac address of the MUMM_LOG_PC in the sniffer sensor and can be used to wake up by Lan
- "Optical_SO2_Man_Meas.txt" file: not used by SURV
- "STATICSHIPDATA_xxx.txt" file: contains a record of the observed ships per operator
- "MMSI_Date.csv" file: database containing Keel Laying Years and MMSI data for the global fleet
- "Thresholds, BIAS and SFOC-2022.xls" file: reference file containing the SFC calculation tool, thresholds for FSC and NOx, the bias for FSC, this file also contains a conversion for the NOx measurements by using the actual SFC

- "borlndmm.dll", "cc32230.dll", "cc32230mt.dll", "Fetchlog.txt", "Logfile.txt", "Memo1-1.txt": are other additions files

The operational use of the software is described in Section 1 of the Sniffer QMS. The data storage, data processing, … is described in Section 3.

1.4. Particle filters

Two fine particle filters are installed in a box outside of the sniffer system (see Figure 58 andFigure 58 Arco PALL filter (filter after 6 months of use) Figure 59). The very fine pore size (1µm) prevents water and particles to enter the system. The 2 filters installed in a parallel configuration to allow for a maximum flow. The box is installed between the air inlet and the sniffer system. The specifications of the filters are:

- Manufacturer: PAL
- Type: ACRO 4003 PTFE
- Size: 50 mm
- Pore size: 1µm
- Connection: 1/8 in. MNPT (with Teflon tape)

A valve is installed before the filter inlet to switch between ground (GND) and in-air (AIR) operations. In GND mode, the air inlet comes from inside the cabin and passes through a carbon and Purafil filter to avoid contamination. In AIR mode the air flow comes straight from the Pitot tube.



Figure 58 Arco PALL filter (filter after 6 months of use)

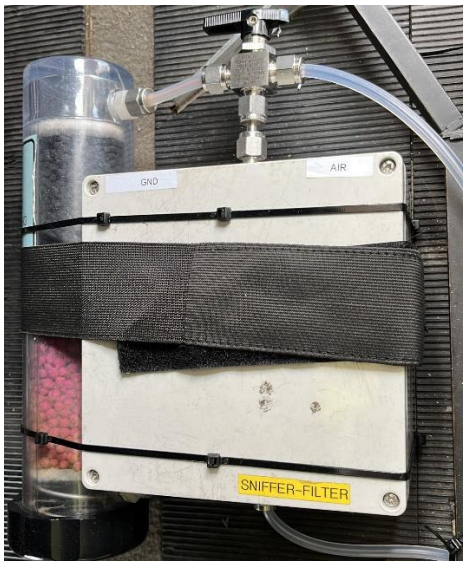


Figure 59 Figure 20 Filter box containing the particle filters and valve to switch between ground (GND) and in-air (AIR) operations

1.5. Pneumatics

1.5.1 Swagelok fittings

For all connections, both internal and external connections, Swagelok connections are used. For tubing, Nylon (NY), Teflon or PVC tubing can be used. For the permanent tube connections stainless steel fittings (SS) are used (fitting with nut, front and back ferrule, see Figure 60). The main size for tubing and tube connections is 1/4" although the pitot-tube and exhaust uses 3/8" connections and

tubing, the connection toward the NOx is done in 1/8" to minimize the delay time between the NO_x signal and the CO_2, signal.

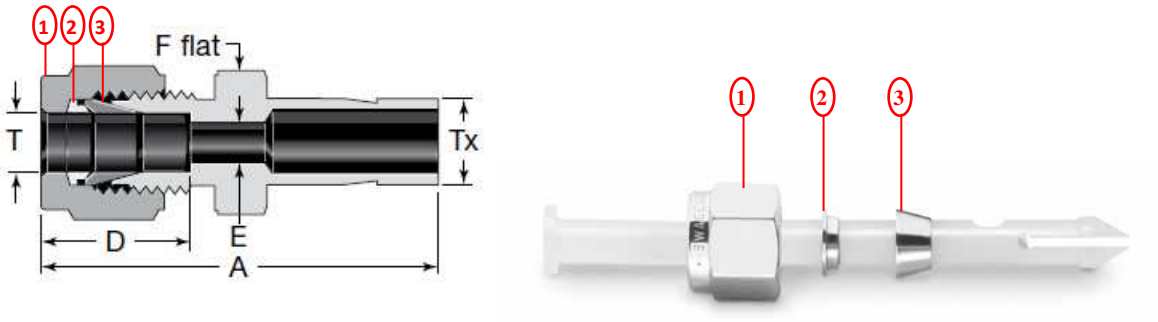


Figure 60 Swagelok fitting with nut (1), front (3) and back (2) ferrule (Swagelok, 2016)

1.5.2 Pitot tube and exhaust

The sniffer pitot-tube or sample probe consist of a Swagelok bulkhead connector (SS-600-61-4) to pass through the fuselage of the aircraft (see Figure 61), with on the inside a 1/4" connection connected with a port connector (SS-401-PC) by a 90° turn (SS-400-9) and on the other side a 3/8" connection connected to 10 cm 3/8 stainless steel tubing 316/316L 0.65in thickness (SS-T6-S-065-20). The exhaust tube is similar bulkhead connect but with both sides in 3/8" (SS-600-61) and without 3/8" Stainless steel tube extension.

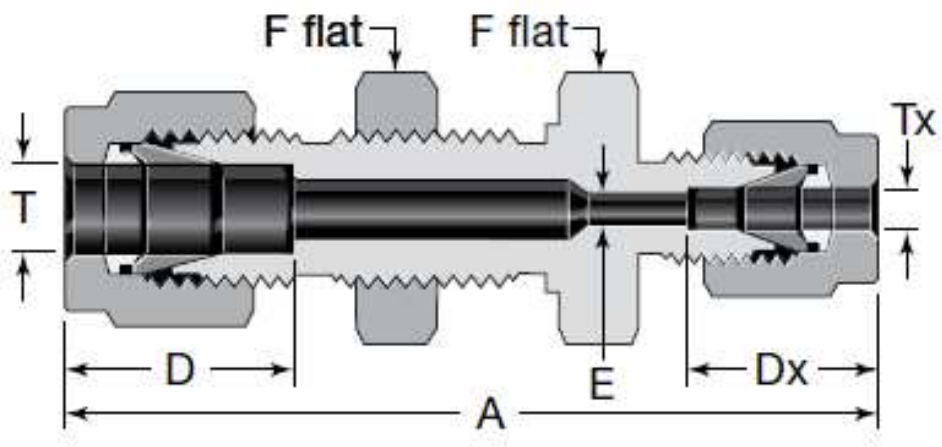


Figure 61 Bulkhead connector used for the pitot-tube to pass through the aircraft fuselage

1.5.3 Reference gas cylinder equipment

The reference gas cylinders used during the calibration are equipped with a pressure regulator, flow-meter (volume meter) and rotameter (see Figure 62) with following specifications:

- Regulator CO_2: HBS 200-3-2,5 (Airliquide): 200 to 0.1-3 bar (B4 or DIN 6 connection)
- Regulator SO_2/NO: HBSI 200-1-2 (Airliquide): 200 to 0.05-1 bar (B8 or DIN 1 connection)
- Volume-meter CO_2: Dynaval Azote (Airliquide), 0-15 l/min
- Volume-meter SO_2/NO: Millimite.S_200-0,02 AN (0.02 Kv)
- Rotameter: Brooks 2510 A 2A13 S N VT (Jadition), 0-1 l/min

A different regulator is used for CO_2 and SO_2/NO cylinders (opposite thread for SO_2/NO). The volume meter is connected to the regulator output. The output from the volume meter is split with a Swagelok Tee-connector (SS-400-3), one side can be connected with the flexible hosing and the other side is connected with a rotameter to measure the overflow during calibrations. The outlet of the rotameter is open to the atmosphere. An additional Swagelok toggle valve (SS-1GS4) is installed between the volume-meter and the T-connector, this enables a quick flushing of the regulator.



Figure 62 Installation of reference gas cylinders on chart, every cylinder is equipped with regulator (1), volume-meter (2) and rotameter (3). The gas cylinders are attached to the chart with a heavy duty strap

1.6. External signal wiring

A detailed description of all connection including signal wiring to and from the sniffer is available in Annex B. The Sniffer sensor is connected to the aircraft navigation instrumentation (Garmin GTN-650) using the Arinc protocol information on wind and positioning is provided to the Sniffer sensor.

The sniffer sensor works in a network based structure, the sensor is equipped with an internal computer, but all sensor data can be consulted on a network. Two Ethernet connections area available on the sniffer sensor, one is connected to the Optimare Mission Computer, the other is connected to an ethernet hub, which connects to 1) a Thunderbolt docking station (Startech) that can be used to connect with operator laptops and 2) with the NO_x sensor. The available IP addresses for client stations to connect to the sniffer sensor are available in Table 1, the subnet mask is 255.255.255.1. More information is available in Section 3 of the SMQS on how to change the IP addresses of the client stations.

Table 8 IP addresses for external connection to the sniffer sensor

IP addresses	User
192.168.1.230 -239	available
192.168.1.240	Console via VM
192.168.1.241	PC Ward via Thunderbolt
192.168.1.242	PC Kobe via Thunderbolt
192.168.1.243	PC Annelore via Thunderbolt
192.168.1.244	PC Benjamin via Thunderbolt
192.168.1.245	PC Ward via cable
192.168.1.246	PC Kobe via cable
192.168.1.247	PC Annelore via cable
192.168.1.249	PC Benjamin via cable

1.7. Power distribution to the sniffer

A detailed description of the power distribution from and to the sniffer is available in Annex B. The sniffer is equipped with a master power switch and a remote switch (via J211 pin E see Annex B), the master power switch is best left switched on (upwards) the remote switch is located at the operator intercom panel. A 20A circuit breaker has been installed in the cockpit an additional 20A circuit breaker has been installed on the output of the emergency battery; pull both circuit breakers in case of long-term inactivity or in case of emergency.

1.7.1 Aircraft power

The sniffer is powered from the “Utilities” bus a, relay connected to the “Survey power” is powering the sniffer. A connector for the powering of the sniffer is installed in the ASP connector panel on the left side of the aircraft, behind the sniffer (ASP-CON-07). See Table 9 for the basic specifications or see wiring diagram OO-MMM ASP in Annex B for more detailed information. The original fuse of 20 A was increased to 25 A to include the NO_x sensor.

Table 9 Connection to the aircraft power supply

	Description	Manufacturer
Connector Type Chasis	62GB-12E14-02SN	Amphenol
Contact Type Chasis	FEMALE	Amphenol
Shell Size Chasis	14	Amphenol
Connector Type Cable end	62GB-56TG14-02PN	Amphenol
Contact Type Cable end	MALE	Amphenol
Shell Size Cable end	14	Amphenol
Strain Relief	BS1SRN14999XY	Amphenol

PIN	Conductor Type	Signal Name	Signal Logic / Load (A)
A	AWG 12	+ 28 VDC CB 27 Console	Max 20 A
B	AWG 12	GROUND	Max 20 A

CB 27 20A Instrument Panel Klixon pn 7277-2-20

1.7.2 115 VC

Two 115VC (5 Amp) power sockets are available one is used for the portable computers, the external ethernet hub and the Thunderbolt docking station and the other one is used for the NO_x sensor.

1.7.3 Emergency power

An external removable emergency battery (consisting of 2 Sonnenshein A512 /10 S - 12V 10aH units) is installed between the ASP connector panel and the sniffer. The battery is able to take-over power interruptions up to 10min (<5 min in practice). The battery is attached to the left side of the console with 4 SS bolts (M5X40). A switch has been added to allow the power switching between Aircraft power supply (switch to the nose of the aircraft) and Ground Power supply (switch to the back of the aircraft), or in neutral mode (middle position). A led has also been added to notify to the operator if the sniffer is powered, when the led is on power towards the sniffer is secured, when the led is off, power to the sniffer is only provided by the battery (will be depleted <5 min). To improve the battery duration an additional Mid Continent MD835 (formerly TS835) EPS system is added in the power supply system to allow for longer power shortages.

Table 10. Properties of the external battery units

Type	Type	Nom volt	Nom. Cap: (C20) to 1.75vpc	Discharge current (I20)mA	Max. load appr. A	Max. current 5 sec. appr. A	Weight appr. kg	Length in mm	Width in mm	Height in mm	Connection type
795525	A 512/10 S	12	10.0	500	80	300	4.1	152.0	98.0	98.4	Faston terminal 4.8
TS835	MD835-1	20-32	4.5	-	20	-	2.16	322.58	58.42	78.74	ITT Connaon DPXB-13-33S-0001 In 1/4 ATR rack

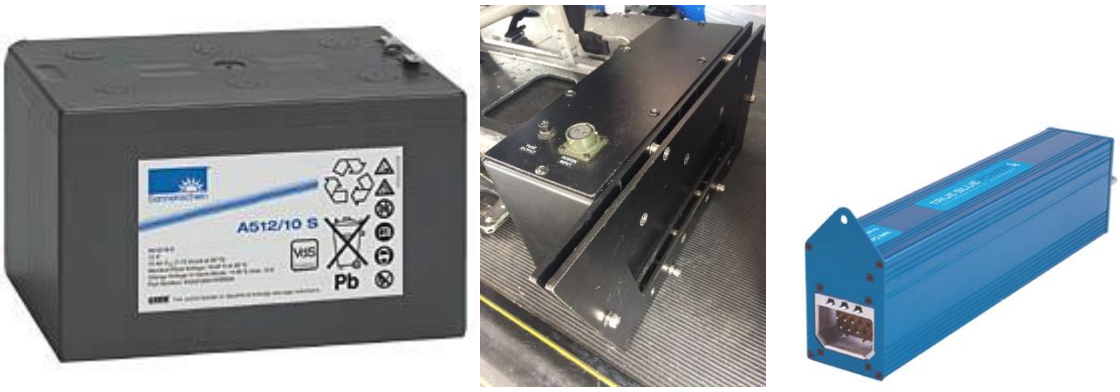


Figure 63 Sonnenschein A512/10 S Dryfit 12V Lead Acid Battery (2x) used in the emergency power battery

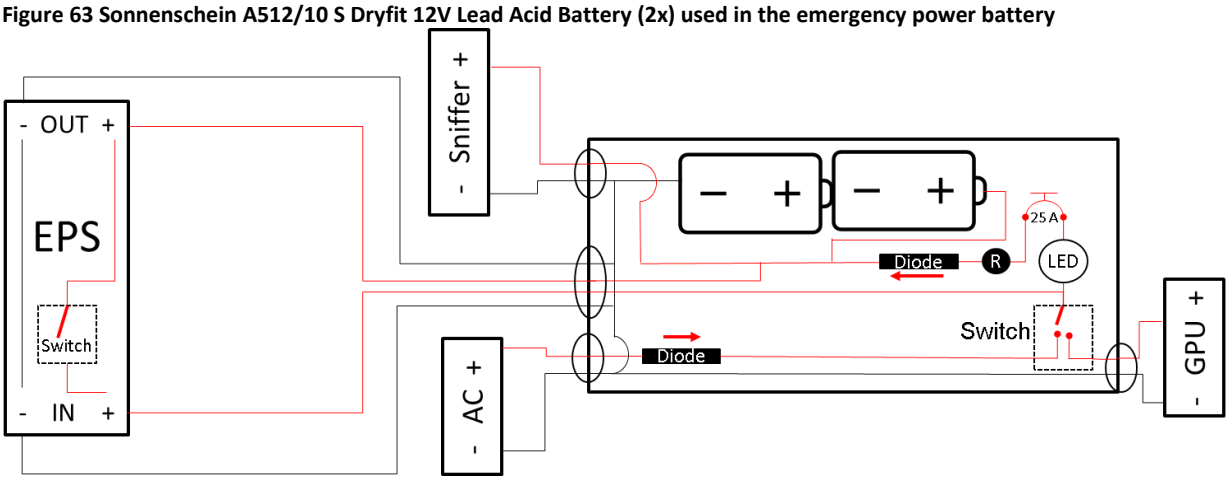


Figure 64 Emergency battery system, with 2 12VDC batteries and EPS system

1.7.4 GPU

The Sniffer can be powered on ground by using a GPU (Startpac 53050) connected to the AC external power bus (See Figure 3). An additional connector (with 25A CB) is installed on the GPU to power the sniffer sensor independent from the AC power supply (connection to the external battery) or outside of the AC (connection straight to the Sniffer sensor 28V input connector). The used connector is the same as the one used for ASP-CON-07A for the AC power to the sniffer (62G-12E14-02SN), therefor no other cabling is required. Note that this GPU cannot be used to start the aircraft engines. A power meter is added to allow the operator to evaluated the current power use (on the external connection)

Note: Always connect the GPU to the sniffer/battery/AC first before powering on the GPU.

- Voltage 28.5 VDC (50A)
- AC input is universal 90-240 Volts.
- Over current, voltage and temperature protection
- Forced air-cooling
- 4.5 kg with aircraft cable
- DIMENSIONS : L 36cm x W 13cm x H 14 cm
- CE Certified
- Equipped with Amphenol 62G-12E14-02S connector (pin A: +28V, Pin B: ground)
- Equipped with RS power meter (0-50A) on additional connector



Figure 65 Start Pac GPU used for powering the aircraft systems on ground, with addition connector and power meter

1.8. Sniffer equipment rack

The sniffer sensor is installed in a 19 inch equipment rack that also holds the Terma SLAR transceiver (see Figure 5) both sniffer and SLAR are attached with 3/8 bolts (Sniffer: AN3-4A, SLAR: AN3-5A). The rack is installed behind the pilot seat. The SLAR is attached to the rack with 4 bolts in the front plate (RH side of the AC). The sniffer sensor is fixed in the rack with one front side bracket (RH side of AC), one backside bracket (LH side of AC) and 2 top brackets. The side brackets are attached to the equipment rack with 2 bolts on each side, the top brackets are attached to the sniffer rack with 1 bolt on each side. The equipment rack is mounted to the remote sensing base plate with 8 bolts. This baseplate also supports the console of the Mission Management system. The base plate is attached with 8 custom made bolts (7/16”) to the airframe of the aircraft by using the slots used for the passenger seats (row 3-5).

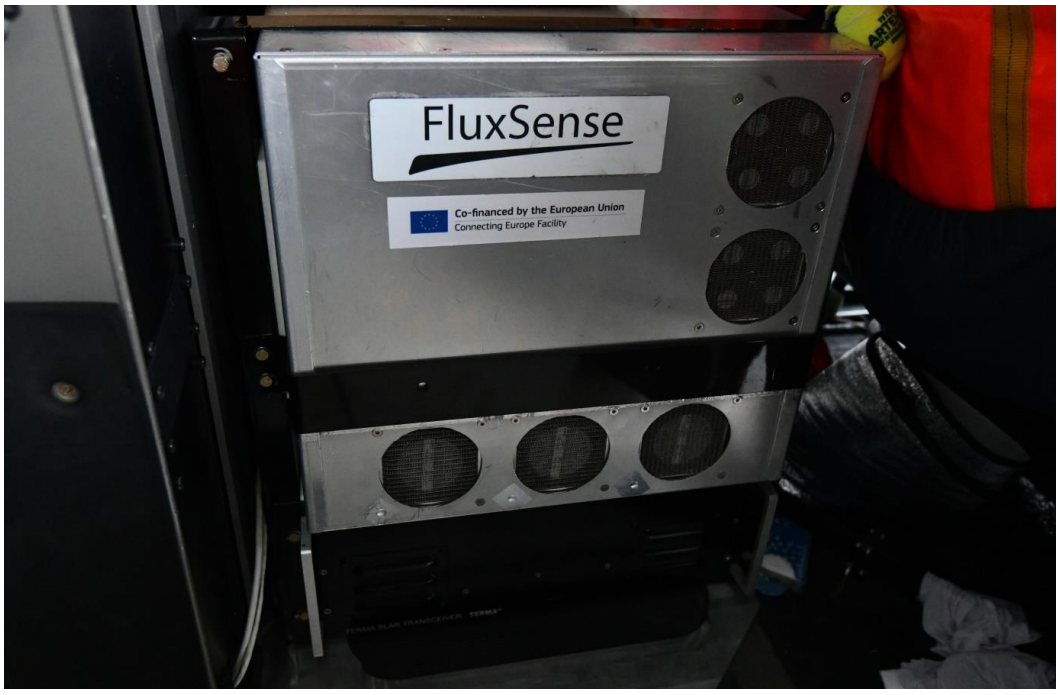


Figure 66 Sniffer 19” Equipment rack

CHAPTER 2. INTERVENTION AND SERVICING SCHEME

The sniffer sensor system intervention and servicing scheme is in provided in Table 11. A centralized maintenance intervention archive is available in the LOG sheet in the SQMS-Follow-up.xlsx file under the SURV Seafile directory: "5-Instrumentation/05-FluxSense_Sniffer/QMS/QA_Follow-up" every executed intervention or service operation whether or not included in the intervention scheme is logged into this system for record keeping. In case of malfunctioning, the issue should be reported in the comprehensive SURV issue tracking system "OO-MMM issue tracker.xlsx" which can be found under the SURV Seafile directory: "06-Issue-Tracker".

Table 11 Intervention scheme for the sniffer sensor system on board of the OO-MMM aircraft, "Recurrence Time" and "Additional service indicators" determine when a service intervention is requested *(use "ctrl+ click" on "Ref. Chapter" to navigate to the required section)*

Ref. Chapter	Description	Intervention Type	Recurrence	Additional service indicators
Daily				
Chapter 3	Software calibration	Calibration	Before every mission	-after maintenance or hardware calibration **indicated in SQMS-Follow-up.xlsx CO2/SO2 sheet**
Chapter 4	NO_x Hardware calibration	Calibration	Before every mission	-after maintenance **indicated in SQMS-Follow-up.xlsx CO2/SO2 sheet**
Monthly				
Chapter 4 4.1	CO2 Hardware calibration	Calibration	1 month	Optional: before every flight (before software calibration) -SW CO2 zero is outside -3<offset<10 -If SW k outside 0.6<k<1.5 - After Reference gas calibration **indicated in SQMS-Follow-up.xlsx CO2 sheet**
Chapter 4 4.2	SO2 Hardware calibration	Calibration	1 month	-SW SO2 zero is outside -5<offset<20 -If k outside 0.6<k<1.5 - If drift of more than 10% observed on SO2 reference gas calibration **indicated in SQMS-Follow-up.xlsx SO2 sheet**
Seasonal - 4 Months				
Chapter 5 5.5	Active SO2 reference gas cylinder calibration	Calibration	4 months	-If HW calibration shows difference of more than 10% -If k outside 0.9<k<1.1

Ref. Chapter	Description	Intervention Type	Recurrence	Additional service indicators
				indicated in SQMS-Follow-up.xlsx SO2 sheet
Chapter 5 5.5	Active NO reference gas cylinder calibration	Calibration	4 months	-If HW calibration shows difference of more than 10% -If k outside 0.9<k<1.1 **indicated in SQMS-Follow-up.xlsx NO sheet**
Chapter 6 6.4.4	Regulators	Leakage test	4 months	After disassembling and reassembling on the reference gas cylinders
Biannual - 6 Months				
Chapter 6 6.2	Filters	Replacement	6 months	When dirty
Chapter 6 6.1.9	Internal tubing and connections	Leakage test	6 months	With non-normal flow or pressure
Chapter 6 6.4.2	External tubing and connections	Leakage test	6 months	After removing sniffer from AC
Chapter 6 6.4.3	Pitot tube	Contamination test (Cleaning) Replacement	6 months	Visual inspection and cleaning (outside) with methanol during washing of the aircraft
Annual – 12 Months				
Chapter 5 5.4	Active CO2 reference gas cylinder calibration	Calibration	12 months	If hardware calibration shows difference of more than 10% on second span **indicated in SQMS-Follow-up.xlsx CO2 sheet**
Chapter 5 5.4	Spare SO2 reference gas cylinder calibration	Calibration	12 months	If active cylinder < 50 bar, next cylinder in line should be calibrated during calibration of the active cylinder **indicated in SQMS-Follow-up.xlsx SO2 sheet**
Chapter 5 5.4	Spare NO reference gas cylinder calibration	Calibration	12 months	If active cylinder < 50 bar, next cylinder in line should be calibrated during calibration of the active cylinder **indicated in SQMS-Follow-up.xlsx NO sheet**
Chapter 6 6.1.5	LOG-PC PC maintenance, updates and backup	Computer maintenance	12 months	Software updates and SSD clone

Ref. Chapter	Description	Intervention Type	Recurrence	Additional service indicators
Chapter 6 6.2	Clients PC maintenance and updates	Computer maintenance	12 months	Software updates
Chapter 6 6.5	External battery capacity test	Battery test / replacement	12 months	Battery test to be executed when external battery fails to power sniffer for less than 15 min In case battery test shows less than 7.5 Ah, battery units need to be replaced
Chapter 6 6.1.8	KNF Air pump (2) Diaphragm replacement	Diaphragm replacement	12 months	External damage, lack of airflow, particles found next to pump (caused by damaged bearing)
Chapter 6 6.1.10	Hydrocarbon tubing leak test + flow test	Leakage test	12 months	Check for leaks in the hydrocarbon kicker tubing, replace particle filter and check the flow though the outer compartment
Two yearly - 24 Months				
Chapter 5 5.4	Spare CO2 reference gas cylinder calibration	Calibration	24 months	If active cylinder < 50 bar, next cylinder in line needs to be calibrated during calibration of the active cylinder **indicated in SQMS-Follow-up.xlsx CO2 sheet**
Chapter 6 6.1.1	Licor 7200RS	Factory Cal. Maintenance Change IR source	24 months 72 months	On demand after inspection from Licor
Chapter 6 6.1.2	Thermo 43 I TLE	Maintenance UV source	24 months 5 year	Some components may need to be replaced when malfunctioning. UV source needs to be replaced when lamp intensity is >95% or <50% or when alternating clicking sound is no longer constant (missing clicks)
Chapter 6	Sniffer holistic inspection by FluxSense	Inspection	24 months	Alternating with the CO2/SO2 maintenance
Five yearly - 60 Months				
Chapter 6 6.1.8	KNF Air pump (1&2)	Diaphragm replacement	60 months	Replace diaphragm and valve plates when pump capacity is decreasing
Chapter 6 6.1.4	Bronkhorst regulators	Inspection / Calibration	60 months	When non-stable pressure/airflow is observed When errors are reported in the diagnostics

Ref. Chapter	Description	Intervention Type	Recurrence	Additional service indicators
				When LED on top of the instrument is burning red
Chapter 6 6.1.10	Hydrocarbon kicker capillary cleaning	Cleaning	60 months	When airflow though outer compartiment is low or when tales are observed on FSC
Ad hoc				
Chapter 6 6.1.6	AIS+GPS receiver	Evaluate data reception	Ad hoc	If no longer functional
Chapter 6 6.1.7	Arinc	Inspection / Replacement	Ad hoc	When no Arinc data is received (blue matrix)
Chapter 6 6.1.8	KNF Air pump (1&2)	Inspection/ replacements	Ad hoc	External damage, lack of airflow, particles found next to pump (caused by damaged bearing)
Chapter 6 6.1.10	Internal signal wiring	Inspection	Ad hoc	Replace when damaged
Chapter 6 6.1.12	Internal power distribution	Read out Replacement	Ad hoc	Read-out power distribution and cabling when component failure observed
Chapter 6 6.1.13	Fans	Visual Inspection / cleaning	Ad hoc	During opening of Sniffer casing When scraping sound is heard
Chapter 6 6.1.14	Sniffer casing	Inspection	Ad hoc	When opening sniffer
Chapter 6 6.5	External power	Inspection	Ad hoc	When current is out limits 24V<GPU<30V
Chapter 6 6.6	External signal wiring	Inspection/ replacement	Ad hoc	When connection issues or signal reception
Chapter 6 6.7	Sniffer rack	Inspection	Ad hoc	When removing sniffer from AC

The planning schedule is also available in SQMS-Follow-up.xls under the “Planning” sheet, as soon as a new maintenance operation was performed, the maintenance block should be marked as “v”, the maintenance block will be highlighted green. If the active block is highlighted in yellow, it means the maintenance operation should be performed in the active block, if the maintenance block is red, the maintenance operation has passed its due date and should be performed as soon as possible.

Ref. Chapter	Description	Intervention Type	Recurrence	Additional service indicators	01/01/2018	01/02/2018	01/03/2018	01/04/2018	01/05/2018	01/06/2018	01/07/2018	01/08/2018	01/09/2018	01/10/2018	01/11/2018	01/12/2018
Daily																
Chapter 3	Software calibration	Calibration	Before every mission	-after maintenance or hardware calibration **indicated in SQMS-Follow-up.xlsx CO2/SO2 sheet**		v	v	v	v	v	x	x	x	x	x	x
Monthly																
Chapter 4 4.1	CO2 Hardware calibration	Calibration	1 month	Optional: before every flight (before software calibration) -SW CO2 zero is outside -3<offset<10 -If SW k outside 0.6<k<1.5 - After Reference gas calibration **indicated in SQMS-Follow-up.xlsx CO2 sheet**		v	v	v	v	v	x	x	x	x	x	x
Chapter 4 4.2	SO2 Hardware calibration	Calibration	1 month	-SW SO2 zero is outside -5<offset<20 -If k outside 0.6<k<1.5 - If drift of more than 10% observed on SO2 reference gas calibration **indicated in SQMS-Follow-up.xlsx SO2 sheet**		v					x	x	x	x	x	x
Seasonal - 4 Months																
Chapter 5 5.5	Active SO2 reference gas cylinder calibration	Calibration	4 months	-If HW calibration shows difference of more than 10% -If k outside 0.9<k<1.1 **indicated in SQMS-Follow-up.xlsx SO2 sheet**		v				v						x
Chapter 6 6.3.4	Regulators	Leakage test	4 months	After disassembling and reassembling on the reference gas cylinders		v				v						x
Biannual - 6 Months																
Chapter 6 6.1.3	Filters	Replacement	6 months	When dirty		v					v					
Chapter 6 6.1.9	Internal tubing and connections	Leakage test	6 months	With non-normal flow or pressure		v					v					
Chapter 6 6.3.2	External tubing and connections	Leakage test	6 months	After removing sniffer from AC		v					x					

Figure 67 Planning sheet in SQMS-Follow-up.xls file

CHAPTER 3. SOFTWARE CALIBRATIONS

Note: the sniffer has to be warmed at least 60-120 min. before an SO2 software calibration!

SOP 2.1. To conduct a software calibration

1. When:
    a. Before take-off of the first flight of the day
    b. A software calibration must be performed after every hardware calibration. In case only a hardware calibration was performed, the calibration coefficient should be cleared on the IGPS software.
    c. In case of a 2-day mission, where the sniffer was shut down over night and when a non-compliant ship has been observed that was already penalized and the airborne results may be used for an administrative penalty, in this case a calibration needs to be done after the last flight to confirm the validity of the used calibration factors.
2. Equipment[1]:
    a. Reference gas SO_2: 300-400ppb (1)
    b. Reference gas CO_2: 350-420 ppm (1)
    c. Reference gas CO_2: 450-470 ppm (2)
    d. Cart with gas cylinders equipped with regulators flowmeters and rotameter
    e. Flexible Teflon tube (3m) with Swagelok 3/8" connection (NY front ferrule) and 1/4" connection (SS)
    f. Ground Power Unit (GPU)
    g. SQMS-Follow-up.xlsx file, available on Seafile, with the active cylinders in use for calibration (see Figure 12)
3. **Duration**: 20-30 min (including warming up time: 150 min)
4. Power on Sniffer
    a. **POWER on sniffer battery with GPU** (minimum 120min before calibration)[2]
        - Connect power extension cord (if operated in Ostend, place cable protector)
        - Power on GPU and connect GPU to external sniffer battery (side connector on GPU)
        - Check on power meter if battery is fully charged (<5A) if not wait 30 min
        - OR
        - Power on GPU, plug in GPU to external AC power bus (see Figure 13)
        - In cockpit Switch on "External power supply"
        - Switch on "utility"
        - Switch on "survey power"
        - Check sniffer circuit breaker in cockpit (must be pressed down)
        - Wait 30 min
    b. Power on Sniffer
        - Master switch on sniffer box needs to be put in upward position
        - Switch on sniffer switch in cabin (at intercom jacks)

[1] No software calibration procedure is available for NO at the moment

[2] In case of cold weather <10°C the warming up time must be increased to 120 min or until the chamber temperature must is >43°C, this can checked while connecting the thermo panel (cfr 4.2 T)

- Check circuit breaker on GPU and emergency sniffer battery (must be pressed in)
- Put chart with cylinders next to aircraft (ca 3 m)
- Connect flexible hose to pitot tube via Swagelok 3/8 with inner Nylon ferrule (tighten finger tight and use 3/4 wrench to tighten 1 quarter)

5. Wait 60 min

6. Connect Laptop to MUMM_LOG_PC

a. Connect Thunderbolt cable to MUMM-LOG-PC

b. On personal Laptop open SQMS-Follow-up.xlsx on Sniffer data>>Calibration

7. CO2 software calibration

a. Enter date in first column, use Ctrl+; as shortcut

b. Check if the ref concentration matches the CO2 reference gas

c. Open IGPS (on MUMM_LOG_PC using TeamViewer)

d. Go to SNF in IGPS Software

e. Open first calibration for CO2, if none present create new one (Figure 14)

- Select “Main component”: CO2 (other components should be none)
- Check concentration and edit if necessary (300-450 ppm)
- Set “Time”: 60 Sec

f. Open gas cylinder valve

g. Connect flexible hose to required CO2 reference gas cylinder via Swagelok 1/4” (tighten finger tight and turn 1 quarter with a 7/16 wrench)

- Check pressure of the gas bottle on first manometer (min 5 bar)
- Check pressure of the output on second manometer (must be 2 bar)
- Check if over flow is 0.8 l/min, if necessary adjust volume (ca 9-11 l/min)
- Check reading of CO2 on IGPS software (check also if SO2 is zero)
- Optional Flush the regulator 5 times [3]
  i. close gas bottle,

h. when pressure is almost zero, close (volume) valve

  i. Open gas bottle,
  ii. Open (volume) valve

- Check reading on IGPS, wait (60 sec) until stable

i. On IGPS software start calibration (green light appears)

j. After calibration (60 seconds) a comment will be shown in comment log

k. go to Settings>>Utilities and check “k” en “o” Licor 7200 - CO2 (see Figure 15)

l. Disconnect flexible hose from the cylinder via Swagelok 1/4” (7/16 wrench)

m. Write down cylinder pressure and close cylinder valve

n. In SQMS-Follow-up.xlsx fill in:

- “Pressure” in active CO2-sheet
- “k” in active CO2-sheet
- “SW Offset (o)” in active CO2-sheet

8. SO2 software calibration

a. Open the SQMS-Follow-up.xlsx file go to SO2 (#) sheet and enter date (use Ctrl+;)

b. Check if the ref concentration matches the SO2 reference gas

[3] The need for flushing has to be evaluated (regularly) during operations, this can be done by comparing the CO2 gas measurement before and after flushing, if the readings are similar, flushing can be skipped for software calibrations (always do flushing for HW calibrations).

c. Open IGPS (on MUMM_LOG_PC using TeamViewer)
d. Go to SNF in IGPS software
e. Open calibration for SO2, if none present create new one (see Figure 14)
- Select "Main component": SO2 (other components should be "none")
- Check concentration and edit if necessary (300-400 ppb)
- Set "Time": 120 Sec

f. Open gas cylinder valve
g. Connect flexible tube with the SO2 reference gas cylinder via Swagelok 1/4" (tighten finger tight and turn 1 quarter with a 7/16 wrench)
- Check pressure of the gas bottle on first manometer (min 5 bar)
- Check pressure of the output on second manometer (must be 1.5 bar)
- Check if overflow is 0.8 l/min, if necessary adjust volume (ca 9-11 l/min)
- Check reading of SO2 on IGPS software
- Optional: Flush the regulator 5 times[4]:
  i. close gas bottle,
  ii. when pressure is almost zero, close (volume) valve,
  iii. Open gas bottle,
  iv. Open (volume) valve
    - Check reading on IGPS, wait (60 sec) until stable (write down CO2 SW zero)

h. Select "Start calibration"
- green light appears
- message appears: merge with old calibration: click "yes"

i. After calibration (120 seconds) a comment will be shown in comment log
j. go to Settings>>Utilities and check "k" and "o" for SO2 stream (See Figure 15)
k. Disconnect flexible hose from the cylinder via Swagelok 1/4" (7/16 wrench)
l. Write down cylinder pressure and close cylinder valve
m. In SQMS-Follow-up.xlsx fill in:
- "Pressure" in SO2-sheet
- "k" in SO2-sheet in "SW k-factor" column
- "o" in SO2-sheet in "SW Offset (o)" column

n. Disconnect GPU
o. Check if external sniffer battery takes-over power supply without interruption
p. In case interruption is more than 20 min, use AC battery to power the sniffer

9. Plume simulation mixture
a. Make sure the background values are stable for 1 min
b. Keep the opening of the tubing upwind, avoid breathing out close to the tubing end
c. Place the plume simulation mixture cylinder with the opening downwind
d. Open the cylinder valve, check the pressure
e. Release a few sudden bursts of gas to purge the regulator
f. Hold the opening of the tubing a few cm in front of the regulator
g. Open the toggle valve for <1 sec
h. Check if the values for SO2 and CO2 are within limits

[4] The need for flushing has to be evaluated (regularly, eg. every 50 bar) during operations, this can be done by comparing the SO2 gas measurement before and after flushing, if the readings are similar, flushing can be skipped for software calibrations (always do flushing for HW calibrations).

- CO2 should be below 2000 ppm
- SO2 should be below 2000 ppb
- Clear peaks no background

i. Conduct a FSC measurement and link the measurement to the emulated AIS detection in the equator

j. Wait 1 min

k. Repeat steps f-j two more times

l. Write down the highest and the lowest of the two measurements in xls file sheet CO2+SO2

m. The updated FSC span and offset are displayed in column K and J

n. Check if the measured FSC falls within the acceptable limits

- On graph the average FSC (Red line) must fall withing the dotted lines
- The FSC values that fall outside the limit will be highlighted in red

o. In case the average values falls outside the limits, the new span and offset must be entered in the ini file for all IGPS stations used for the measurements (1 operator laptop + MUMM-LOG-PC)

- Close IGPS present
- On MUMM-LOG-PC only: close watchdog and close IGPS present again
- Open C:\IGPS\AISPresent.ini
- Scroll down to:

….
FSC_Span = 1.2571
FSC_Offset = 0.0007
….

- Replace the old span and offset values with the new offset and span values
- Save the AISPresent.ini file
- On MUMM-LOG-PC reopen watchdog from C:\IGPS\WatchdogIGPSpresent
- Set the value in column K to “Y”
- Open C:\IGPS\Thresholds, BIAS and SFOC-2022.xls go to sheet “FSC→Bias correctie”
- Enter flight number and date
- Copy the new FSC span and offset values

p. In case the average FSC value does not fall not outside the limits

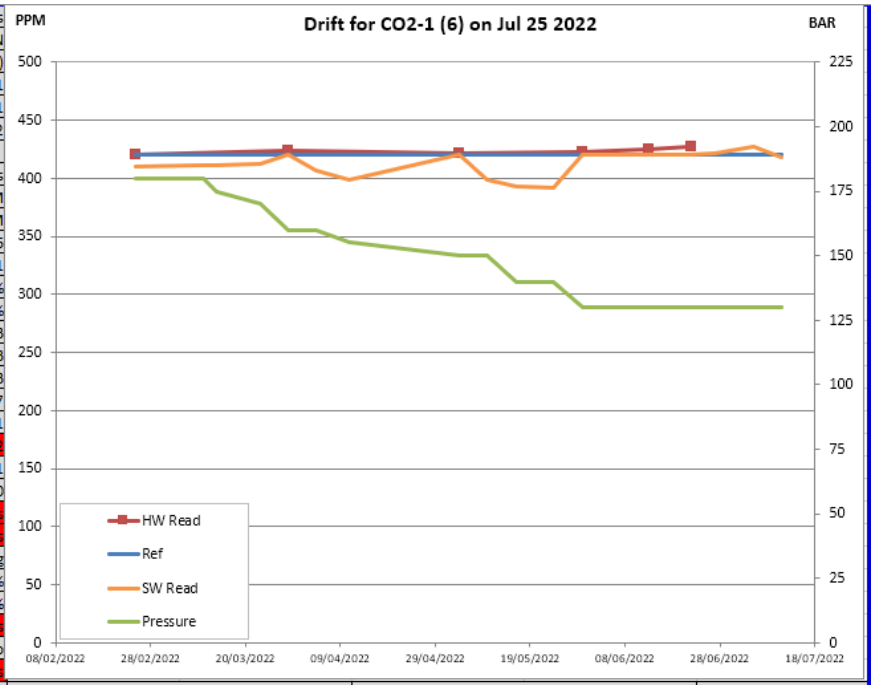
- Set the value in column K to “N”

10. Before take-off

a. Disconnect tubing and remove chart

b. Keep GPU power up to 5 min before starting of the engines

Manufacturer	Airplus
Gas botle ref	GQ84FNN
MUMM reference	CO2-1 (6)
Purchase date	27/08/2021
Delivery date	01/12/2021
Start date	21/02/2022
End Date	
Duration	154 Days
Requested concentration	420.0 PPM
Commercial concentration	420.0 PPM
Warranty	10/09/2026
Error absolute	2.1
Error percentage	0.500%
Actual error	0%
Traces of SO2	0.1 PPB
Traces of NO	0.3 PPB
Traces NO2	0.0 PPB
Nr of calibrations for 50 bar	17
Pressure for GAS calibration	3.1
Date of last HW calibration	22/06/2022
Date of last gas calibration	11/10/2021
Date of last HW Check	27/01/2020
SW calibration needed	Yes
HW calibration needed	Yes
Referene Gas Drift	Data missing
Software drift	2.59%
Sensor drift	0.62%
Gas calibration warning	Yes
Gas +1 calibration warning	No
HW check needed	Yes



Date of calibration	REF	Software		Hardware		Pressure
		SW k-factor	SW Offset (o)	HW Read	HW Zero	
30/05/2022	420.0 PPM	1.000	0.000	422.0 PPM	-2.0 PPM	130 Bar
13/06/2022	420.0 PPM	1.000	0.000	421.0 PPM		130 Bar
22/06/2022	420.0 PPM	1.000	0.000	422.0 PPM	0.0 PPM	130 Bar
27/06/2022	420.0 PPM	0.995	0.530			130 Bar
05/07/2022	420.0 PPM	0.991	-3.621			130 Bar
11/07/2022	420.0 PPM	0.997	2.750			130 Bar

Figure 68 Print screen from the SQMS-Follow-up.xlsx file



Figure 69 During calibration the aircraft is powered with the GPU (note: charging should occur through the emergency power battery and not via the external power port)

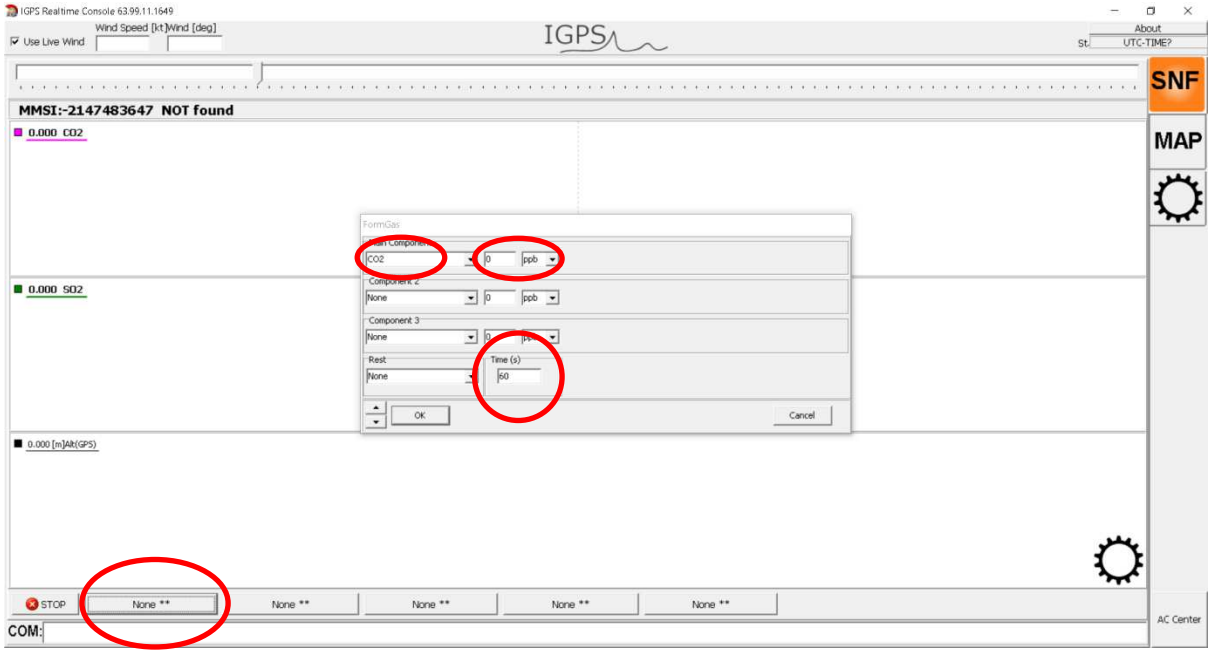


Figure 70 To start new calibration setting, select "None" in "SNF" view, a pop-up window will open, select the component (SO2 or CO2) enter concentration (in ppb or ppm) and select time (120 sec for SO2; 6O sec for CO2)**

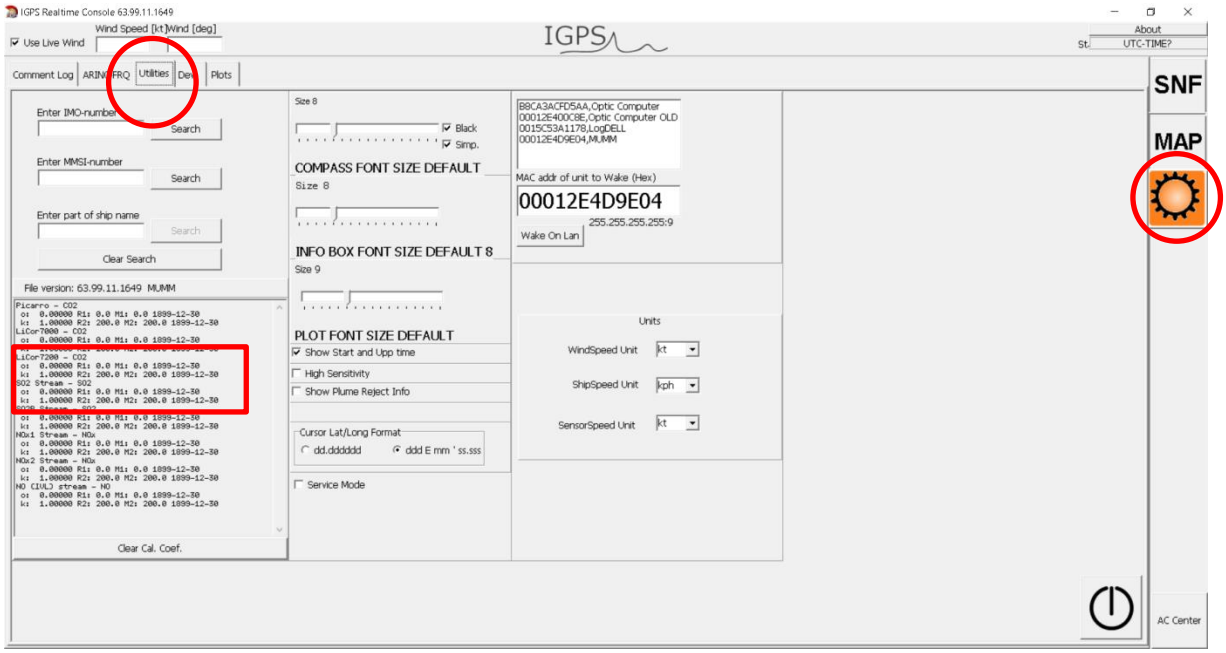
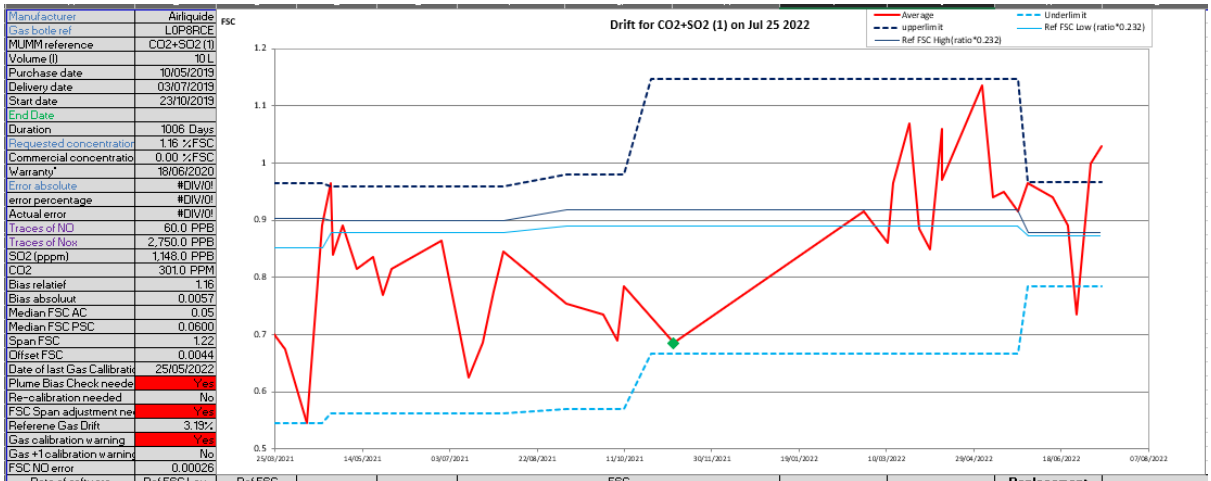


Figure 71 After (complete) calibration the new calibration factors (k and o) are visible under settings view (cog wheel) under "Utilities" tab



Manufacturer	Airliquide
Gas botle ref	L0P8RCE
MUMM reference	CO2+SO2 (1)
Volume (l)	10 L
Purchase date	10/05/2019
Delivery date	03/07/2019
Start date	23/10/2019
End Date	
Duration	1006 Days
Requested concentration	1.16 %FSC
Commercial concentratio	0.00 %FSC
Warranty*	18/06/2020
Error absolute	#DIV/0!
error percentage	#DIV/0!
Actual error	#DIV/0!
Traces of NO	60.0 PPB
Traces of Nox	2,750.0 PPB
SO2 (pppm)	1,148.0 PPB
CO2	301.0 PPM
Bias relatief	1.16
Bias absoluut	0.0057
Median FSC AC	0.05
Median FSC PSC	0.0600
Span FSC	1.22
Offset FSC	0.0044
Date of last Gas Callibratic	25/05/2022
Plume Bias Check neede	Yes
Re-calibration needed	No
FSC Span adjustment ne	Yes
Referene Gas Drift	3.19%
Gas calibration warning	Yes
Gas +1 calibration warning	No
FSC NO error	0.00026

Date of softw are calibration	Ref FSC Low (ratio*0.232)	Ref FSC High(ratio*0.23	Underlimit	upperlimit	FSC min FSC	FSC max FSC	FSC Average	Span (FSC)	Offset (FSC)	Replacement Span and offset	Pressure
16/05/2022	*0.89 %FSC*	*0.92 %FSC*	0.67 %FSC	1.15 %FSC	0.90 %FSC	1.00 %FSC	0.95 %FSC	**1.0953**	**0.0078**	**N**	65 Bar
24/05/2022	*0.89 %FSC*	*0.92 %FSC*	0.67 %FSC	1.15 %FSC	0.89 %FSC	0.94 %FSC	0.92 %FSC	**1.1401**	**0.0056**	**N**	65 Bar
30/05/2022	*0.87 %FSC*	*0.88 %FSC*	0.79 %FSC	0.97 %FSC	0.89 %FSC	1.04 %FSC	0.97 %FSC	**1.0411**	**0.0106**	**Y**	65 Bar
13/06/2022	*0.87 %FSC*	*0.88 %FSC*	0.79 %FSC	0.97 %FSC	0.91 %FSC	0.97 %FSC	0.94 %FSC	**0.9644**	**0.0152**	**N**	60 Bar
22/06/2022	*0.87 %FSC*	*0.88 %FSC*	0.79 %FSC	0.97 %FSC	0.86 %FSC	0.92 %FSC	0.89 %FSC	**1.0225**	**0.0117**	**N**	55 Bar
27/06/2022	*0.87 %FSC*	*0.88 %FSC*	0.79 %FSC	0.97 %FSC	0.70 %FSC	0.77 %FSC	0.74 %FSC	**1.2571**	**0.0007**	**Y**	50 Bar
05/07/2022	*0.87 %FSC*	*0.88 %FSC*	0.79 %FSC	0.97 %FSC	0.97 %FSC	1.03 %FSC	1.00 %FSC	**1.0917**	**0.0080**	**N**	
11/07/2022	*0.87 %FSC*	*0.88 %FSC*	0.79 %FSC	0.97 %FSC	0.99 %FSC	1.07 %FSC	1.03 %FSC	**1.0568**	**0.0098**	**N**	

Figure 72 SQMS-follow up file with CO2+SO2 sheet

CHAPTER 4. HARDWARE CALIBRATIONS

Note: the sniffer has to be warmed up 120 min. before an SO2 hardware calibration!

SOP 2.2. Hardware calibration general preparation

1. **When:** Hardware calibration of SO2 and CO2 sensors is required in following cases:
    a. minimum every month, **OR**
    b. SW calibration factors are outside boundaries (see 4.1 and 4.2), **OR**
    c. After lab-calibration of reference gasses (see Chapter 4.1)

Note: The need for a HW calibration will be automatically displayed in the header of the different cylinder sheets in the SQMS-Follow-up.xlsx file (see Figure 12).

2. General Equipment:
    a. Chart with gas bottles equipped with regulators flowmeters and rotameters
    b. Flexible hose of 3m with Swagelok 3/8" (with inner NY ferule) to Swagelok 1/4"
    c. Ground Power Unit (GPU)

4.1. Licor 7200RS

Note: the hardware calibration for the LOCOR 7200RS sensor is not time consuming and can be done without removing the sniffer. Therefore, it can be advised to perform a hardware CO2 (span) calibration before every software CO2 calibration.

SOP 2.3. CO2 hardware calibration

1. Boundaries
    a. Offset: -3-10 ppm
    b. Slope K: 0.6-1.15
2. Specific equipment:
    a. Low Span gas CO_2 (Span 1): 350-400 ppm in synthetic air
    b. High Span Gas CO_2 (Span2): 400-450 ppm in synthetic air
    c. Zero gas or SO_2 reference gas, all SO_2 concentrations (in synthetic air) can be used

Note: difference between 2 span gasses should not be smaller than 30 ppm or bigger than 100 ppm, ideally this should be round 50 ppm.

3. **Duration**: 10 min (including warm up time: 30 min)
4. Preparation
    a. Connect power extension cord
    b. Plug in GPU to external AC power bus
    c. Power on GPU
    d. In cockpit Switch on "External power supply"
    e. Switch on "utility"
    f. Switch on "survey power"
    g. Check sniffer circuit breaker in cockpit (must be pressed down)
    h. Master switch on sniffer box needs to be put in upward position

i. Switch on sniffer with remote switch in cabin (at intercom jacks)
j. Check circuit breaker on emergency sniffer battery (must be pressed in)
k. Put chart with cylinders next to aircraft (ca 3 m)
l. Connect flexible hose to sampling tube via Swagelok 3/8 with inner Nylon ferrule (tighten finger tight and use 3/4 wrench to tighten 1 quarter)

5. Wait 30 min
6. Connect Laptop to MUMM_LOG_PC
   a. Connect laptop with Thunderbolt cable
   b. Connect to MUMM_LOG_PC using TeamViewer (V12) use 192.168.1.9 (make sure TeamViewer accepts LAN connections) and pwd: "mumm"
   c. Go to LICOR software GHG V8.0 (on MUMM_LOG_PC)
   d. Connect to Licor sensor via Ethernet (IP: 192.168.1.95; Port 7200; Update frq: 1 Hz)
   e. Open SQMS-Follow-up.xlsx on Sniffer data>>Calibration
7. CO2 zero calibration
   a. On Zero gas or SO2 span gas
   b. Open gas cylinder valve
   c. Connect flexible hose to the zero gas cylinder via Swagelok 1/4" (tighten finger tight and turn 1 quarter with a 7/16 wrench)
      - Check pressure of the gas bottle on first manometer (min 5 bar)
      - Check pressure of the output on second manometer (must be 1.5 bar)
      - Check if over flow is 0.8, if necessary adjust volume (ca 9-11 l/min)
      - Check reading of CO2 on GHG software
      - Flush the regulator 5 times:
        i. close gas bottle,
        ii. when pressure is almost zero, close (volume) valve,
        iii. Open gas bottle,
        iv. Open (volume) valve
      - Check reading on GHG, wait (60 sec) until stable (HW zero)
   d. On GHG software: Go to LI-7200>>Calibration>>Zero
   e. Select "zero CO2"
   f. Message appears, "This will do a CO2 zero, Do you want to continue?" click "yes"
   g. Check if the CO2 read is 0, if not repeat steps d to f
   h. Disconnect flexible hose from the cylinder via Swagelok 1/4" (7/16 wrench)
   i. Write down cylinder pressure and close cylinder valve
   j. In SQMS-Follow-up.xlsx fill in "HW zero" in both CO2-1 and CO2-2 sheets
8. CO2 span calibration (1)
   a. Two span gasses are needed for the HW calibration (with difference of 50 ppm). It is advised to regularly switch the sequence of the SPAN gasses between HW calibration, therefore use the span gas for which no SW calibration is needed first (span gas with indication "No" behind "SW calibration needed" in SQMS-Follow-up.xlsx s file header, see Figure 12)
   b. Open gas cylinder valve
   c. Connect flexible hose to the span 1 gas cylinder via Swagelok 1/4" (tighten finger tight and turn 1 quarter with a 7/16 wrench)
      - Check pressure of the gas bottle on first manometer (min 5 bar)
      - Check pressure of the output on second manometer (must be 2 bar)

- Check if over flow is 0.8 l/min, if necessary adjust volume (ca 9-11 l/min)
- Check reading of CO2 on GHG software
- Flush the regulator 5 times:
  i. close gas bottle,
  ii. when pressure is almost zero, close (volume) valve,
  iii. Open gas bottle,
  iv. Open (volume) valve
- Check reading on GHG, wait (60 sec) until stable (HW Read)

d. On GHG software: Go to LI-7200>>Calibration>>Span (2)

e. Check "Span gas concentration" with concentration on cylinder and SQMS-Follow-up.xlsx

f. Select "Span (2) CO2"(two flags must be green)

g. A message appears: "confirm span calibration?", Click "Yes"

h. Check if the CO2 read is span gas concentration, if not repeat steps d to g

i. Disconnect flexible hose from the cylinder via Swagelok 1/4" (7/16 wrench)

j. Write down cylinder pressure and close cylinder valve

k. In SQMS-Follow-up.xlsx fill in:

- "Pressure" in CO2-1 (2) sheet
- "HW read" in CO2-1 (2) sheet (value before calibration)

9. CO2 span2 calibration

a. Two span gasses are needed for the HW calibration (with difference of 50 ppm). It is advised to regularly switch the sequence of the SPAN gasses between HW calibration, therefore use the span gas for which a SW calibration is needed at last (span gas with indication "Yes" behind "SW calibration needed" in SQMS-Follow-up.xlsx s file header, see Figure 12)

b. Open gas bottle

c. Connect flexible hose to the span gas cylinder (selected for SW calibration) via Swagelok 1/4" (tighten finger tight and turn 1 quarter with a 7/16 wrench)

- Check pressure of the gas bottle on first manometer (min 5 bar)
- Check pressure of the output on second manometer (must be 2 bar)
- Check if over flow is 0.8 l/min, if necessary adjust volume (ca 9-11 l/min)
- Check reading of CO2 on GHG software
- Flush the regulator 5 times
  i. close gas bottle,
  ii. when pressure is almost zero, close (volume) valve,
  iii. Open gas bottle,
  iv. Open volume valve
- Check reading on GHG, wait (60 sec) until stable (HW Read)

d. On GHG software: Go to LI-200>>Calibration>>Span (2)

e. Check "Span (2) gas concentration"

f. Select "Span (2) CO2"(two flags must be green)

g. A message appears: "confirm span calibration?", Click "Yes"

h. Check if the CO2 read is span gas concentration, if not repeat steps d to g

i. Disconnect flexible hose from the cylinder via Swagelok 1/4" (7/16 wrench)

j. Write down cylinder pressure and close cylinder valve

k. In SQMS-Follow-up.xlsx fill in:

- "Pressure" in CO2-2 sheet

- "HW read" in CO2-2 sheet (value before calibration)

10. Reset the IGPS calibration factors (see 7.1 Reset software calibration factors) [5]

Note: H2O should not be calibrated as this information is not used in the sniffer sensor setup

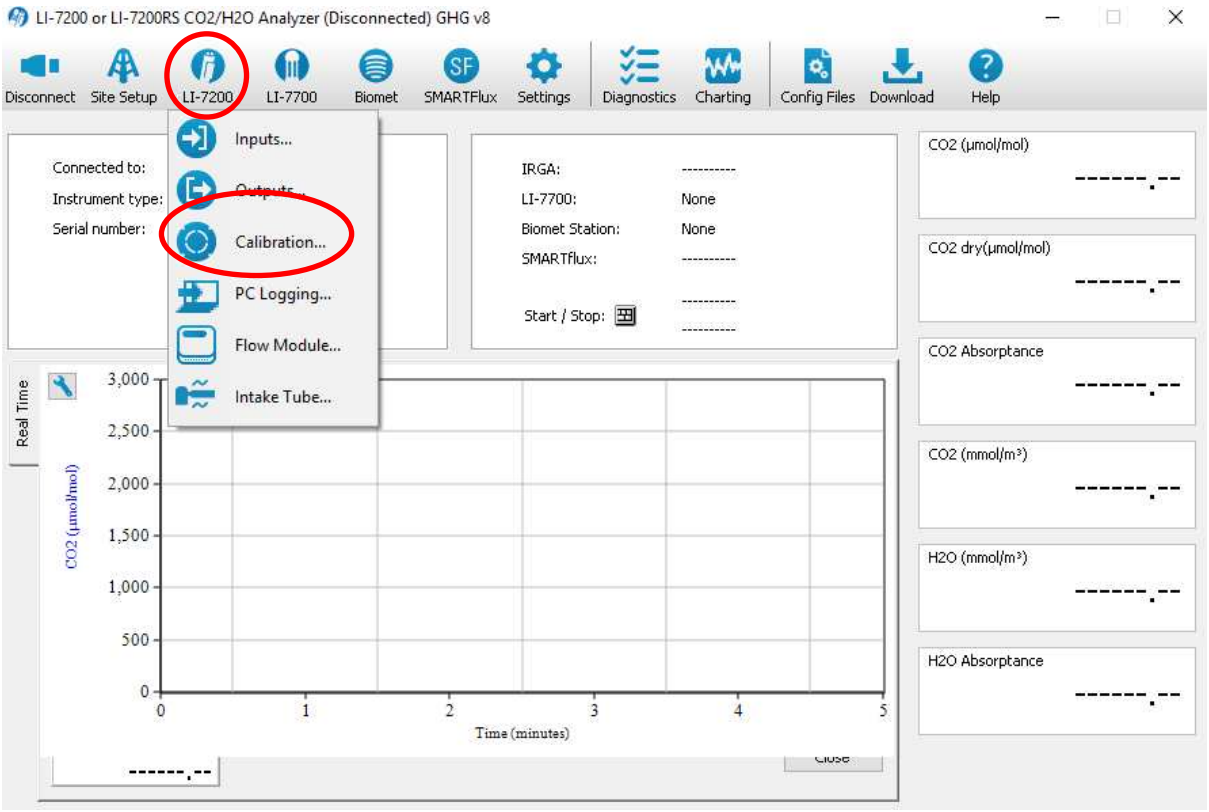


Figure 73 Main view of the Licor GHG v8 software, to start calibration go to LI-7200>>Calibration

[5] Note that after reset of the calibration factors either a SO2 hardware or SO2 software calibration must be performed

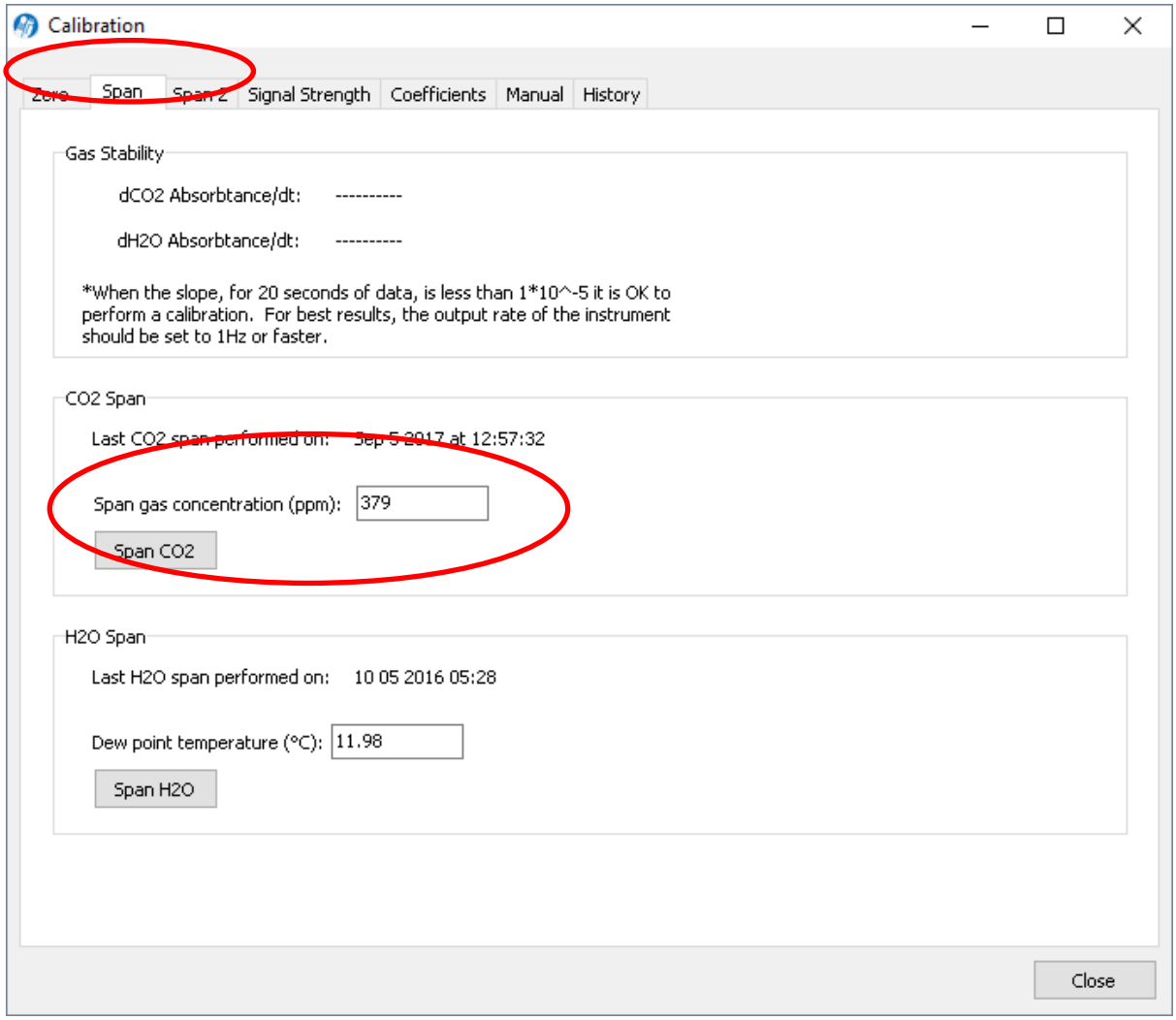


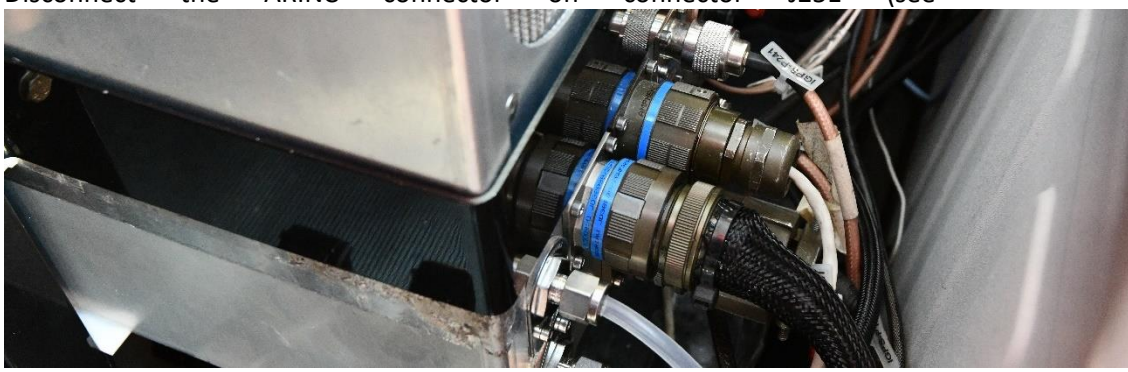
Figure 74 Use the Zero, Span or Span 2 tabs, enter the span gas concentration and press span CO2

4.2. Thermo 43i TLE

Note: the preparatory work under option 2 is more time consuming as in this case the sniffer has to be demounted and opened, therefore option 2 should only be used in case the sniffer has to be opened for other purposes.

SOP 2.4. SO2 hardware calibration

1. Boundaries
    a. Offset: -5-20 ppb
    b. Slope K: 0.6-0.15
2. Specific equipment
    a. Thermo box (front panel mounted in ruggedized case)
    b. Zero (background) gas: zero gas or both CO_2 reference gas cylinders can be used (use the one with highest pressure) also a zero filter can be used.
    c. Span Gas SO_2: 300-450 ppb (in synthetic air)
3. Specific equipment for Option 2 (demounting of the sniffer)
    a. Tools: wrenches 3/8, 7/16, electrical screwdriver, Torx T10,
    b. Flatbed screwdriver
    c. Optional: ribbon cable
    d. Flexible tubing with 1/4 Swagelok connectors
    e. white jumper for power supply cable to the
4. **Duration preparatory work**: option 1: 5 min, option 2: 60 min (warming up time: up to 180 min)
5. Duration HW calibration: 10 min
6. By who: Can only be executed by qualified representative or members from FluxSense/MUMM, 2 persons are needed for the preparatory work under option 2 for the Thermo calibration
7. Preparatory work
    a. Preparatory work option 1
        - Disconnect the ARINC connector on connector J251 (see



        - Figure 75)
        - Put Thermo box on top of the sniffer and take out the cable with the MIL connector
        - Connect the cable with connector J251 (see Figure 76)
        - Connect flexible hose to sampling tube via Swagelok 3/8 with inner Nylon ferrule (tighten finger tight and use 3/4 wrench to tighten 1 quarter)

- Connect power extension cord (place cable protector if needed)
- Plug in GPU to external AC power bus and power on GPU
- Switch on “External power supply”
- Switch on “utility”
- Switch on “survey power”
- Check circuit breaker of sniffer in cockpit
- Switch on sniffer in cabin
- Check circuit breaker on emergency sniffer battery
- Switch on main power switch on sniffer (switch has to be faced upward)
- Check if the Thermo panel lights up and if data is collected

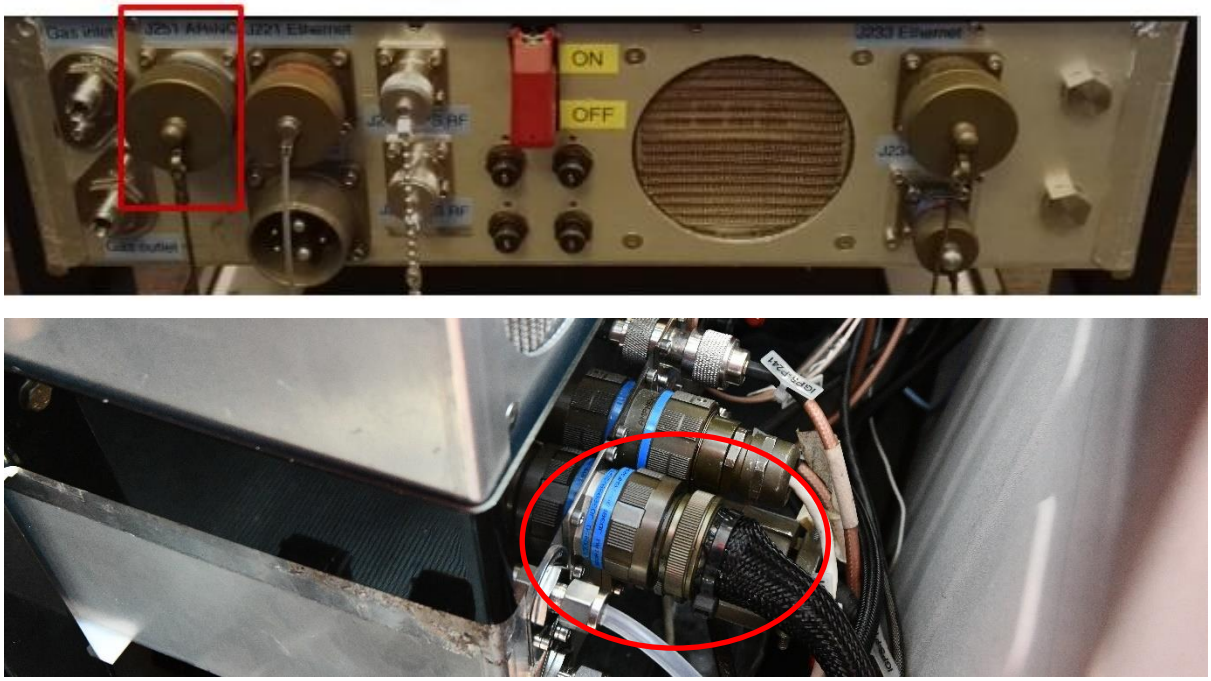


Figure 75 Location of the J251 ARINC connector



Figure 76 Placement of the Thermo panel box on top of the sniffer and connection to the J251 connector

b. Preparatory work option 2 (requires opening of sniffer)

Danger for equipment damage! Some internal components can be damaged by small amounts of static electricity. A properly ground antistatic wrist strap must be worn while handling any internal component while the sniffer is powered on.

- Demount the sniffer from the aircraft (see 6.1), move the Sniffer to the workshop
- Open the top compartment (see 6.1)
- In case the Arinc connector can be used the thermo box can be connected using the J251 cable **OR**
- In case the Arinc connector cannot be used: take the thermo panel out of the ruggedized case and position it close to the motherboard of the Thermo, connect the ribbon cable from the front panel straight to J1 on to the motherboard (see Figure 77)
- Demount the sniffer pitot tube from the aircraft belly and position it next to Sniffer, connect the pitot tube to the air inlet using the flexible tube with 1/4" Swagelok connections on both ends used for troubleshooting (tighten finger tight and use 7/16 wrench to tighten 1 quarter)
- Put the SO2 reference gas cylinder next to the sniffer
- Connect flexible hose to the regulator of the SO2 cylinder with 1/4" Swagelok connector (tighten finger tight and use 7/16 wrench to tighten 1 quarter)
- Connect flexible hose to pitot tube via Swagelok 3/8 with inner Nylon ferrule (tighten finger tight and use 3/4 wrench to tighten 1 quarter)
- Connect 115V power socket (J233) with Thunderbolt docking station power adapter

- Connect HDMI cable with VGA converter and connect to monitor
- Connect Ethernet cable to Thunderbolt dock (J221)
- Connect power cable to GPU (62GB-56TG14-02PN)
- Connect the other outlet of the power cable to the sniffer (J211)
- Install white jumper on the power cable
- Power on GPU
- Switch on main power switch on sniffer (switch must be faced upward)

8. Wait 60-120 min (check chamber temperature (ALARM), must be between 43 and 47°C)

9. Connect Laptop to MUMM_LOG_PC

a. Connect laptop with Thunderbolt cable

b. Switch off all other non-used network adapters (WIFI and Ethernet)

c. Connect to MUMM LOG-PC using TeamViewer us 192.168.1.9 (make sure TeamViewer accepts LAN connections)

d. On Laptop open SQMS-Follow-up.xlsx on sniffer data>>Calibration

Note: To use the PC next to the Sniffer sensor, an Ethernet cable can be used instead of the Thunderbolt Dock, in this case it is required to adjust the IP address of the network adapter, a list with the available IP addresses is provided in the IGPS folder and in 1.6 External signal wiring

10. SO2 background calibration

a. Connect flexible hose to a Zero gas or CO2 reference gas via Swagelok 1/4" (tighten finger tight and turn 1 quarter with a 7/16 wrench)

b. Open gas bottle

- Check pressure of the gas bottle on first manometer (write down)
- Check pressure of the output on second manometer (must be 2 bar)
- Check if over flow is 0.8 l/min, if necessary adjust volume (ca 9-11 l/min)
- Check reading of SO2 on front panel (must be close to 0)
- Flush the regulator 5 times:
  i. close gas bottle,
  ii. when pressure is almost zero, close (volume) valve,
  iii. Open gas bottle,
  iv. Open (volume) valve
- Check reading on front panel, wait (60 sec) until stable

c. On front panel, open menu

d. Go to Calibration by using click enter

e. Go to SO2 Background (see Figure 79)

f. Select enter

g. Wait 10 seconds

h. Select enter again

i. Continue until SO2 reading is close to 0

11. SO2 span calibration

a. Connect flexible hose to SO2 reference gas via Swagelok 1/4" (tighten finger tight and turn 1 quarter with a 7/16 wrench)

b. Open gas bottle

- Check pressure of the gas bottle on first manometer (min 10 bar)
- Check pressure of the output on second manometer (must be 1.5 bar)
- Check if overflow is 0.8 l/min, if necessary adjust volume (ca 9-11 l/min)

- Check reading of SO2 on front panel
- Flush the regulator 5 times
  i. close gas bottle,
  ii. when pressure is almost zero, close (volume) valve,
  iii. Open gas bottle,
  iv. Open (volume) valve
- Check reading on front panel, wait (120 sec) until stable (HW Read)

c. On front panel, open menu
d. Go to Calibration by using click enter
e. Go to SO2 coefficient (see Figure 79)
f. Enter the concentration (using)
g. Select enter
h. Wait 10 seconds
i. Select enter again
j. Go back to Main menu and Open calibration factors submenu
k. Continue until SO2 value is close to the reference gas value
l. Open SQMS-Follow-up.xlsx>> SO2 (#) sheet
m. Enter the "SO2 COEF" value in "HW k-factor (COEF)" column
n. Enter "SO2 BKG" value in "HW Offset (BKG)" column
o. Enter cylinder pressure at end of measurement in "Pressure" column

12. Reinstallation sniffer in case of option 2

a. Power down Sniffer (shut down from the MUMM_LOG_PC)
b. Remove the Thermo front panel and ribbon cable
c. Reinstall the cover, make sure to reconnect the cable for the fan and make sure it does not touch the fans
d. Reinstall the sniffer in the aircraft and reconnect all cabling
e. Reinstall the pitot tube at the AC belly
f. Perform SO2 software calibration (see chapter 2) or clear the IGPS calibration factors (see 7.1 Reset software calibration factors)

Note: The replacement of the filters and other sensor maintenance can be combined during the SO2 hardware calibrations to minimise the dismantling of the sniffer (see Chapter 6)

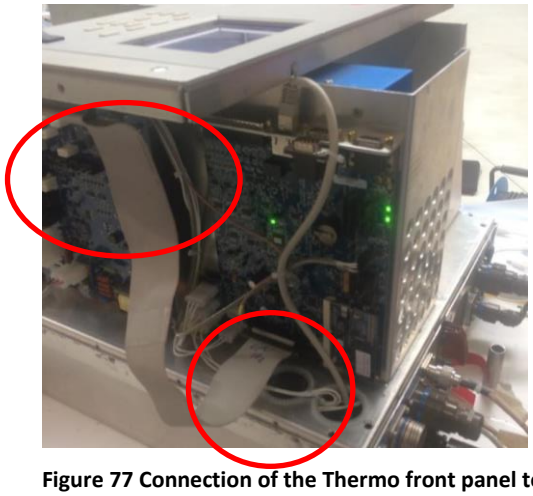


Figure 77 Connection of the Thermo front panel to the internal Thermo motherboard (J1) with ribbon cable

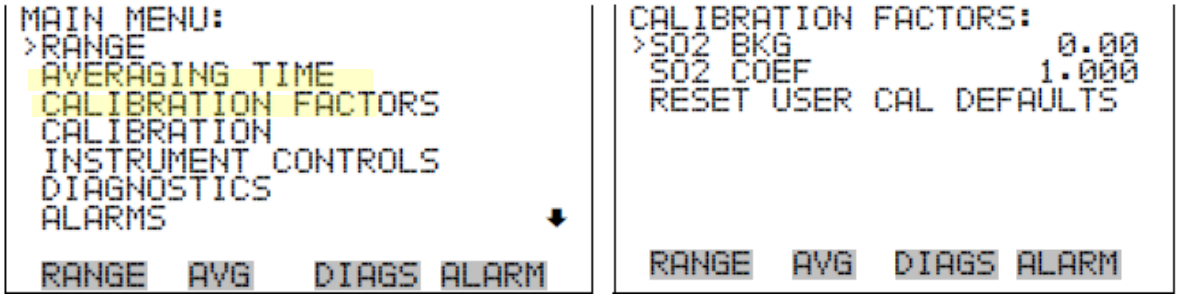


Figure 78 Main menu and calibration factor menu

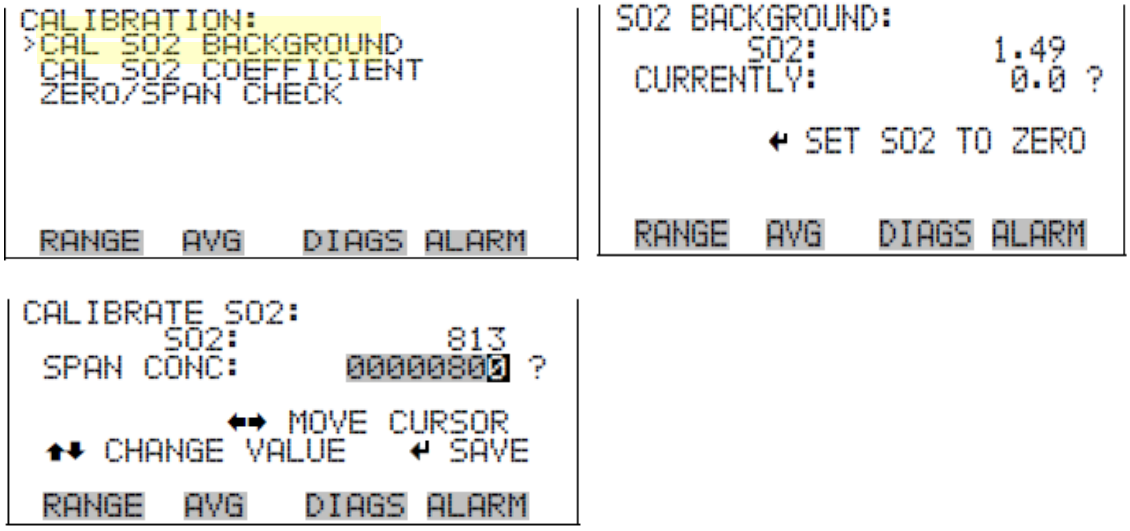


Figure 79 Calibration menu, SO2 background calibration and SO2 Coefficient calibration

4.3. Ecotech Serinus 40

To perform a hardware calibration of the Ecotech Serinus 40 sensor. The most convenient way is to use an android smartphone with Bluetooth connection, this will copy the display of the sensor and the command buttons. The application used for the connection is Serinus and is currently only available on android. A dedicated android smartphone is available with the Serinus application.

SOP 2.5. NOx hardware calibration

1. Specific equipment
    a. Smartphone with Serinus application)
    b. Zero (background) gas: zero gas or both CO_2 reference gas cylinders can be used (use the one with highest pressure) also a zero filter can be used.
    c. Span Gas NO: 300 ppb (in N2)
2. Duration warming up: up to 180 min
3. Duration HW calibration: 10 min
4. By who: SURV crew
5. Hardware NO zero and NO2 zero calibration
    a. Connect smartphone:
        - On the smartphone open Serinus app,
        - Scan devices and select the NOx sensor ()

b. Set gas to measure to NOx, NO and NO2
- Go to the Quick menu>>Gas to measure>>
- Select "All" and click accept

c. Set filter to 30 seconds
- Go to main menu>>Measurement settings>>Filter
- Set to to 30 seconds
- Go back to main menu
- Wait 2 minutes

a. Enter the read of the sensor for NO in the xls file (Zero read).
b. Go to the main menu>>calibration menu.
c. Select "Zero calibrate NO" and select "enter".
d. In case an error message appears, click "ok".
e. Select "Zero NO2" and select "enter".
f. In case an error message appears, click "ok".
g. Zero values should be within range of +/- 2ppb , if not repeat steps c-f.
h. Remove the flexible tubing and close toggle valve.

6. Hardware NO and NOx calibration

a. Open NO gas cylinder and connect flexible hose (wait 120 sec)
b. Enter the read of the sensor for NO in the xls file (HW read).
c. Go to the main menu>>calibration menu.
d. Select "Span Calibrate NO", check value with last noted value on cylinder, and select "Accept".
e. In case an error message appears, click "Yes".
f. Select "Span Calibrate NOx" check value with the sum of the last noted value + traces of NO2,
g. Verify on IGPS if the values for NO remain slightly lower than the values for NOx for 30 seconds and are within +/- 5ppb range of span value.
h. If this is not the case reperform span calibration of NO and/or NOx until values are satisfactory.
i. Disconnect flexible hose from regulator and close toggle valve
j. Set filter back to 1 second
- Go to main menu>>Measurement settings>>Filter
- Set to 1 second

k. Set gas to measure to NOx
- Go to the Quick menu>>Gas to measure>>
- Select "NOx" and click accept

CHAPTER 5. MANAGEMENT REFERENCE GASSES

Both the sensor as the reference gasses may experience drift behaviour, to avoid sensor drift, regular software and hardware calibrations are required, these calibrations have only meaning if the concentrations in the reference gas is correct. When the gas concentration of SO2 or CO2 is not stable, this is called drift when this occurs it has significant implications on the sensor and hardware calibrations and therefore also on the emission measurements. This chapter describes the required aspects of an appropriate management of the reference gasses to ensure the proper calibrations of the sniffer sensor system and the provision of accurate measurements.

5.1. Gas mixtures

Following gas mixtures are required for the Sniffer sensor system:

- **CO2 span gasses** are used for the calibration of the IGPS software and Licor sensor. They can be purchased from Airproducts in cylinders of 10l with a DIN6 connection. The gasses should be ordered with an accuracy of at least 5% . They last 1 to 2 years and come with a warranty of 2 years. 2 concentrations are required:
  1. Low Span gas CO_2 (Span 1): 420 ppm in synthetic air
  2. High Span gas CO_2 (Span2): 470 ppm in synthetic air

Note: difference between 2 span gasses should not be smaller than 30 ppm or bigger than 100 ppm, ideally this should be round 50 ppm.

- **SO2 span gas** is used for the calibration of the IGPS software and Thermo sensor. This mixture can be purchased from Airproducts in cylinders of 10l with a DIN1 connection. Ordered gasses should have an accuracy of 5%. They last 1 year and come with a warranty of 1 years. Only 1 concentrations is required:
  3. Span gas SO2: 400 ppb (in synthetic air)
- **NO gas** is used for the calibration of the Ecothech sensor. This mixture can be purchased from Airproducts in cylinders of 10l with a DIN1 connection. Ordered gasses should have an accuracy of 5%. Only 1 concentrations is required:
  4. Span gas NO: 300 ppb (in nitrogen)
- **Zero gas/zero filter** is used for the background or the zero calibrations of the Thermo and Licor sensor, a dedicated Zero gas mixture or filter can be purchased from Airproducs. Alternatively, a SO2 gasmixture can be used for the calibration of the Licor sensor and the CO2 gasmixtures can be used for the zero calibrations of the Thermo sensor and the Ecotech sensor.
- Special **plume simulation gas mixture**, this mixture is used to provide a real life test of the sniffer sensor and allows to adjust the FSC span and FSC offset values. This mixture corresponds to an FSC of ca. 1% and consists of:
  5. Mixture of 10000 ppm CO2 and 50000 ppb SO2 in synthetic air

Note: When using respective SO2 and CO2 gas mixtures for the zero calibration of the Licor and Thermo sensors, the gas mixtures have to be analysed for their trace levels of CO2 and SO2

5.2. Installation cylinders on the gas chart

The cylinders should be installed on the gas chart when used during calibration. Preferably the following setup should be used when installing the cylinders: CO2-1, CO2-2, SO2, NO on the back and synthetic air and the plume simulation mixture in front (Figure 80). When installing the cylinders, pay attention to the position of the valve so that the regulators can be installed afterwards without further manipulation of the cylinder. Attach the cylinders to the cart using a heavy-duty strap with ratchet, make sure to avoid a loose end on the strap. After the installation of the cylinders the regulators can be mounted on the cylinders.



Figure 80 Attachment of 5 cylinders on the gas chart

5.3. Assembling regulator

The pressure regulator for the reference gas cylinders depends on the type of gas. CO2 gas mixtures are considered non corrosive and cylinders are ordered with DIN6 connection (W 21.80x1/14" right turn). SO2 and NO mixtures are considered corrosive, therefore special regulators are used, these come with DIN1 connection (left turn).

Following regulators with volumeters are used

- CO2

1. Regulator: HBS-200-3-2-5 (Airliquide)
2. Volumeter: DYNAVAL_N2

- SO2 and NO

3. Regulator: HBSI_200-1-2 (Airliquide)
4. Volumeter: MILLIMITE.S_200-0_02_AN

- Synthetic air

5. Regulator: R303 (Air products)
6. Volumeter: MILLIMITE.S_200-0_02_AN

- Plume simulation mixture

7. Regulator Messer: Spectron FM51

In addition, to make sure there is sufficient overflow, regulators 1-3 are equipped with a Brooks rotameter: 2510 A 2A13 S N VT and all regulators have a Swagelok toggle valve SS-1GS4.

Note: The plume simulation mixture is not equipped with an overflow as this regulator should never be connected straight to the tubing.

SOP 2.6. To install the regulator on the cylinder

1. Place main air inlet (see nr 4 in Figure 81)
2. Tighten the main nut
   a. For CO2 cylinders turn the nut clockwise
   b. For SO2 cylinders turn the nut counter-clockwise
3. Tighten with relative force with an adjustable spanner

SOP 2.7. To remove the regulator from the reference gas cylinder

1. Make sure the cylinder valve is closed and the pressure is equal to the atmospheric pressure on the regulator (1 bar), therefore the toggle valve should be open (upward position).
2. Untighten the nut at the regulator intake (see nr 4 in Figure 81)
   a. For CO2 cylinders turn the nut counter-clockwise
   b. For SO2 cylinders turn the nut clockwise

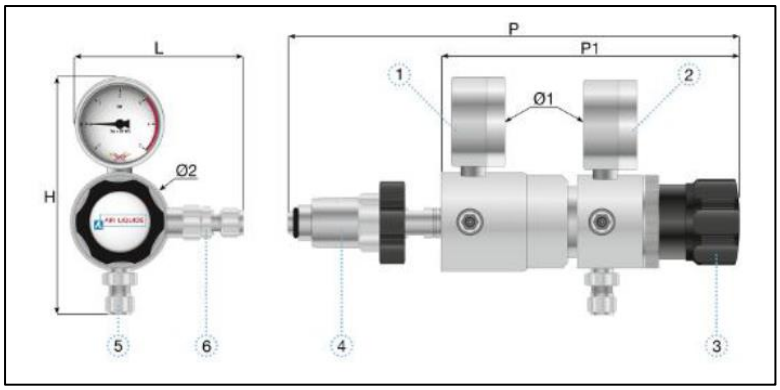


Figure 81 Regulator HBS-200-3-2-5 for Airliquide cylinders (used for CO2 mixtures)

5.4. Purchase orders / administration

Lead times may vary from a few weeks to several months, therefore it is advised to always have at least 2 cylinders of a reference gas in storage. As soon as the active gas cylinder is below 25 bar a new cylinder should be ordered. The main contractors for MUMM are Airliquide (before) and Airproducts (current), other contractors are e.g. Messer (note that changing contractor may require the purchase of a new regulator). Documentation about the orders can be found in the Calibration gasses folder (soft and hard copy).

Note: Before returning a cylinder make sure the cylinder is empty (clearly write "empty" on bottle)

5.5. Calibration of reference gasses

Reference gasses are provided with a factory accuracy of 5% and a 1-3 year warranty, nevertheless it has been observed that actual concentrations may differ up to 20% from the factory concentrations and aren't proofed to be stable over time. Every reference gas must therefore on regular interval be calibrated in an accredited lab.

SOP 2.8. Calibration of the reference gasses

1. **When:** Following scheme should be used
    - **a.** SO2 and NO reference gas
        - Minimum every 4 months
        - Before a campaign (after longer periods of inactivity)
        - At the end of a campaign (if last calibration was more than 2 months ago and next calibration is more than 2 months away)
        - In case the calibrations show a significant error (difference of more than 10%)
        - Before using the cylinder in the field for the first time
        - In case the active cylinder in use has a pressure <50bar the next cylinder in line should be calibrated
    - **b.** CO2 reference gas
        - Minimum every 12 months
        - Before a campaign (after longer periods of inactivity)
        - At the end of a campaign (if last calibration was more than 6 months ago and next calibration is more than 6 months away)
        - In case the calibrations show a significant error (difference of more than 10%)
        - Before using the cylinder in the field
        - In case the active cylinder in use has a pressure <50bar the next cylinder in line should be calibrated
    - **c.** Zero gas
        - After delivery

Note: In the beginning of the year the planning of the cylinders is drafted and agreed upon with the lab, these dates are also put in the SURV agenda. When the cylinders are due for calibration as they are out of boundary, this is indicated in the "SQMS-Follow-up.xlsx" file, and in that case a calibration might be advanced in collaboration with the lab

2. Equipment:
    - **a.** Office chart
    - **b.** Cylinders

c. Regulators
d. Aluminium case with protective material
e. Adjustable spanner
f. 7/16 wrench
g. Straps

3. Time: 1-2 days
4. Methodology
a. When time is due, the regulator is disassembled from the cylinder and put in the aluminum transport box and fully covered with protective material
b. The cylinders are disassembled from the chart
c. The cylinders and regulators are transported to MUMM premises in Brussels (see 5.7 Transport of reference gasses)
d. The cylinders and regulators are stored at the storage room (see 5.6 Storage of reference gasses)
e. The day of the calibration, the cylinders and regulators are brought to the lab using the office chart, make sure to use a (simple) strap to attach the cylinders to the office chart.
f. The regulators must be assembled on the cylinders prior to the calibration
g. A leak test should be done after assembling the regulator (see 6.4.4 Regulator)
h. Note down the pressure before calibration
i. The calibration of the reference gasses is fully executed by the lab, assistance may be provided with the positioning of the bottles and the purging
j. Write down the pressure after calibration
k. After calibration a calibration certificate is provided by the lab
l. Write the date, concentration and pressures on the cylinder
m. The trace elements
- When a cylinder is used for the first time traces for the other gasses should be measured
- For CO2 measure NO and SO2,
- Write down trace levels on the cylinder
- Write down the traces in the header of the specific gas sheets.
- For NO, the NOx concentration should be measured every time

n. Enter the calibration information in the “SQMS-Follow-up.xlsx” file in the “GAS CAL” sheet
o. Transport the cylinders back to Deurne (see 5.7 Transport of reference gasses)
p. Remount the cylinders on the chart
q. Install the regulators
r. Perform a leak test after installing the regulators on the cylinders (see 6.4.4 Regulator)
s. In case the drift of the gas cylinder was more than 10% a hardware calibration should be executed (see Chapter 4 Hardware calibrations)
t. When calibration is reset (see step 21), **NO** software calibration is needed for the first flight after a hardware calibration (for SO2 and CO2).
u. Remove the old software calibration file
- On MUMM-LOG-PC

- Close TCP log
- Close watchdog
- Close IGPS present
- Close watchdog
- Close IGPS present
- Go to C\IGPS\TCP-LOG
- Look for the CALLIBRATION.txt file
- Change the file name to CALLIBRATION_DATE(XX-XX-XX).txt file
- Reopen the watchdogs
    i. C\IGPS\Watchdog-IPGS
    ii. C\IGPS\Watchdog-TCP-LOG
- Check if the calibration factors in IGPS present under utilities are all 0 (offset) and 1 (slope) and the gasses under the SNF graph are “NOT SET”

v. In case the previous step did not work a software calibration must be performed (see Chapter 3Chapter 3 Software calibrations)

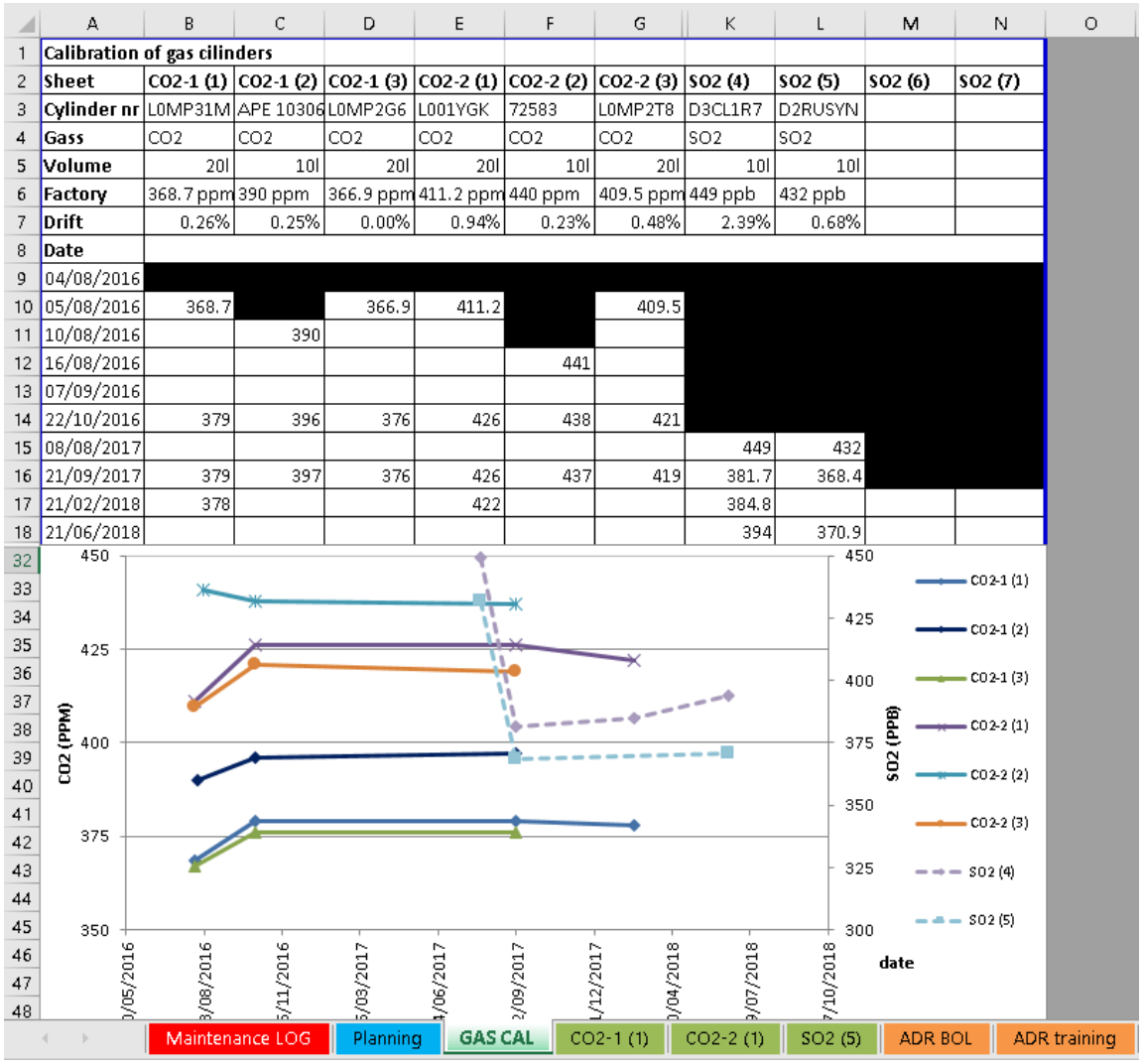


Figure 82 SQMS-Follow-up.xlsx file with cylinder overview (GAS CAL) sheet, active cylinders sheets, ADR sheets and LOG sheet.

5.5.1 Certifications

An ISO6414 certification should be provided for the calibrations of the reference gasses. This certificate should include:

- Certification number
- Date
- Serial number of cylinder
- Calibration method
- Indicated concentration
- Actual concentration
- Uncertainty (with 95% CI or factor k = 2)
- Environmental Conditions (temperature, pressure)
- Stamp or signature from the lab or manager
- Guaranteed period

Note: For the CO2 reference gasses, no accredited governmental lab is available that is able to provide certificates, but the lab of the Brussels Environmental Agency is nevertheless able to perform the calibrations (without providing a certification).

5.6. Storage of reference gasses

Following rules apply for the storage of the reference gasses:

- Gas cylinders should be stored in dry dark (heated) room.
- Room should be locked
- A warning should be placed on the door that cylinders are stored in the room
- The maximum volume should not exceed 120 volumetric l
- Temperature range from 10-30°C.
- Empty cylinders can be stored outside in a dedicated area
- Full cylinders that are not used in the chart should be attached to the wall
- Cylinders in use should be attached to the chart with strap
- When a new cylinder is used this should be marked on the bottle (and the plastic indicator “full” should be removed)
- If the cylinder is empty this should be marked on the bottle (and the plastic indicator “in use” should be removed)

Note: Gas cylinders are stored in room 418 at Gulledelle 100, 1200 Brussels, empty bottles are stored on the right side, full bottles are stored left side.

5.7. Transport of reference gasses

Reference gasses should be transported according to the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR). An exemption to the general conditions for transport applies for small loading (ADR1.1.3.6), following rules apply:

- CO2 Class: 2A Non-flammable, Transport category 3 (maximum volume 1000L)
- SO2 Class: 2TC Toxic corrosive, Transport category 1 (maximum volume: 20L)

- NO Class: 2TOC Toxic oxidizing corrosive, Transport category 1 (maximum volume 20L)
- A bill of loading should be available at the driver's seat, a printout can be made from SQMS-Follow-up.xlsx, under "BOL" sheet, it suffices that the driver details are filled in and the cylinder reference are selected from the drop-down list to generate a bill of loading.
- General training for the driver should be performed, with records (ADR 1.3.2), the records of the training are available in the SQMS-Follow-up.xlsx under "ADR" sheet.
- A fire extinguisher of 2 kg dry powder should be on board (ADR 8.1.4.2)
- Regulators should be removed from cylinders, valves should be closed and cylinder protective top cap should be in place.
- Cylinders should be stowed properly (perpendicular with driving direction and attached with heavy duty straps. Make sure the cylinders are not able to role under the straps by using the cylinder holder tool, especially when only 1 or 2 cylinders are transported (see Figure 83).
- No access to tunnels with category E with pressurized cylinders on board (in Belgium: Small Ring Brussel and tunnel under Van Praet bridge)



- Optionally a sign stating the transport of gas cylinders can be placed behind the window.



SOP 2.9. Attachment of cylinders in car

1. See Figure 83 for attachment of layout of the cylinders (colours are only illustrative)
2. Take the loose end of the strap and follow the numbers on the layout, keep the buckle at start position.
3. Turn the strap around the cylinder (4) when only 1 or 2 cylinders are transported.
4. Unlock the buckle, turn on the small lever in the big handle and pull the big handle forward
5. Put the loose end in the opening (enter from bottom side of the buckle)
6. Pull tight on the strap end (min 20 cm loose end is required to pass through the buckle)
7. Tighten buckle by alternatingly pulling big handle forwards and backwards.
8. When strap is tightened, put big handle backward and lock handle (pull small lever back and push big handle backwards).

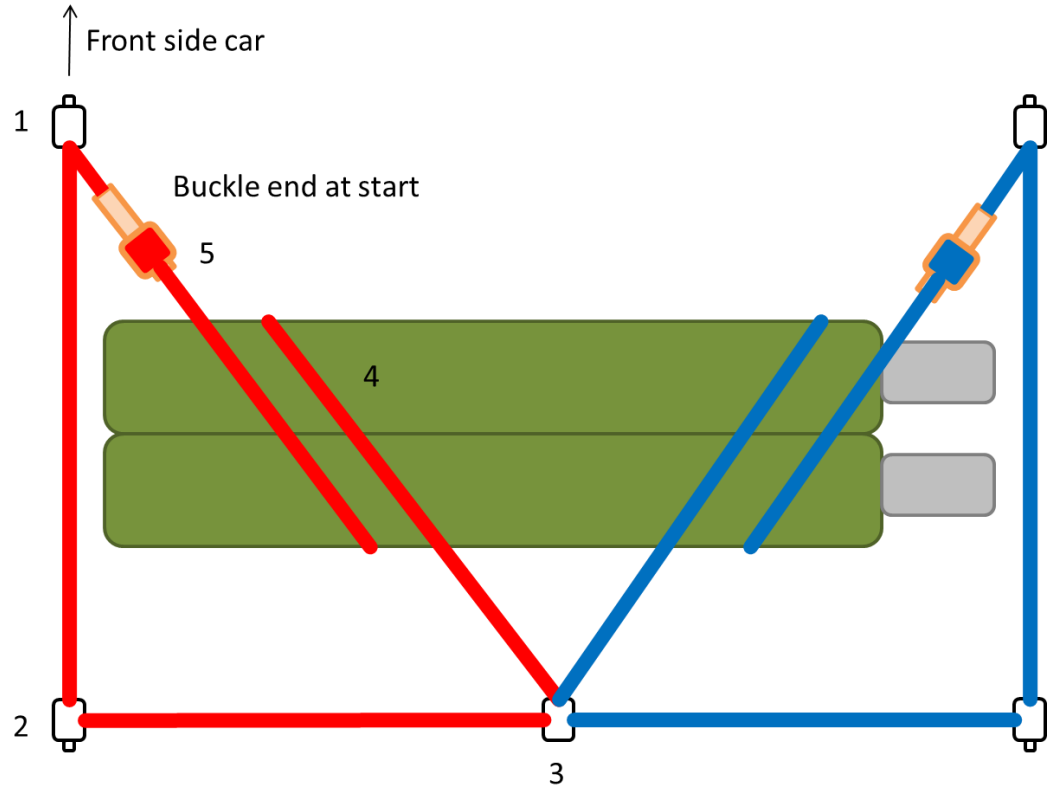
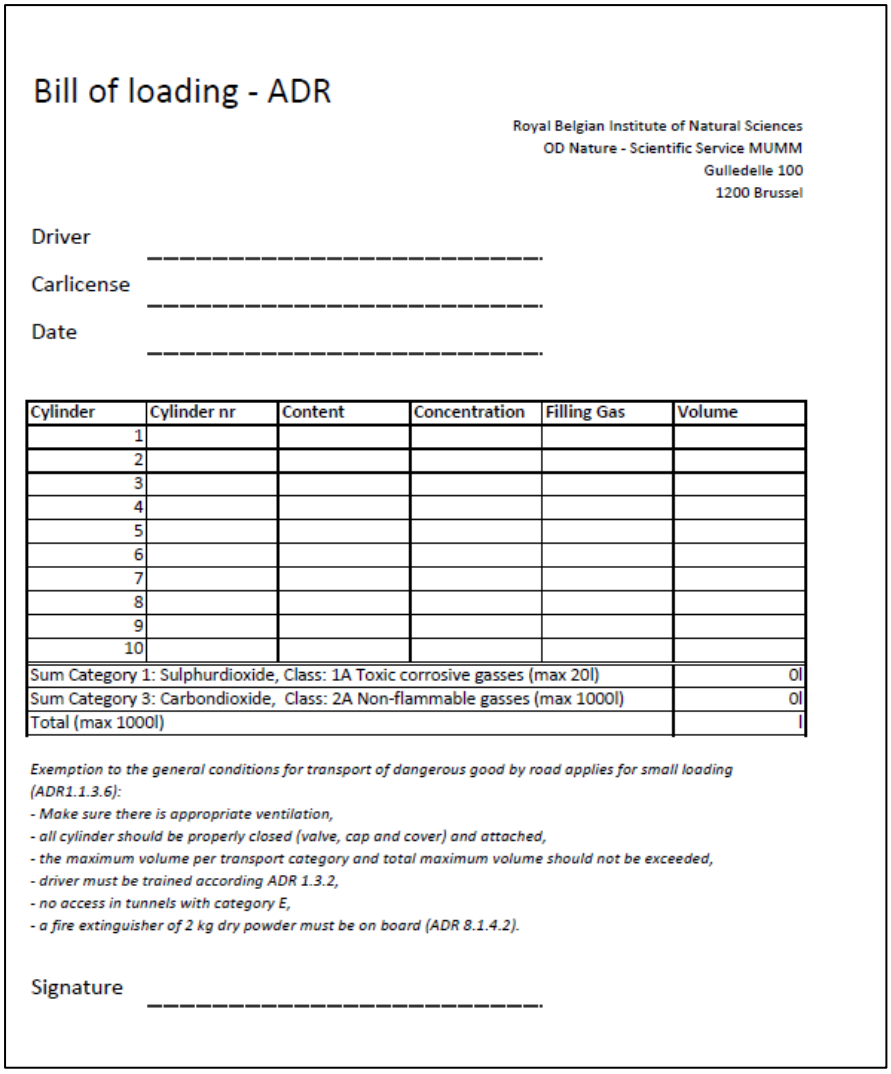


Figure 83 Attachment procedure for transporting reference gas cylinders in the trunk of a vehicle.



Figure 84 office chart, strap with ratchet (for attachment on chart and in car) and simple straps



Bill of loading - ADR

Royal Belgian Institute of Natural Sciences
OD Nature - Scientific Service MUMM
Gulledelle 100
1200 Brussel

Driver _____.

Carlicense _____.

Date _____.

Cylinder	Cylinder nr	Content	Concentration	Filling Gas	Volume
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
Sum Category 1: Sulphurdioxide, Class: 1A Toxic corrosive gasses (max 20l)					0l
Sum Category 3: Carbondioxide, Class: 2A Non-flammable gasses (max 1000l)					0l
Total (max 1000l)					l

Exemption to the general conditions for transport of dangerous good by road applies for small loading (ADR1.1.3.6):
- Make sure there is appropriate ventilation,
- all cylinder should be properly closed (valve, cap and cover) and attached,
- the maximum volume per transport category and total maximum volume should not be exceeded,
- driver must be trained according ADR 1.3.2,
- no access in tunnels with category E,
- a fire extinguisher of 2 kg dry powder must be on board (ADR 8.1.4.2).

Signature _____.

Figure 85 Bill of loading to be filled in, signed and stored in the front of the car

CHAPTER 6. PREVENTIVE SERVICING

This chapter describes preventive service operations for the different components of the sniffer sensor. For more detailed information look at the dedicated manuals of the different components, available under the "QMS>>QA_MANUAL>>Sensor" manual folder. All servicing operations should be executed by qualified persons. Beside the dedicated component service, a holistic sniffer sensor service should be executed by the sensor developer, FluxSense.

6.1. Internal sniffer sensor components

Twice a year the sniffer should be demounted from the aircraft and opened for service operations, this can be combined with the SO2 hardware calibration (see Chapter 3).

SOP 2.10. General preparation sniffer servicing: demounting sniffer

1. When:
2. General Equipment:
    a. Ground Power UNIT (GPU)
    b. Optional power cord to bypass AC power
3. Tools: wrenches 3/8, 7/16, electrical screwdriver, Torx (T10), Hex (3mm), Hex ()
4. Duration preparatory work: 60 min
5. Duration of bi-annual service and hardware calibration: 1 day
6. General preparation:
    a. In case maintenance on the Licor is executed make sure to make a configuration backup (see 6.1.1 LICOR 7200RS)
    b. Unmounting sniffer from sniffer AC
        - Untighten all screws of upper and from brackets (3/8") of sniffer rack
        - Loosen screws of SLAR (3/8")
        - Slide Sniffer 20 cm to the front
        - Disconnect all wiring from the sniffer side and use covers to protect the connectors
        - Disconnect all tubing, install caps to protect all gas inlets and outlets (also on open tubing)
        - Disconnect the tubing to the filter box, install caps, remove the filter box (Velcro)
        - Remove sniffer and place sniffer on a table (at the cockpit door or in the office)
7. Unmounting NOx
    a. Loosen straps
    b. Disconnect wiring and tubing (use covers to protect connectors)
    c. Remove NOx sensor
8. On sniffer: to access the top compartment (LICOR, Thermo, NOx pump, Bronkhorst)
    a. Open top hatch cover of the sniffer by removing top screws on the sides of the sniffer, don't forget to remove the screws under the quick release plate
    b. Be careful to disconnect the connector from the fan wiring (back left corner)
    c. Connect all wiring
9. To access the bottom compartment (MUMM LOG PC, Power converters, Ethernet hub AIS+GPS receiver, SO2 and CO2 air pump, buffer)

a. Turn sniffer upside down
b. Open bottom hatch cover of the sniffer by removing bottom screws on the sides of the sniffer, don't forget to remove 4 screws on the front bottom side of the sniffer
c. Be careful to disconnect the connector from the fan wiring (back left corner), when replacing make sure the wiring is positioned behind the buffer
d. Connect all wiring (accept ARINC wiring – J251)

10. To access the NOx sensor
a. Remove the front protection panel (Allen key, nr 4)
b. Remove the bolts on the side
c. Slide backwards top panel and remove panel

⚠ Work on the internal component can only be done by qualified persons, an antistatic should be used in all times when touching internal components from the Thermo 43i TLE

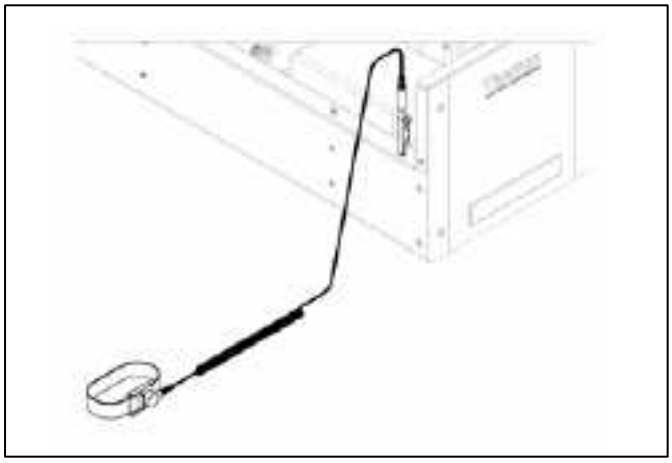


Figure 86 Use antistatic when operating on the internal components

6.1.1 LICOR 7200RS

A 2-year maintenance cycle is applicable for the sensor, this consist of following operations

- Cell Cleaning
- Factory calibration
- Thermocouple replacement
- Replacing the IR source (every 6 years)

Special maintenance can be done by Catec. More information about the Licor system including software, manuals and configurations can be found in the Thermo folder under the FluxSense sniffer folder.

Note: The general maintenance includes typically the update of the LICOR7200RS with the latest GHG software and embedded software. The latest embedded software version fully compatible with the IGPS software is software version 8.0, the LICOR should therefore **not be updated** before special approval from FluxSense, as the added verbose mode in the embedded software from version 8.5 onwards are resulting in a non-stable data output, resulting in a 10 seconds data blackout once per minute. It is advised to always use the same software version for the embedded software as the GHG software.

To access the Licor system for maintenance the Sniffer sensor has to be opened, therefore this can be optimally combined with the Thermo maintenance or filter replacement.

SOP 2.11. To access the Licor system for maintenance and inspections

1. Before conducting any maintenance on the Licor sensor, a configuration backup file needs to be created as backup, this has to be done before demounting the sniffer from the aircraft.
    - **a.** Connect power extension cord
    - **b.** Power on GPU
    - **c.** Plug in GPU to external AC power bus
    - **d.** In cockpit Switch on “External power supply”
    - **e.** Switch on “utility”
    - **f.** Switch on “survey power”
    - **g.** Check sniffer circuit breaker in cockpit (must be pressed down)
    - **h.** Master switch on sniffer box needs to be put in upward position
    - **i.** Switch on sniffer with remote switch in cabin (at intercom jacks)
    - **j.** Check circuit breaker on emergency sniffer battery (must be pressed in)
    - **k.** Connect laptop with Thunderbolt cable
    - **l.** Switch off all other non-used network adapters (WIFI and Ethernet) in “Network and sharing center” >> “Change adapter settings”
    - **m.** Connect to MUMM_LOG_PC using TeamViewer (V12) use 192.168.1.9 (make sure TeamViewer accepts LAN connections) and pwd: “mumm”
    - **n.** Go to LICOR software GHG V8.0 (on MUMM_LOG_PC)
    - **o.** Go to Config Files>>Safe as
    - **p.** Safe all settings as configuration file and store the file under
    - **q.** QMS>>QA_Follow-up>>Configuration files>>Licor
2. Shut down sniffer
3. Demount the sniffer and open the top cover (see 6.1 Internal sniffer sensor components)
4. The LICOR is located on the right side of the Sniffer (see Figure 33)
5. To access the interface (Licor 7550) open the Licor 7550 cover (small bolts)
6. If necessary the sensor head (LI-7200 RS) can be disassembled and shipped to Catec for inspection:
    - **a.** Mark the position of the fittings and cables to the Sensor head
    - **b.** Disconnect the Swagelok intake connectors left side
    - **c.** Disconnect the Swagelok outlet connectors (cross)
    - **d.** Disconnect the 2 cables between the LI7200 and the LI7550 unit (turn counterclockwise)
    - **e.** Disconnect the small pressure sensor tube
    - **f.** Loosen the metal straps with a Philips screwdriver
    - **g.** Carefully remove the sensor from the frame
7. Use appropriate protection when shipping the sensor to Catec
8. Turnover time can be several weeks

⚠ Opening the Licor sensor head can only be done by Catec or FluxSense

SOP 2.12. To reinstall the Licor system after maintenance by Licor

1. Open the top cover (see Chapter 3)

2. Reinstall the Licor 7200RS sensor head:
    a. Carefully put the sensor in the right metal strip, loosen the metal strap further with a Philips screwdriver if necessary
    b. Slide the sensor backward, be careful with the cabling
    c. Slide over the front metal strip, loosen the metal strap further with a Philips screwdriver if necessary
    d. Check the matching of the markings of the straps on the sensor and tighten both straps with Philips screwdriver
    e. Mark the position of the fittings and cables to the Sensor head
    f. Connect the small pressure sensor tube
    g. Connect the 2 cables between the LI7200 and the LI7550 unit (turnclockwise)
    h. Connect the Swagelok outlet connectors (cross), tighten until the marking
    i. Connect the Swagelok intake connectors (left side) until the marking
3. Close the top cover of the sniffer sensor

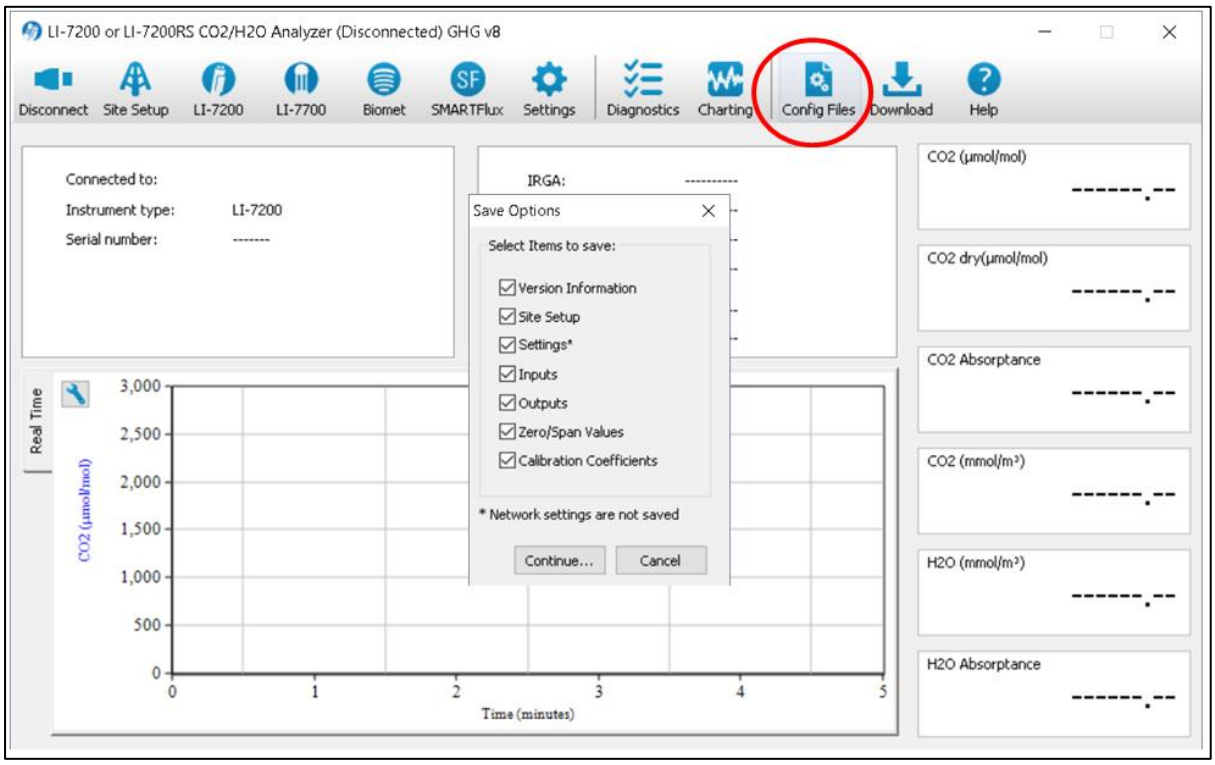


Figure 87 Save all setting of the sensor as Configuration file

6.1.2 THERMO 43i TLE

Periodic maintenance should be performed to ensure a proper working of the sensor, as the Thermo sensor is adapted for the sniffer system, not all of the general maintenance operations are applicable. For all maintenance on the Thermo sensor of the sniffer sensor the top side of the sniffer needs to be made accessible (see 6.1). The maintenance should optimally be executed in the office or workshop and not with the sniffer in the aircraft. Following operations should be performed on 2 year basis:

See Annex B - Block Diagram for the structure of the Thermo 43i TLE menu's.

SOP 2.13. Thermo 43 bi-annual service

1. Connect Thermo Display panel

   a. Connect the 34 pin 2.54 spacing IDC ribbon cable (IEI 32200-000017-RS) from Thermo front panel to THERMO motherboard (J18) (or use the Thermo box with cable to J251)
   b. Disassemble the pitot tube from the aircraft and connect the pitot-tube to the air-inlet of the sniffer (7/16 wrench)

2. POWER on sniffer bypassing AC power
   a. Connect sniffer power cable to GPU (Mil connector)
   b. Connect the sniffer power cable to the sniffer (J211)
   c. Put a jumper in the white connector (Figure 88)
   d. Connect GPU to 220VAC socket
   e. Switch on main power switch on sniffer (switch must be faced upward)
3. Wait 45 minutes or check alarm (chamber temperature must be between 43 and 47°C)
   a. Press on the button underneath the alarm symbol on the panel
   b. Check the alarm counts (must be 1, only flow should provide an alarm as the flow meter is not installed in the sniffer sensor)
4. Check calibration factor (Figure 89)
   a. Click on menu
   b. Go to Calibration factor by using click enter
   c. In case the calibration factor is <0.9 and inspection of the sensor might be required (to be done by Fabricom)
5. Check diagnostics (see Figure 90, Figure 91, Figure 92)
   a. Click on menu
   b. Go to diagnostics by using click enter
   c. Go to Voltages >> Interface board >> Flash supply should be <950V
   d. When lamp voltage is out of boundary (>1050V) this can be lowered manually (to be done by Fabricom)
   e. Go to temperatures, internal and chamber temperature should be 40-60°C
   f. Check Lamp intensity (<95%)
   g. Check for regular clicking sound (if not present, lamp should be replaced)
6. Clean Optical Bench
   a. Disconnect tube fittings, make sure to remove the pressure sensor to avoid damage
   b. Use air compressor to clean the optical bench
   c. Reconnect tube fittings
   d. Check for leaks by doing leak test (see 6.1.9)
7. Perform factory (hardware) calibration (see 4.2)
8. Lamp replacement procedure
   a. When consequent drift is observed, when lamp intensity is either too low (<50%) or too high (>95%) or when clicking sound is not stable, the lamp and/or lamp trigger may need to be replaced
   b. Before replacing lamp, the lamp trigger should be replaced as this often already solves the problem
   c. Replacement of the Lamp and lamp socket should be performed by accredited Thermo servicing company or FluxSense.
   d. To replace lamp and /or lamp (flash) trigger:
      - demount the measurement chamber from the bench (Allen key nr 4)

- unscrew the retaining screw on the lamp socket in front of the flash trigger
- the lamp socket can be removed from the sensor head by unscrewing 4 screws
- pull the lamp + flash trigger out of the lamp socket
- remove the lamp from the trigger
- put the new lamp in the trigger, or put the old lamp in the new trigger
- reinstall the lamp + trigger in the lamp socket
- reattach the socket to the sensor head
- reinstall the retaining screw
- In case the trigger is replaced, the wiring of the new trigger must be connected
- Reinstall the sensor head to the bench

e. Follow the installation procedure described in the Thermo manual for the configuration of the lamp

9. Replace any other malfunctioning cables, tubing or components

Maintenance can be provided by Fabricom. An arrangement must be made 2 weeks in advance, Fabricom can perform, sensor inspections, factory calibrations, component replacement (all components are in stock).

More information about the Thermo system can be found in the Thermo folder under the FluxSense sniffer folder.

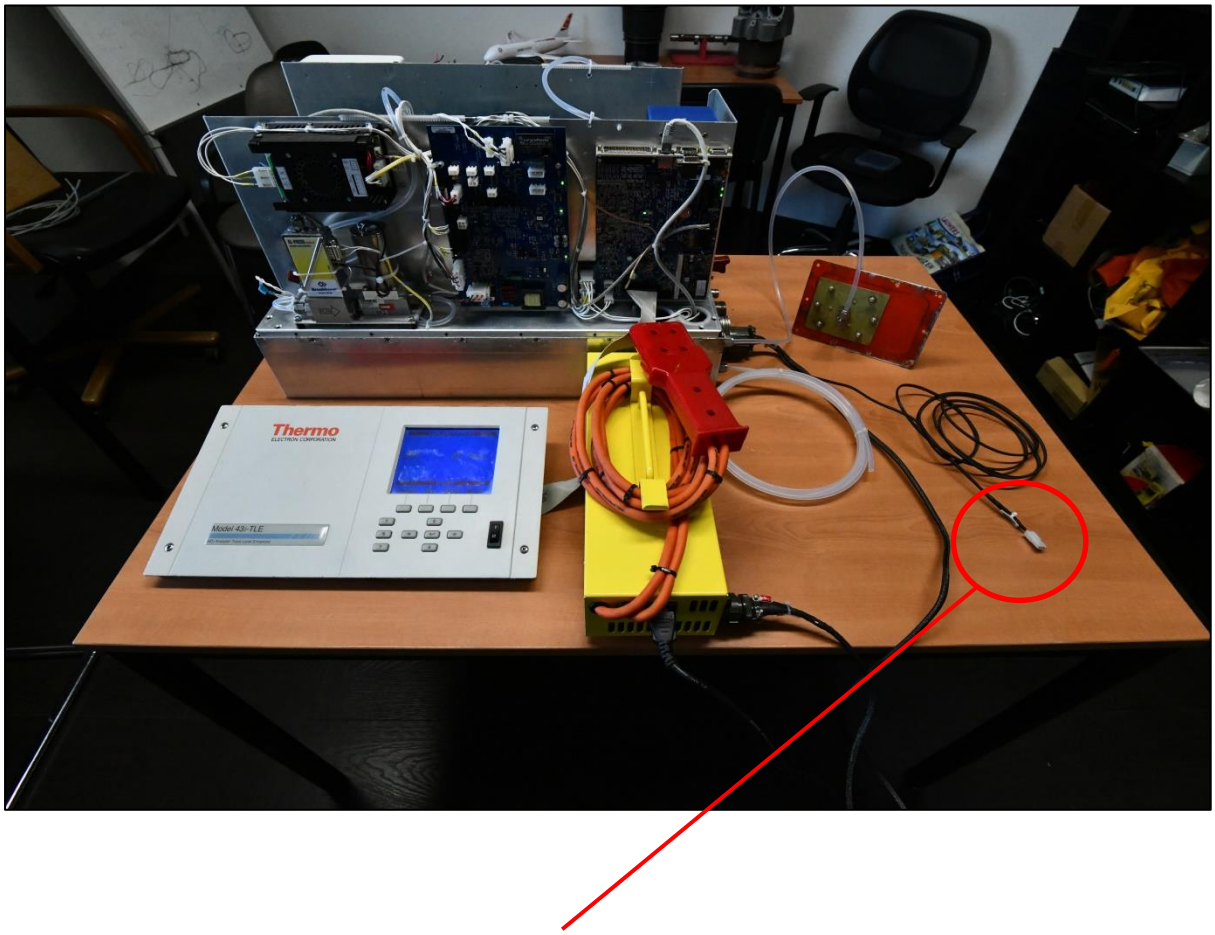




Figure 88 Setup of Thermo maintenance, with Pitot-tube, GPU, Thermo front panel and jumper in white connector

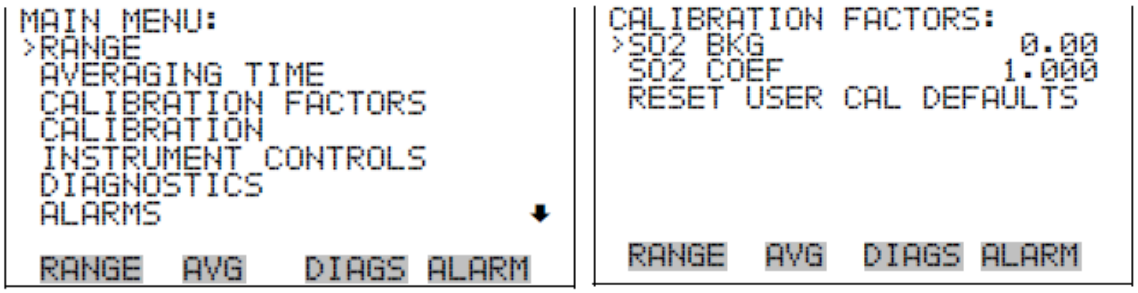


Figure 89 Main menu and calibration factor menu

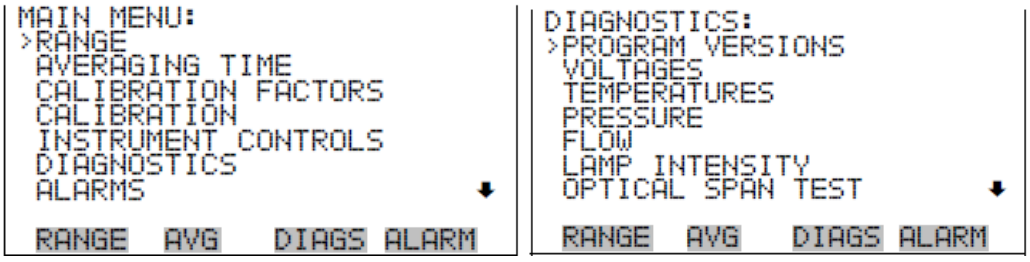


Figure 90 Main menu and Diagnostics Menu

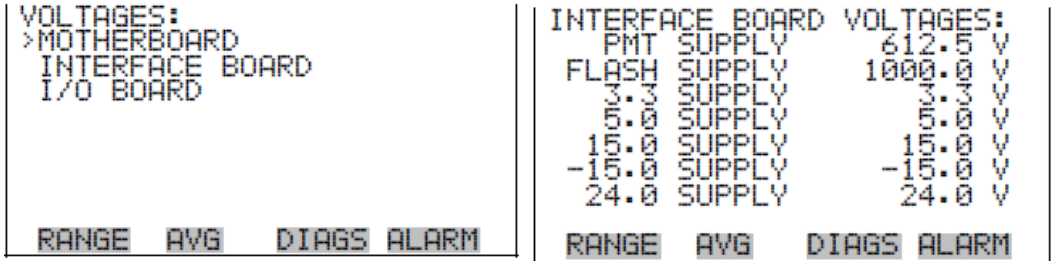


Figure 91 Diagnostics voltages – interface board voltages

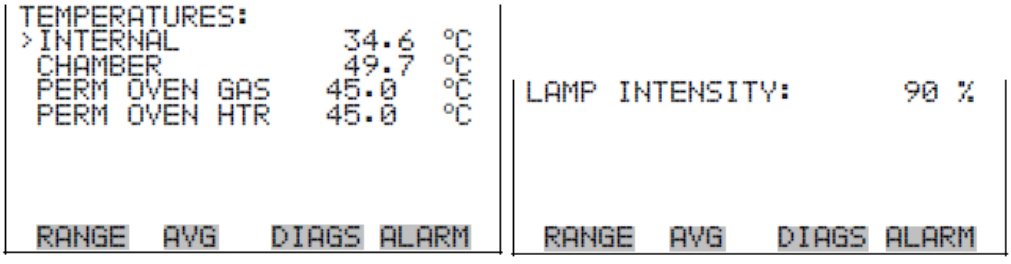


Figure 92 Diagnostics menu, temperatures (internal and chamber >40°C) and lamp intensity (<95%)

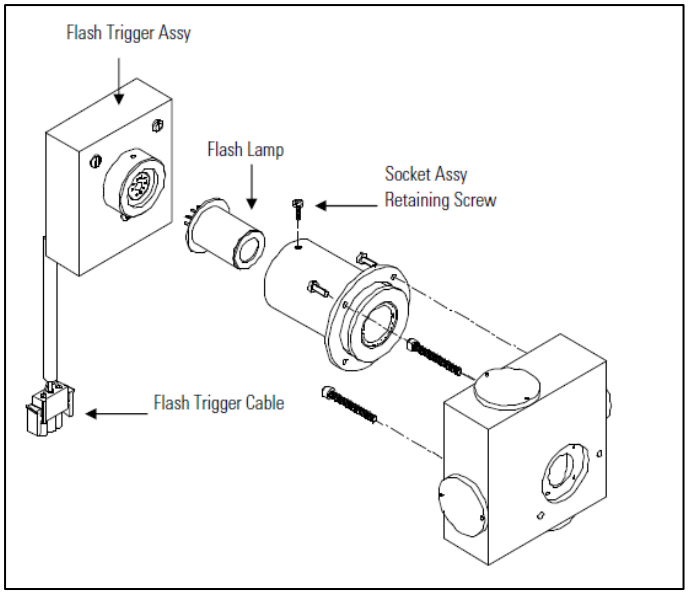


Figure 93 Lamp replacement

6.1.3 Ecotech Serinus 40

The Ecotech Serinus 40 should undergo a bi-annual maintenance. This maintenance should be executed by a licensed maintenance organization. In Belgium ETS is able to conduct this maintenance (contact person Roger van Uden - roger@etserv). During this maintenance, a cleaning is performed as well as flow calibration a hardware calibration and a filter replacement.

6.1.4 Bronkhorst regulators

Both flowmeter and pressure regulator from Bronkhorst are installed. No information is available about the maintenance. The Bronkhorst meters may require recalibration or replacement when malfunctioning, make sure to use following hardware settings when installing a new instrument.

- Flowmeter: LSD:1; MSD:0
- Pressure regulator: LSD: 0 MSD: 2

The Bronkhorst regulators are connected to Ethernet via a RS232 to Ethernet connection. Following port sand IP addresses have been used

- Flowmeter:
    1. Serial Port: COM 4
    2. Baud rate: 38400
    3. IP: 192.168.1.102 (port 1471)
    4. Serial Nr: SNM16206036A
- Pressure regulator:
    1. Serial Port: COM 4
    2. Baud rate: 38400
    3. IP: 192.168.1.106 (port 1470)
    4. Serial nr: SNM12205648E

Bronkhorst High-Tech B.V. FLOW-BUS DDE-server

Date: 2018-03-26 Time: 13:59:45

FlowDDE V4.74

FLOWBUS.DLL V6.38.0.1

Database V3.73

System configuration overview:

chan	node	proc id	module number	description
001	001	001	07 DMFC SNM16206036A	Digital Mass Flow Controller
002	002	001	09 DEPC SNM12205648E	Digital Pressure Controller

To access the Bronkhorst regulators, use the dedicated Bronkhorst software FLOWDDE and FLOWPLOT. Output can be used for limited troubleshooting. For more information on the Bronkhorst flowmeters, manuals, software and configuration files see Bronkhorst folder under the Fluxsense Sniffer folder.

⚠ Reinstalling and configuration the Bronkhorst regulators should be done by FluxSense

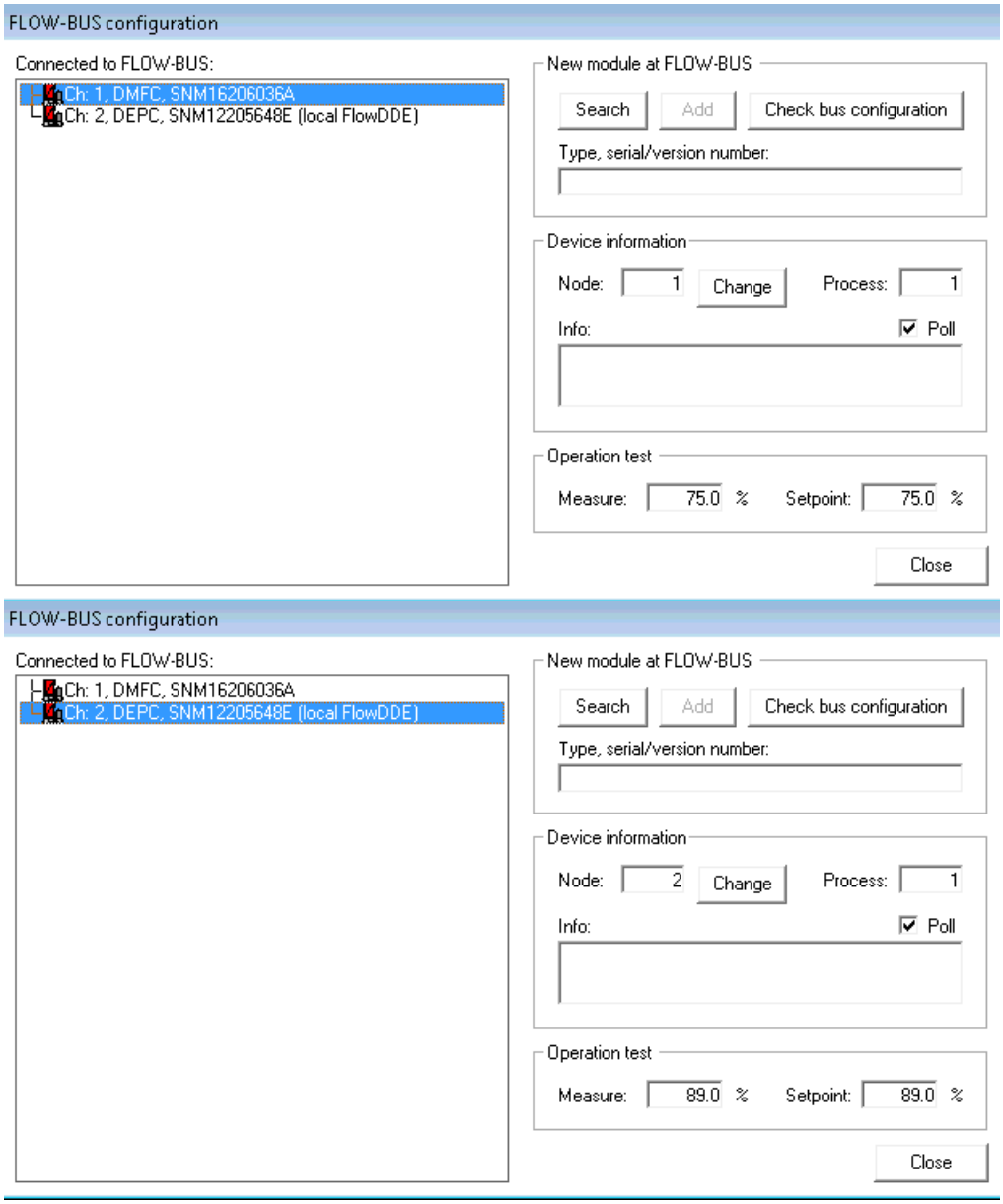


Figure 94 Bronkhorst regulators flowbus configuration

6.1.5 MUMM_LOG_PC

General computer maintenance should be executed on the MUMM_LOG_PC (ZOTAC) from time to time (virus test, cleaning up of log files, backups, clone of hard drive). The IGPS software on the MUMM_LOG_PC should be updated after having been thoroughly tested on a client station. For most computer maintenance the sniffer sensor does not have to be disassembled from the aircraft, only for the replacement of the HDD (or SSD) the sniffer must be opened

SOP 2.14. MUMM-LOG-PC maintenance

1. When:
    a. Update: as soon as a new stable version is available from FluxSense
    b. General maintenance: Every 12 months
    c. HD replacement: After failure
2. General Equipment:

   a. Ground Power UNIT (GPU)
   b. Optional power cord to bypass AC power

3. Software update
   a. Connect GPU to the AC
   b. Close the Watchdogs, TCP log, IGPS present, and all other files and programs
   c. Make a backup of the program files, log files and emission files from the IGPS folder from the LOG_PC (to 25-Sensor-Data/Sniffer/MUMM_LOG_PC Seafile)
   d. Copy the latest IGPS software to the IGPS folder on MUMM_LOG_PC
   e. Remove or rename the old "AISPresent.exe" version
   f. Rename the new version to "AISPresent.exe"
   g. Shut down the MUMM_LOG_PC
   h. Power off the sniffer, wait 10 seconds and power on the sniffer
   i. Reboot the sniffer

The original HDD hard drive of the sniffer sensor system has been replaced by a faster and more reliable Samsung EVO 850 2.5 inch SSD of 1TB (SSD1). The previous hard drive was cloned prior to this operation. On annual basis a clone of the installed SDD to a second Samsung EVO 850 2.5 inch SSD of 1TB (SSD2) should be made:

SOP 2.15. To clone SSD

1. Place SSD-2 in Kingston drive case and connect to USB port on the back of the sniffer
2. Power on the Sniffer sensor
3. Connect to the MUMM_LOG_PC using TeamViewer
4. Close all programs and files
5. Open Samsung Data-Migration software
6. Run the cloning software, make sure both drives area visible, select start (cloning will take 30 min)
7. Shut down the Sniffer sensor
8. Disconnect the SSD

Note: Do not override the original HDD, this should be kept for safekeeping,

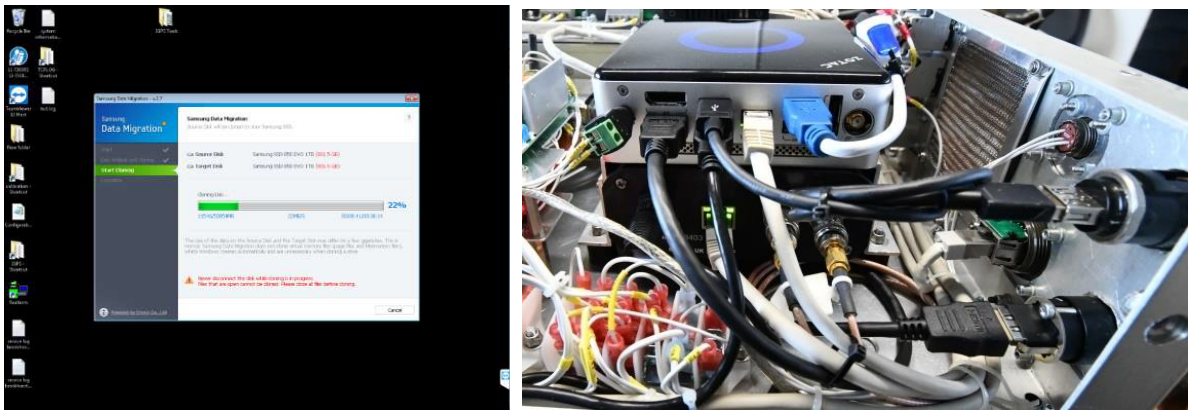


Figure 95 Samsung data migration software and location MUMM_LOG_PC on top of AIS+GPS receiver

In case of SSD failure or significant software issue, the SSD1 can be replaced with SSD2. The hard drive is located under the MUMM_LOG_PC to replace the SSD follow following procedure:

SOP 2.16. Replacement SSD

1. For this procedure the Sniffer sensor should be disassembled and bottom part needs to be opened (see 6.1 Internal sniffer sensor components)
2. Mark all cabling from the MUMM_LOG_PC and AIS+GPS receiver (tip: make a picture)
3. Disconnect all cabling from the MUMM_LOG_PC and the AIS+GPS receiver
4. Unscrew the fixation for the MUMM_LOG_PC +AIS (Hex 7)
5. Remove the AIS+GPS receiver (Hex 8)
6. The hard drive is located under the MUMM-LOG-PC, use PH1 screwdriver to remove SSD
7. Mount the other SSD
8. Replace the AIS+GPS receiver
9. Reinstall the MUMM_LOG_PC and AIS+GPS receiver
10. Reconnect all wiring

In addition to regular maintenance the MMSI MID country codes and Keel Laying date should be updated on annual basis or when crashes or commonly observed. See Section 3 for more information on how to update the data reference files.

6.1.6 AIS+GPS receiver

The AIS+GPS receiver used in the sniffer is a Comar SLR200NG receiver. A VHF receiver is installed on the belly of the aircraft and connected to the ASP connector panel (TNC), a GPS receiver is installed on the top of the aircraft and connected to the ASP connector panel (TNC). The receiver is located in the bottom compartment of the sniffer underneath the LOG-PC. If AIS+GPS is malfunctioning a troubleshooting (see 7.6 Problems with AIS+GPS receiver) can be done to identify the issue. The unit, cabling and/or antennas may need to be replaced, in case of antenna or cabling issues, this has to be done by ASP. In case of a unit failure, the needs to be replaced by a new Comar SLR200NG unit, this can be done by either MUMM or FluxSense. Note to remove the AIS+GPS receiver, special care should be made with the MUMM_LOG_PC as it is required to demount the MUMM_LOG_PC to change the AIS+GPS receiver (see above).

Note: replacement of the AIS+GPS unit should only be done when the Sniffer sensor is shut down and fully disconnected from the aircraft.

6.1.7 Arinc

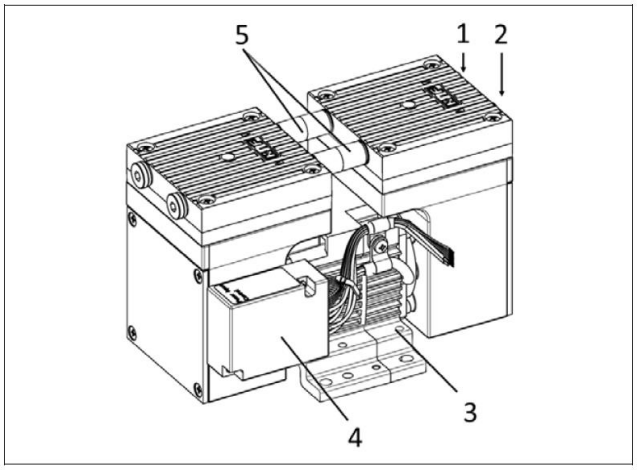
An Arinc converter is installed in the sniffer (ARINC ADC 20160815), no maintenance is foreseen. Ad hoc replacement in case of failure can be executed by FluxSense. In case of failure a first inspection can be carried out by MUMM to inspect the wiring and the power supply. Also the 5 volt RS232-Ethernet converter can be inspected by MUMM.

6.1.8 Air pumps

The air pumps perform a crucial part in the sniffer as they provide the airflow needed for the sensors to measure the gas concentrations. Air pumps have moving parts and are therefore more susceptible to wear and break-down and must be closely watched.

Pump 1 used for the SO2 and the CO2 sensors and pump 2 used for the hydrocarbon kicker are from the same line and use the same diaphragms

1 Outlet (pressure side)
2 Inlet (suction side)
3 Motor
4 Motor controller
5 Pneumatic connection



1 Outlet (pressure side)
2 Inlet (suction side)
3 Motor controller
4 Motor

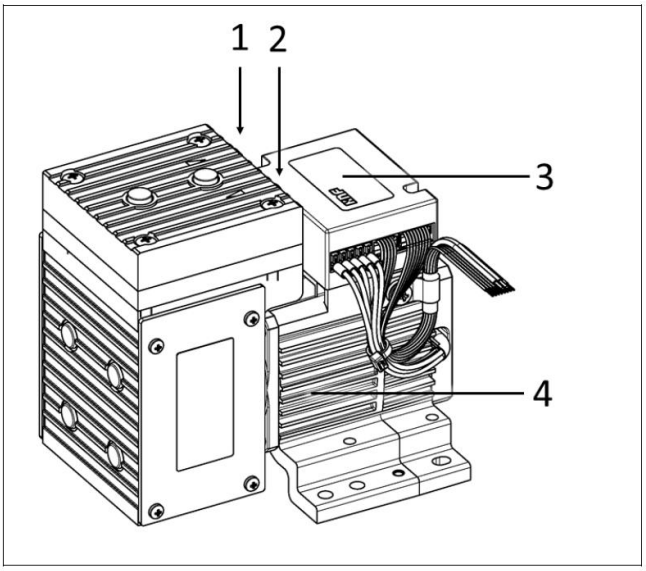
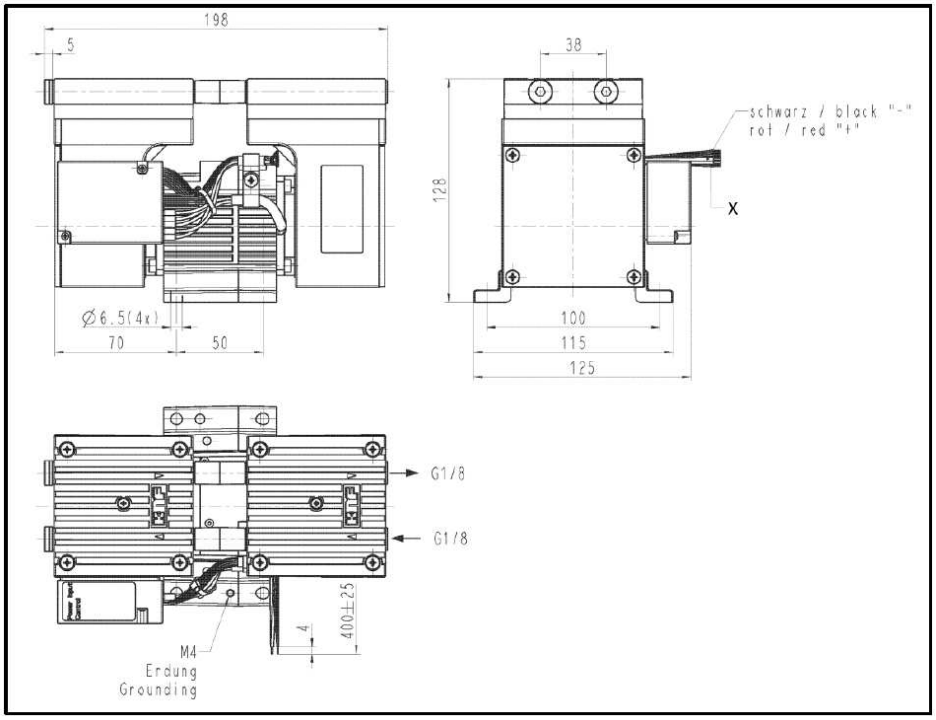


Figure 96 Pump 1 (N 838.1-2 KNDC-B) and Pump 2 (N 838.1 KNDC-B) connection



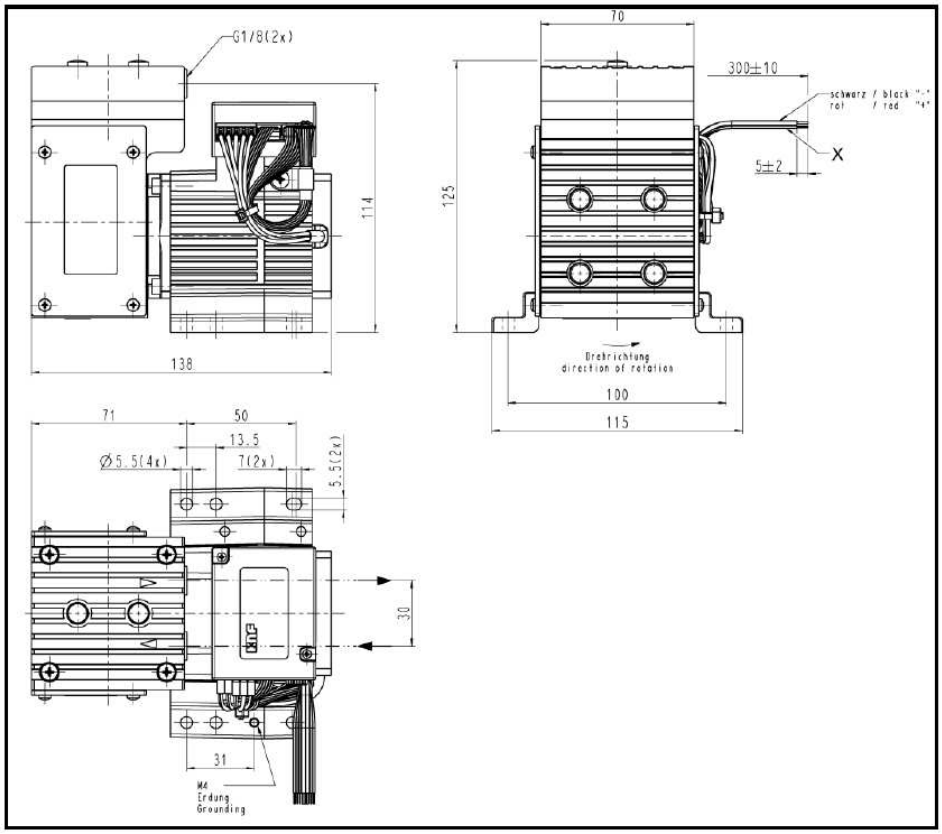


Figure 97 Diagram of the N 838.1-2 KNDC and N 838.1 KNDC pump, note that the pump used in the sniffer sensor is a special order with the head turned 90° counter clockwise

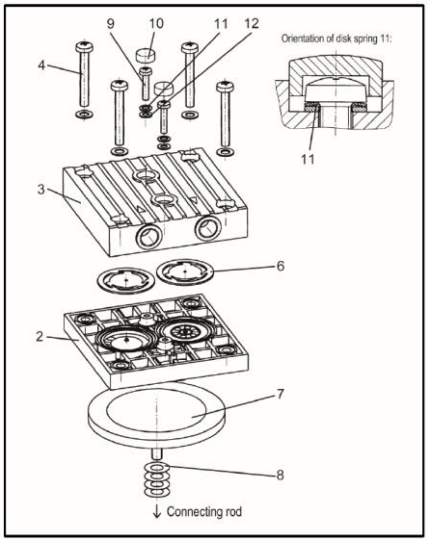
For more information on the maintenance of the air pump go N838 technical file (KNF 121249-121517) in the KNF folder under Reference Docs. No information is available on the frequency of the maintenance, therefore the pumps must be closely watched, when strange noises, vibration, a lack of flow or visual damaged parts are observed during the annual maintenance, the diaphragm of the pump might need to be replaced.

SOP 2.17. To replace the diaphragm on the N838 pump

1. Demount the Pump from the sniffer case
    a. Put the sniffer upside down
    b. Disconnect the power supply to the pump
    c. Disconnect the air inlet and outlet.
    d. Unscrew the 4 bolts that attach the CO2 frame to the sniffer casing
    e. Use Allen key to loosen the bolts of the pump
    f. Remove the pump from the sniffer
2. Unscrew the 4 bolts on the pump head
3. Remove the pump head and sealing (NOTE: pay attention to the direction of the pump head before removing)
4. Inspect the pump head sealing, replace if necessary
5. The diaphragm is installed under the pump head
6. Bring the diaphragm to pump top dead end by turning the fan
7. Remove the diaphragm by taking the edges of the lip and turning clockwise
8. Remove spacers on diaphragm
9. Check for dirt and clean if required by using pressured air or microfiber cloth

10. install spacers on the diaphragm
11. Put the pump in the top dead end position
12. Install the diaphragm
13. Reinstall the pump head and (new or old) sealing (orientation!)
14. Reinstall the pump in the sniffer
15. Reattach the tubing, make sure to block the G 1/8 (ISO parallel thread) to not damage the pump head (plastic)
16. Reconnect the power connection
17. Check for leaks using the soap solution

A buffer is installed just before the inlet of the air pump , no information is available about the maintenance or inspection of this buffer (PVC tube of 10 cm diameter and ca. 15 cm long). Nevertheless it is advised to check for leaks during the annual checks.



Legend

1	Housing
2	Intermediate plate
3	Head plate
4	Screw
5	Cover
6	Valve plate/sealing
7	Structured diaphragm
8	Diaphragm spacer
9	Screw
10	Screw cap
11	Disk spring
12	Washer

Figure 98 Assembling of the pump head

Pump 3 is used for the NOx sensor, this pump is from the same manufacturer but from a different line. This pump is the only of the 3 that uses 110VAC and is therefore not connected to the EPS power supply.

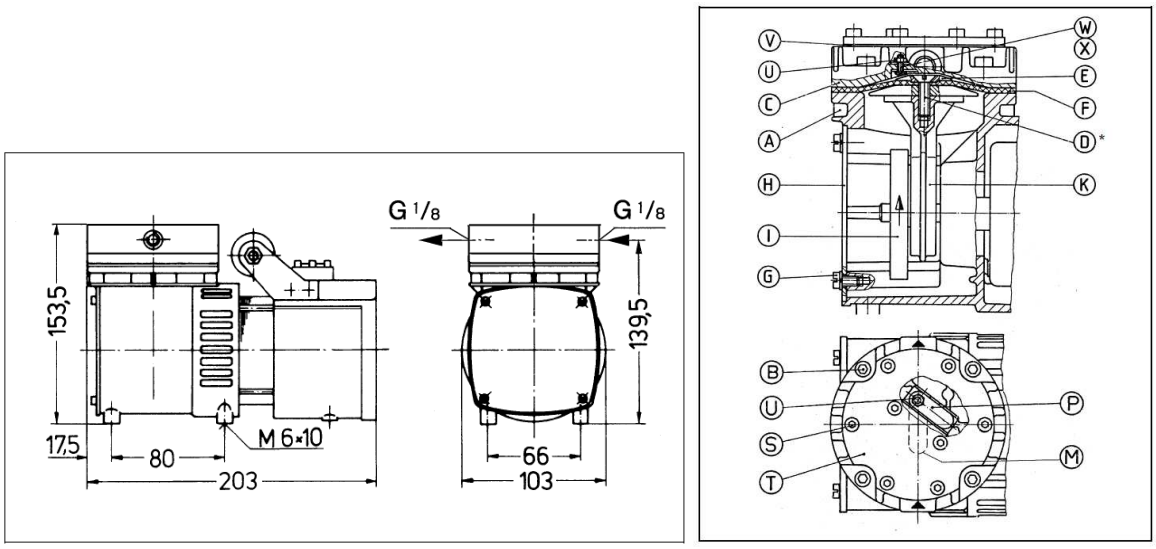


Figure 99 Diagram and parts of the N022 pump of the N022 pump

For more information on the maintenance of the air pump go N022 technical file (KNF 121226-121491) in the KNF folder under Reference Docs. As this sensor is producing ozone, the valves need to be replaced bi-annually. Nevertheless also this the pumps must be closely watched, when strange noises, vibration, a lack of flow or visual damaged parts are observed during the annual maintenance, the diaphragm of the pump might need to be replaced.

SOP 2.18. To replace the diaphragm on the N838 pump

1. Demount the Pump from the sniffer case
    a. Disconnect the power supply to the pump
    b. Disconnect the air inlet and outlet.
    c. Unscrew the bolts that attach the pump tray to the sniffer casing (Torx T40)
    d. Remove the pump tray from the sniffer
    e. Demount the pump from the pump tray
2. Mark the position of the pump head (C) with a pencil
3. Unscrew the 4 bolts on the pump head (Allen key 4)
4. Unscrew countersunk screw (D), remove retainer plate (E) and the diaphragm (F)
5. Remove screws (G) to remove cover plate (H)
6. Turn the counterweight so that the connection rod (K) is in the mid position, fit the new diaphragm, tighten the new countersunk screw (D) (5 Nm)
7. Change reed valves M and P
    a. Loosen the Allen screws S, remove the cover plate T and the gasket V
    b. Unscrew nut U, remove screw W, incl. washer X and reed valves P and M
    c. Fasten new reed valves P and M and fit new wash X and nut U
    d. Replace the cover plate with a new gasket V and tighten screws S
8. Reinstall the diaphragm head according to the marks
9. Tighten the bolts 5.5Nm

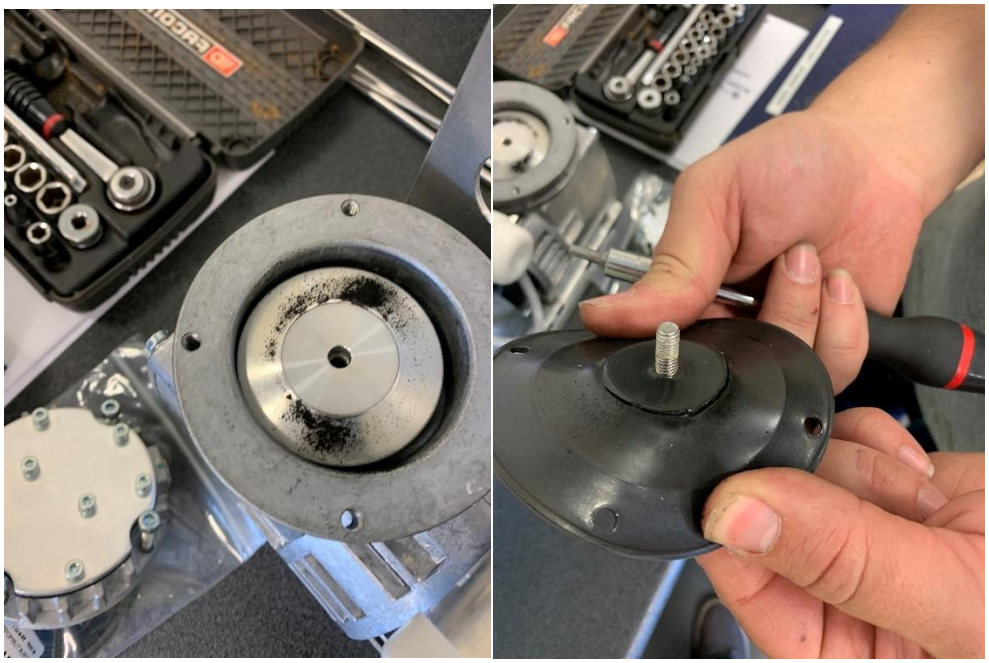


Figure 100 Example of damaged diaphragms

6.1.9 Internal tubing

A visual inspection can be executed during every opening of the sniffer sensor, not regular servicing is required for replacement. A leak test can be done together with the leak test of the external tubing during Hardware calibrations to look for damaged tubing or faulty fittings (see 6.4.2.)

6.1.10 Hydrocarbon kicker

No frequent regular maintenance is required for the hydrocarbon kicker. But due to wear or codding of the capillaries an annual leakage and flow test are recommended

SOP 2.19. To conduct a leak test on internal tubing

1. Remove hydrocarbon kicker from the sniffer casing
2. Add covers on the outer compartment and on the end
3. Connect to the synthetic air pressure cylinder
4. Add cover on the overflow valve
5. Add pressure of 1 bar
6. Spray soap liquid on tubing
7. Note the time to decrease to 0.5 bar (> 5min)
8. Remove covers from outer compartment and put them on the inner compartment
9. Repeat the steps 3-7 with the outer compartment

SOP 2.20. To test flow

1. Add covers on the inner compartment
2. Connect the inlet of the outer compartment to a fresh particle filter
3. Connect the outlet of the outer compartment to a flowmeter
4. Connect the outlet of the flowmeter to the Thomas pump
5. Use the 220-110V power converter to power the pump
6. Measure the flow, this should be min 5l/min

in case the flow is lower than 5l/min in the outer compartment, this is most likely due to clogging of one of the capillaries, the clogged capillary will need to be cleaned or replaced. On 5yr basis all capillaries should be disassembled and tested.

SOP 2.21. To clean a capillary

1. Disassemble different HC kickers
2. Remove the capillaries
3. Use isopropyl alcohol to clean the capillaries, use an air compressor or synthetic air to dry
4. Test the flow through each capillary
    a. Connect capillary to synthetic air cylinder,
    b. increase pressure to 2 bar and check if air flows through the capillary
    c. Not all capillaries have the same flow
    d. Capillaries with deviating flows should be replaced
5. Reassemble HC kickers
6. Reassemble Hydrocarbon kicker and reinstall it in the sniffer casing

6.1.11 Internal signal wiring

No maintenance is required for the wiring, if visually cable damage is observed this can only be replaced after identifying the wiring and consulting FluxSense. A standard Ethernet hub is used to connect all the Ethernet connectors to the MUMM_LOG_PC (MXU85A0001). These devices show generally no maintenance and are very reliable, in case of issues with Ethernet, the power supply and wiring can be inspected. If necessary the Ethernet hub can be replaced by an identical model.

6.1.12 Internal power distribution

In case of malfunctioning components the circuit-breakers must be checked first and if required be replaced. In case of component malfunctioning it is advised to read out the power from the power converters during general maintenance, they may be replaced if the current output is outside the limit (>20% difference).

6.1.13 Fans

Fans should be inspected during every opening of the sniffer sensor, they must be free from any blockage or contact with wiring, replace wiring if damaged. 2 types of fans are used, 3 x 80 mm fans (NMB) running on 115 V on the backside and 12 x 40 mm fans (Sunon) running on 5 V on the front side (installed in 3 blocks of 4 fans). Fans have low rate of failures and high life acceptancy (>20yr @ 100 flight days/year), in case the fans are no longer working, they must be replaced (available on RS or Mouser).

6.1.14 Sniffer casing

No regular maintenance is required for the casing. The screws may need to be replaced when the thread or head is damaged. Spare screws and bolts can be ordered via Styl Aviation.

After servicing and closing of the sniffer sensor, the convergence points between the top and bottom cover should be covered with aluminium tape (e.g. 3M 1436) to avoid EM interference in the cockpit.

6.2. Filters

Note: Optimally the changing of the filters can be combined with the hardware SO2 calibrations

Two fine particle filters are installed in the sniffer system, these filters can become kludged by time. No roll-over time is specified to change the filters, to enable a proper functioning of the sniffer system during intensive campaigns in busy shipping areas it is advised to change the filters on a two-annual basis as a precautionary measure, or when a decrease in flow is observed. The specifications of the filters are:

- Manufacturer: PAL
- Type: ACRO 4003 PTFE
- Size: 50
- Pore size: 1µm
- Connection: Threaded (with Teflon tape)

Filters can be ordered at VWR (customer nr: 41005569).

SOP 2.22. To replace the filters

1. Disassemble tubing to and from the filter box, close the open ends with covers
2. Remove the filter box (Velcro)
3. Open the box using a Philips screwdriver (PH1)
4. Unscrew the 1/4 Swagelok (tube fitting) using a wrench 7/16 (4x)
5. Remove the filters from the filter box
6. Unscrew the Swagelok-1/4”NPT female adapter on the filter
7. Check the adapter for left over Teflon tape
8. Put Teflon tape (5 turns) in clockwise direction on the new filter thread and reconnect the Swagelok adapters (4x) use modest force to tighten the adapters
9. Check if Teflon tape does not block the airflow
10. Reinstall the Filters by tightening the Swagelok tube fittings
11. Reinstall the filterbox and attach the tubing, leave the cover of the box open
12. Perform a leakage test, while the sniffer is powered on and taking in air, blow respiratory air on the filter connections, if no CO2 is measured (IGPS or GHG), the filters are properly installed.
13. Close the box cover.

6.3. Client station PC maintenance and updates

Once a year all emission files should be copied from the IGPS folder and stored on the SURV FREENAS, also available under Seafile, 25-Sensor-Data/Sniffer-Data. If new AIS present or other IGPS software comes available this should be stored under 5-Instrument/FluxSense-Sniffer/Software afterwards the program files can be copied to the IGPS folder. All users should check the proper and full functionality of a new software version before the software can be installed on the MUMM-LOG-PC.

6.4. External Tubing

6.4.1 Assembling Swagelok connections

For assembling of flexible and stainless steel tubing, slightly turn Swagelok connector with back and front ferrules on fitting. Fully Insert the tube into the fitting, rotate the nut finger tight, mark nut at 6 o’clock position, and tightened further 1 and a quarter until the 9 o’clock position using wrenches.

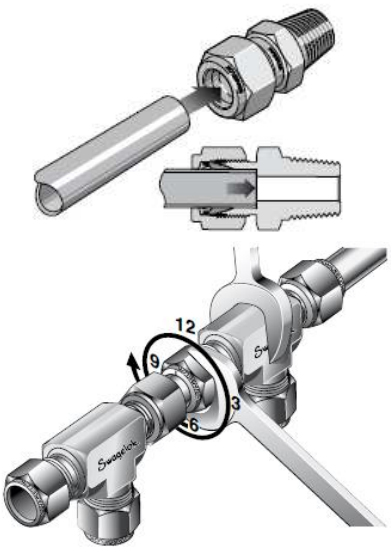






Figure 101 Assembly of Swagelok connections, (Swagelok, 2016)

To connect two male Swagelok connectors port connectors or reducers are used. To assemble adapters (e.g port connector see figure …) that come equipped with a machine ferrule end: discard the front and back ferrules and tighten 1 quarter.



Figure 102 Port connector with machine ferrule

Swagelok tube fitting can be disassembled and reassembled many times. Before disassembling mark the connector and tube, when reassembling, tighten until the mark, and further tighten slightly (1/6 of a turn) with a wrench.



Figure 103 When reassembling, mark the connector prior to disassembling tighten until the mark and tighten slightly (1/6 is a good indication) with a wrench

6.4.2 Flexible tubing and fittings

The flexible tubing between the pitot tube and the sniffer, between sniffer and NOx sensor and between the regulator to the pitot tube should be checked for obstructions and/or leaks. Obstruction can be checked visually or when limited flow is observed. Checking for leaks can be done using a soap solution to check for overpressure leaks and by blowing on the connections to check for under pressure leaks (to be done by 2 persons):

SOP 2.23. To conduct leak test on flexible external tubing

1. When:
    a. **Tubing:** during the 6-monthly Thermo hardware calibration
    b. **Regulators (connections between the gas cylinder and the flexible hosing):** after every removal of the regulator from the cylinder (i.e. during calibration of the reference gasses)
2. Equipment:
    a. Soap solution
    b. Teflon tape (if necessary)
    c. Wrenches (7/16, 9/16, adjustable spanner)
3. Methodology
    a. Connect a CO2 reference gas to the sample tube

b. Make sure the reference gas cylinder valve is open
c. Check if there is a positive outflow of the rotameter
d. Spray soap solution on all the connections
e. If no bubbles appear, there are no leaks
f. Close the reference gas cylinder valve
g. Check if overflow is zero
h. One person blows on all the connections
i. Second persons monitors the CO2 reading and watches for any abrupt change in the CO2 concentration
j. In case no abrupt changes are observed, there are no leaks

In case leaks where observed, the malfunctioning connection should be sealed properly by using Teflon tape. In case a leak is observed in the flexible tubing the tubing should be replaced completely. In case a leak is observed or with a connection in the flexible tubing, the fle

6.4.3 Pitot tube

The Pitot tube can get contaminated with residues which results in absorption of SO2 in the airflow. To ensure the measurement quality, a contamination check needs to be executed on regular intervals and if necessary the Pitot tube should be cleaned with methanol or replaced with a new tube.

SOP 2.24. Cleaning pitot tube

1. When:
a. **Contamination test:** during HW calibrations (6 months)
b. **Cleaning:** when contamination test is positive
c. Preventive Replacement: Once every 24 months
2. Equipment:
a. Pipe cutter
b. Methanol (or iso propyl alcohol)
c. Stainless steel tubing (SS-T6-S-065-20)
d. Soap solution
e. Teflon tape (if necessary)
f. Wrenches (7/16, …, Adjustable spanner)
3. Contamination test
a. Connect the SO2 reference gas strait to the sniffer using a standard 1/4” Swagelok connector on the flexible tubing (remove the 3/8” fitting)
b. Open IGPS>>SNF
c. Open the SO2 gas cylinder
d. Wait 30 seconds, write down SO2
e. Close the valve
f. Connect the hose to the pitot tube,
g. Open the gas cylinder,
h. Write down the SO2 reading at 30 seconds and 35 seconds,
i. If the concentration from the first measurement is not within the range between the readings at 30’th and 35’th, the pitot tube needs to be cleaned
4. Cleaning

a. Unscrew the 12 screws from the pitot tube attachment plate with a Philips screwdriver
b. Disconnect the flexible tubing by unscrewing the 1/4 Swagelok fitting (7/16)
c. Use methanol to clean the tube, make sure to rinse properly with water and dry the Pitot tube before remounting the pitot tube attachment plate.
d. Perform the same test after cleaning, in case the absorption is observed, repeat step 4 until the reading is within limits or replace pitot tube.

5. Preventive replacement

a. Unscrew the 12 screws from the pitot tube attachment plate with a Philips screwdriver
b. Disconnect the flexible tubing by unscrewing the 1/4 Swagelok fitting (7/16)
c. Remove bulkhead connector from the fuselage plate
d. Untighten the 3/8 connection of the bulkhead connector
e. Use a Swagelok pipe cutter to cut new 10 cm section from the Swagelok stainless steel tubing stock
- Place tub in cutter in appropriate position
- Rotate cutter, adjust tension every 2 turns with 1/8 of a turn
- Continue until pipe is cut completely

f. A new fitting should be used when connecting a new section to the bulkhead connector.
g. Place the fitting on the bulkhead connector loosely
h. Enter the tube section in the fitting (to the end)
i. Tighten finger tight
j. Mark connector at 6'ocklock
k. Tighten with wrenches 1 and a quarter turn to the 9'ocklock position (use inside nut of bulkhead connector to provide counterforce)
l. Check for leaks before remounting the pitot plate to the aircraft
- connecting the hose to the Pitot tube (leave the other end open),
- when the sniffer is powered-on, blow respiratory air on the pitot tube and other connectors,
- in case of leakage this shall be seen in the IGPS or GHG graphs (CO2 peak).



Figure 104 Pitot-Tube replacement (90° elbow is optionally)



Figure 105 Cutting a new section with Swagelok pipe cutter

6.4.4 Regulator

The connections (Swagelok of threaded Teflon connections) between the different parts of the regulator on the reference gas cylinders should be checked for leaks using a soap solution. In case a leak is observed, the malfunctioning connection should be first tightened slightly, when this does not close the leak, the connection should be disassembled and sealed properly by using Teflon tape.

SOP 2.25. Regulator inspection

1. **When**: after every removal of the regulator from the cylinder (i.e during calibration of the reference gasses)
2. Equipment:
    a. Soap solution
    b. Teflon tape (if necessary)
    c. Wrenches (7/16, …, Adjustable spanner)
3. Conduct a leak test
    a. After assembling regulator to the reference gas cylinder
    b. Open reference gas cylinder valve
    c. Check if there is a positive outflow of the rotameter
    d. Spray soap solution on all the connections
    e. If no bubbles appear, there are no leaks
4. To repair Threaded Teflon in case of leaks
    a. Disassemble connection
    b. Remove old Teflon from male side of the threaded connection
    c. Check for remaining Teflon tape in female side of threaded connection
    d. Hold new Teflon tap on male side of the threaded connection with finger
    e. Apply Teflon tape clockwise

6.5. External power distribution

The power distribution to and from the sniffer sensor should be visually inspected after every reinstallation of the sniffer sensor in the OO-MMM aircraft. Special attention should be made to avoid cable damages by using cable ties. An inspection may also be required in case of power issues. In case

faulty wiring is observed, all defect wiring should be repaired by an authorized aircraft maintenance company (Part 145). An annual basis a battery capacity test (CAP) should be executed by the aircraft maintenance company on the emergency battery, if the capacity is less than 75% (7.5Ah) the battery units (Sonnenschein A512/10 S) should be replaced.

6.6. External signal wiring

All signal wiring between the sniffer sensor and the ASP connector panel should be visually inspected after every reinstallation of the sniffer sensor in the OO-MMM aircraft. Special attention should be made to avoid cable failure by using cable ties. An inspection may also be required in case of signal issues with Ethernet, AIS, GPS or Arinc. In case faulty wiring is observed, all wiring should be repaired by an authorized aircraft maintenance company (Part 145).

When the sniffer sensor wasn't used for a an extensive period, the IP configuration off the Thunderbolt dock connection might need to be reset on the client stations (see 7.7).

6.7. Sniffer rack

The screws and Teflon plates of the sniffer rack should be inspected during every disassembling of the sniffer sensor and need to be replaced when damage is observed. Styl Aviation can provide the screws, the Teflon plates can be provided by Airplus.

CHAPTER 7. TROUBLESHOOTING

7.1. Reset software calibration factors

The main issue to be expected is the observation of non-reliable reading during flight. In case the SO2 and CO2 concentrations in ambient are not stable or outside the normal range.

- SO2: between -5 to +5 ppb
- CO2: between 380 and 430 ppm
- NOx: between 0 and 20 ppb

Or when FSC measurements are not realistic (>5 or systematic <0), this is most likely due to a calibration issues or non-correct calibration procedures resulting in wrong calibration factors, e.g. by selecting the wrong concentration while doing a calibration or doing a calibration with a leaking or a contaminated tube, in case this problem occurred after a software calibration the software calibration factors can be reset in flight to the previous factors or cleared completely.

SOP 2.26. Resetting calibration factors

1. On MUMM_LOG_PC (via TeamViewer)
2. Close TCP log, if watchdog opens, close watchdog
3. Close IGPS present, if watchdog opens, close watchdog
4. Delete last Log file under IGPS>>TCP LOG (move to Sniffer Data>>LOGS)
5. Copy CALIBRATION.TXT file to QA_Follow up>>Backup>>cal
6. Open Calibration_Clean_up.exe, deselect the wrong calibration and save as CALIBRATION.TXT
7. If the previous calibration are not useful, calibration factors can be cleared completely, therefore delete the CALIBRATION.TXT file from the TCP LOG directory
8. Open Logger watchdog, TCP log will appear in few seconds
9. Open present watchdog, IGPS present will appear in few seconds
10. Go to IGPS present>>Utilities
11. In the left bottom corner the calibration factors are displayed, they can be reset by clicking “Clear Cal. Coef”
12. Calibration coefficients are now reset to 1 for the K-factor and 0 for the intercept
13. When clearing the Cal factors, make sure to check the last software calibration factors in SQMS_Follow_Up.xlsx, if the factors are more than 10% different from 1, a new software calibration is vital before any new measurements can be conducted.

SOP 2.27. Replace SSD

1. In case the reset did not solve the issue, connect the reference gasses to the pitot tube and read out the concentration directly on the instrument (Licor: GHG, Thermo: Front-panel)
2. In case the readings are normal on the instrument but not on the IGPS, the issue is software related and must be solved by replacing the SSD of the MUMM_LOG_PC (7.5 Problems with the MUMM_LOG_PC).
3. If non-reliable measurements are observed on the instruments as well, there might be a problem with the pitot tube, the calibration gasses or the sensor components.

4. Check if the readings change when disconnecting the gas inlet and connect the reference gasses straight to the gas inlet on the sniffer, if the readings are now normal, the gas inlet needs to be inspected (see 6.4.3 Pitot tube).
5. If this did not solve the issue, the calibration gasses have to be inspected, this can be done by using a new cylinder, if the readings are normal with the new cylinder, the reference gasses need to be recalibrated
6. If also this did not solve the issue, the sensor components need to be inspected by using the troubleshooting procedures 7.2 to 7.4.



Figure 106 Utilities window of the IGPS present software

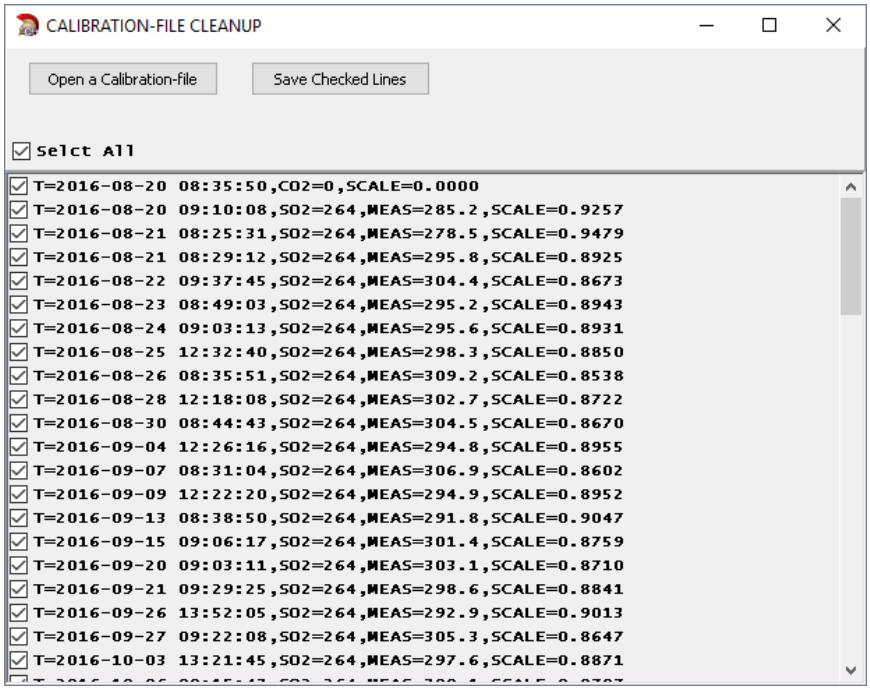


Figure 107 Calibration clean up tool

7.2. CO2 issues

If the data output of the Licor is not realistic and a calibration did not solve the problem or the data-output is not stable, for instance after software or maintenance update, follow the following procedure.

SOP 2.28. CO2 troubleshooting

1. Check data-output on the GHG software
2. If data is similar on the GHG software as on the AIS present, perform hardware calibration (see 4.1 L)
3. If data is different on the GHG software as on the AIS present, check the output settings
    a. Open GHG, select connect (via Ethernet) to 192.168.1.9
    b. Go to Licor>7200 output
    c. Check Setup tab (Delay should be 0 and Bandwidth should be 1 or 5) (see Figure 108)
    d. Check Ethernet tab (update rate should be 1-5, Data labels should be activated, Line feed should be selected, and all data labels should be selected)
    e. The other tabs or not important and can be neglected
    f. Select disconnect to activate changes
4. In case the previous step did not help, compare the current configuration with an old configuration file
    a. Open GHG, select connect (via Ethernet) to 192.168.1.9
    b. Go to “Config Files”
    c. Select “save configuration file”
    d. Save current configuration to QMS>>QA_Follow-up>>Backup>>Licor
    e. Open Excel file “comparison config files.xls”
    f. Go to Sheet “Import Config files”
    g. Select Data>>Get external data from TXT
    h. Select current config file (use all file types to see the config files)
    i. Use delimited, select “(“ as delimiter and select finish
    j. Select the complete row and remove all other “)” characters
    k. Copy the row and paste the row in first sheet using “Paste special>>Transpose”
    l. Repeat steps f-l with a previous config file
    m. The files can be compared row by row with the previous configuration file using the excel file
5. If the configuration file is not similar in number of rows or in non-numeric data (YES/NO), upload a previous config file
    a. On GHG software, go to “Config Files”
    b. Select “Open configuration”
    c. Select the previous configuration file from QMS>>QA_Folluw-up>>Backup>>Licor
    d. Pop-up window will appear that configuration was loaded
    e. Select disconnect
    f. The sensor is no longer calibrated and a hardware calibration is required
6. In case the previous step did not solve the issue, data output from Ethernet can be checked with Realterm software
    a. Open Realterm software on MUMM_LOG_PC (see Figure 114)
    b. Go to Port, use port: 192.168.1.95:7200

c. Select “Change”
d. Go to Capture, select output folder and select “Start overwrite”
e. Compare the data string of the output with the data string from TCP log files (look for the data strings corresponding to the Licor sensor)

7. If the data strings are not similar and the settings cannot be changed using the GHG software (via Ethernet or Serial RS232), an embedded software reset might be required
a. Open the folder QMS\QA_Follow-up\Backup\Licor\downgrade\LI7200_embedded-8.0.0
b. Select Update7x00.exe
c. In case firewall opens, choose: ”allow access”
d. Select the instrument (191.168.95 port 7200)
e. Click start
f. Do not disconnect from the network during the process!

8. In case this did not solve the issue either, the sensor needs to be shipped to Catec for inspection

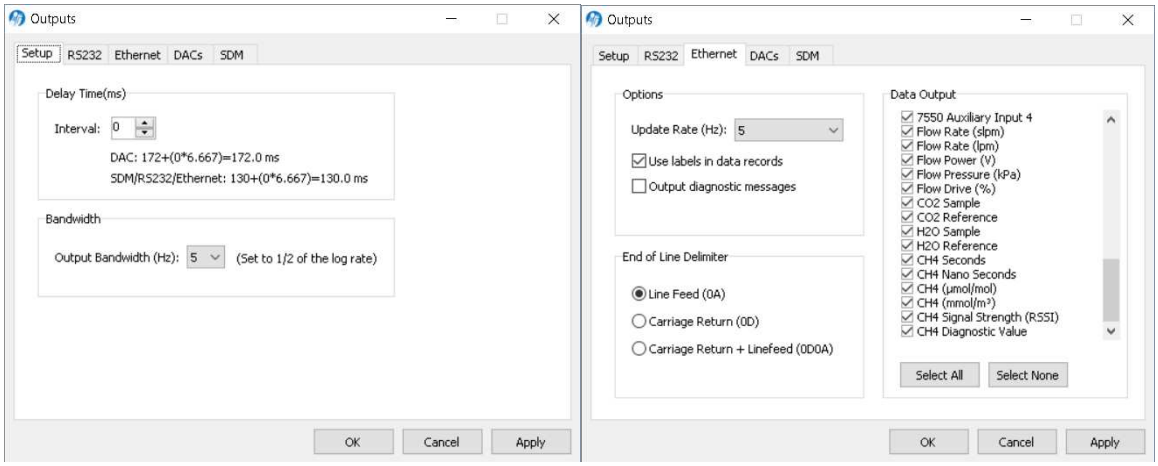


Figure 108 Output settings of Licor

Note that in case the uploading of configuration files and/or read out of the data on Realterm via Ethernet is not working, a serial connection can be used instead. A RS232 serial cable (Licor Turck serial cable 392-10268) can be installed in the sniffer sensor and connected to the MUMM_LOG_PC via the Licor Serial Converter (see image 62), this serial cable is equipped with a circular female 8-pin connector and DB9 female RS232 connector. The circular connector is connected to the connector panel, to use this serial connector an additional ribbon cable needs to be installed between the connector panel and the Licor 7550 unit (Harwin M50-9112042). The procedure for changing the settings or reading out the data is similar to the Ethernet connection with the difference that in this case the connection to the sensor with the GHG software is done via the Serial tab (after launching of the GHG sensor), the COM port can be identified in the Windows Device Manager (when connected a new COM port will be displayed). The same COM port can be used to read out the data with the Real term software (note that standard not all data labels are selected for the Serial output).



Figure 109 Connection to the LICOR sensor using serial cable

7.3. SO2 issues

In case the SO2 gives unreliable or non-stable readings. Diagnostics should be checked. Follow the maintenance procedures described under 6.1.2 THERMO 43i TLE. In case the diagnostics show a faulty component or bad parameter, Fabricom or FluxSense can be contacted to solve the issue. In case no problems are observed with the diagnostics and the readings (SO2 and Background) are normal with reference gasses, the problem is software related, to solve the issue the SSD of the MUMM_LOG_PC can be changed (see 6.1.5 MUMM_LOG_PC), make sure to back up the IGPS folder before doing this exchange to provide detailed information about the issue to FluxSense.

7.4. Airflow or pressure issues

In case the airflow is below the 5l/min (to be observed during the calibration), there might be a problem with either the Bronkhorst flowmeters, tubing or the KNF air pump.

SOP 2.29. Airflow trouble shooting

1. Check external tubing, connect Gas cylinder straight to the gas inlet on the sniffer
2. If normal airflow is observed, an obstruction is likely present in the tubing to the pitot-tube
3. In case this is not the case open sniffer (see 6.1 Internal sniffer sensor components)
4. Check visual all internal tubing for obstructions or leaks (see leak test in 6.4 External Tubing)
5. Replace the filters, even when they seem to be clean (see 6.2 F)
6. In case a visual inspection of the tubing and replacement of the filters did not solve the issue, check flow when connecting gas cylinder straight to the air pump (disconnect both in and outlet of the air pump, start with the output first). In case the same low flow rate is observed, the air pump needs to be inspected
7. In case a normal flow (10-30l/min) is observed the issue is not related to the air pump .
8. Check the Bronkhorst regulators using the FlowDDE and Flowplot software
    a. Open FlowDDE on MUMM_LOG_PC (see Figure 110)
    b. Open communication (COM4)
    c. Check Flow-Bus configuration
        - DFMFC (Flow Controller) should have 75% for Measure and Setpoint.
        - DEPC (Pressure Controller) should have 89% for Measure and Setpoint
    d. Make log file, compare parameters with previous log files, in case parameters are not normal, contact FluxSense to reset parameters or configuration
9. To view both pressure and flow
    a. Open Flowview
    b. Channel 1 will open (flow)
    c. Select advanced
    d. Open another window to view channel 2 (pressure)
    e. Check if pressure % is in line with setpoint
    f. When in flight an unstable pressure is observed (<150ft), lower pressure with 5-10%
    g. Check if flow is stable with new pressure
    h. Check if pressure is still within range for the Thermo sensor
    i. A full new hardware calibration is needed

Note: when Flowview is opened when FlowDDE is not running, an error is displayed and the Flowview need to be reset with the specific tool (on Desktop)

SOP 2.30. To monitor flow

1. In case parameters and configuration are normal check parameters with FlowView
    a. With FlowDDE running
    b. Open Flow View
    c. Check Channel 1 (Flow)
        - Open advanced settings
        - Check set (%)
    d. Check Channel 2 (Pressure)
        - Open advanced setting
        - Check set (%)
2. Use Flowplot to plot the evolution of the flow
    a. Connect Sniffer HDMI to HDMI display (Flowplot does not visualise in 640x480 view on VGA)
    b. Open Flowplot on MUMM_LOG_PC (see Figure 112)
    c. Compare plot with previous plots
3. In case the plots are not normal, the Bronkhorst regulators need to be calibrated (to be done by VMM)
4. In case the plots are normal or the calibration of the flowmeters did not solve the issue, an obstruction might be present in the Licor or Thermo sensor and need to be inspected. The Thermo sensor should be inspected by Fabricom first, before removing the Licor sensor and shipping the sensor to Catec.

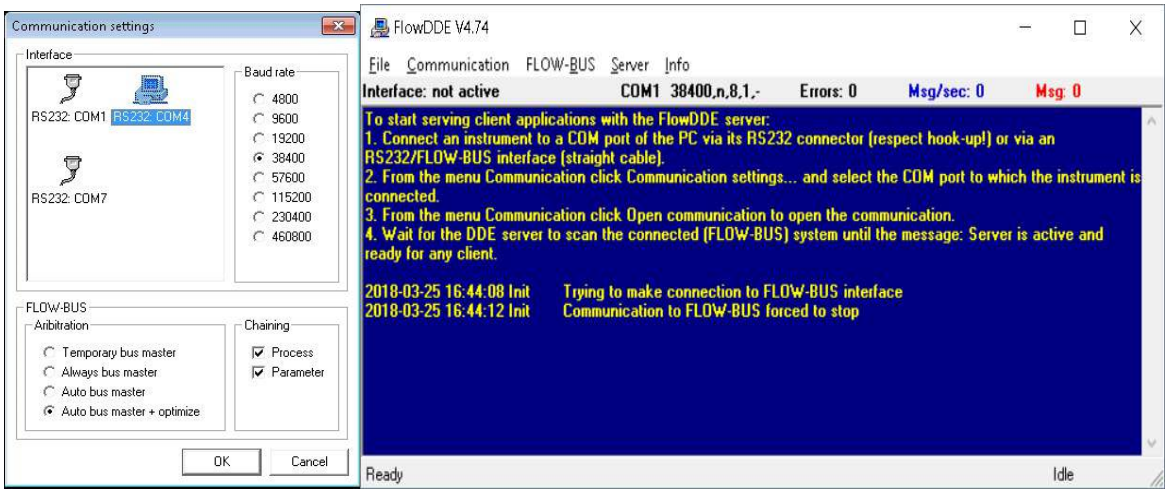


Figure 110 FlowDDE software

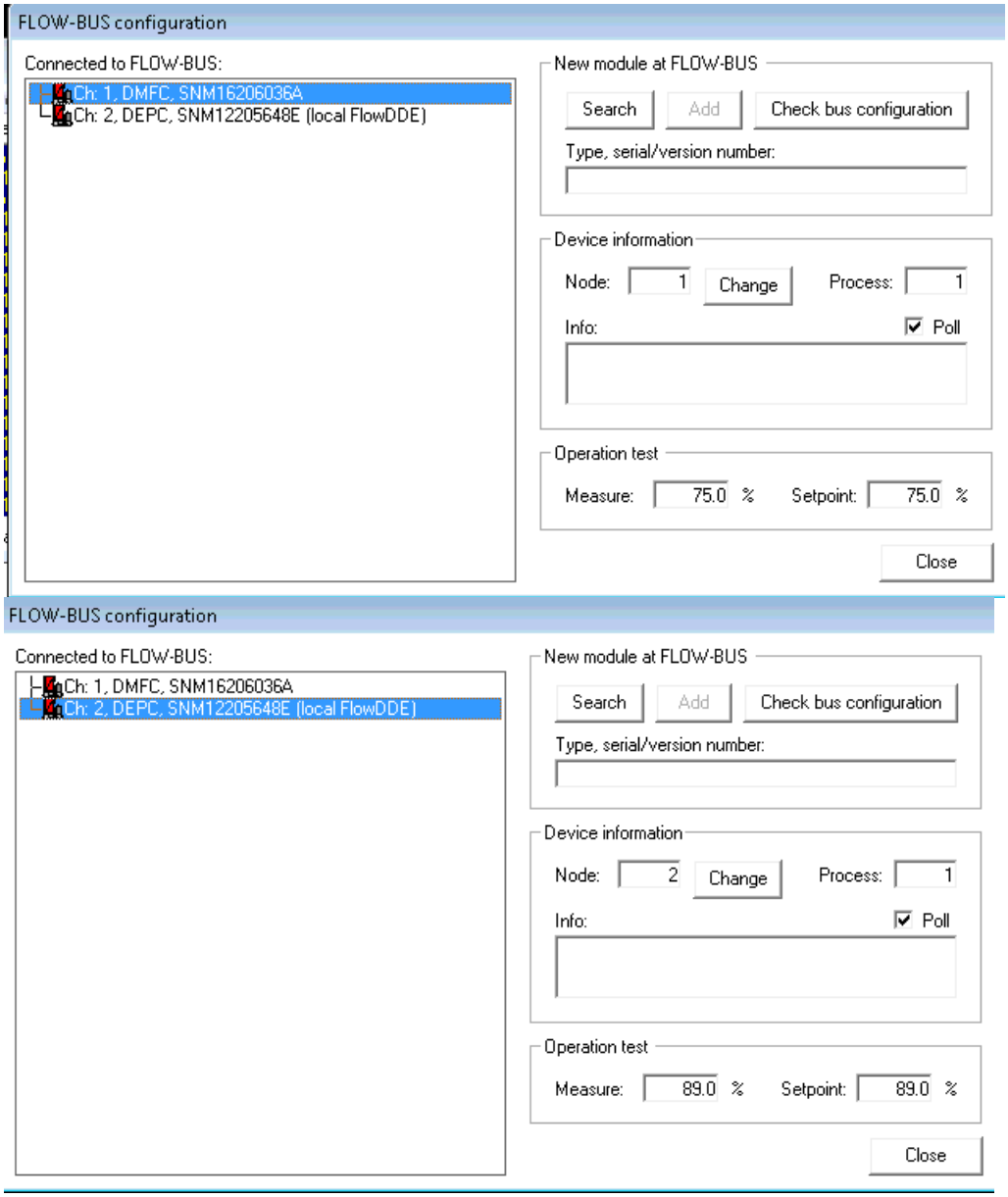


Figure 111 Flow Controller and Pressure controller configuration

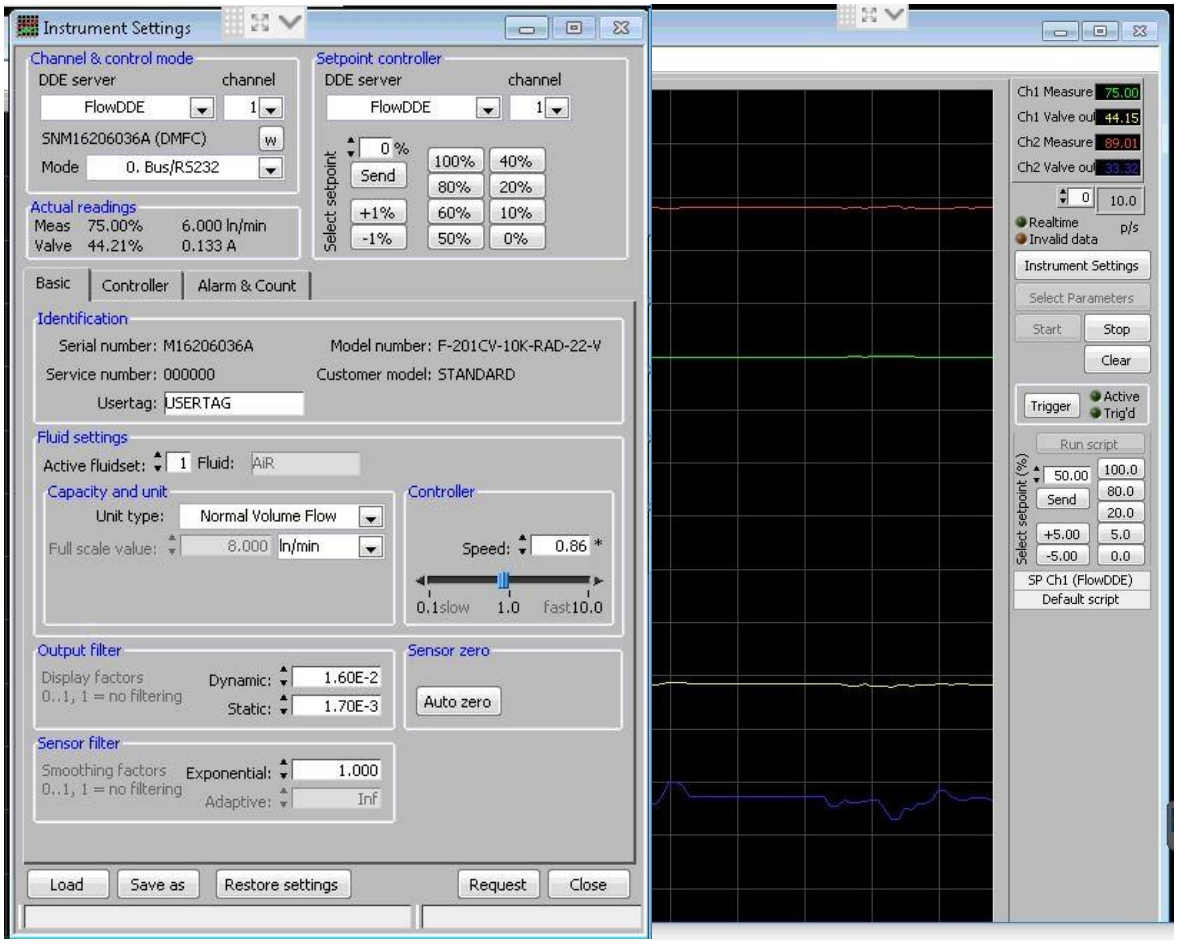


Figure 112 Flowplot

7.5. Problems with the MUMM_LOG_PC

In case the IGPS Present software does not open automatically on the MUMM_LOG_PC after booting, the sniffer needs to be installed in the aircraft with all cables and covers connected (especially the HDMI cable needs to be carefully inspected), the sniffer needs to be rebooted until the IGPS software starts again, several reboots might be required.

In case a MUMM_LOG_PC does not start automatically, check the Cockpit display to see the BIOS setup, connect Keyboard and mouse if necessary to the USB port. Reboot afterwards

If a drive problem or significant software issue is observed, the SSD can be replaced with the backup drive (see 6.1.5 MUMM_LOG_PC)

7.6. Problems with AIS+GPS receiver

SOP 2.31. Troubleshooting for AIS+GPS receiver

1. Check cabling to the ASP Connector panel
2. In case of AIS issues, it is advised to test one of the other 2 VHF antennas
3. In case of GPS issues or in case no AIS data is received with neither of the antennas, inspect data output
    a. Open Realterm on MUMM_LOG_PC
    b. Go to Port

   c. Select port 192.168.1.110:10001
   d. Select “Change”
4. In case data is received on the Realterm window but not on the AIS present, the issue is software related and can be solved by replacing the Hard drives of the MUMM_LOG_PC (see 6.1.5 MUMM_LOG_PC and 7.5 Problems with the MUMM_LOG_PC)
5. In case no data is observed, Open Sniffer (see 6.1 Internal sniffer sensor components) and check wiring (power and signal) visually, replace damaged wiring (to be done by FluxSense)
6. If no cable problems are observed, connect external Ethernet cable straight from the receiver to an external PC
7. Repeat step 3 with Realterm on external PC
8. In case data is received on the external PC, the Ethernet hub or Ethernet wiring might be malfunctioning and should be inspected further or replaced completely
9. In case no data is observed on the external PC either, replace the SLR200NG unit
10. If GPS problem is persistent, replace GPS antenna (to be done by ASP)

7.7. Problem with Thunderbolt dock

The Thunderbolt dock is connected to the sniffer using ethernet. When the laptop is not able to connect to the sniffer using the Thunderbolt do following steps:

SOP 2.32. Troubleshooting docking station

1. Is the laptop still charging?
2. If yes than the connection might be in the Ethernet settings of you Thunderbolt connection
   a. Go to network settings
   b. Go to Change adapter options
   c. Go to Ethernet x (the connection of your Thunderbolt)
   d. In case this is not present check the cabling (see step b)
   e. In case present,
      - go to settings (in admin mode)
      - Select Internet Protocol 4 (TXP/IPv4)
      - Check if your IP address is correct
3. If no, this means either the Thunderbolt is no powered or the cable is not plugged in in the docking station
   a. Open the front panel of the console
   b. Check cable connection to the docking station

7.8. Problem with Arinc info

In case no wind information is available for the IGPS software, the plumes will all be observed in the wake of the vessel. If this is observed in flight, the best thing to do is to manually add the wind information (from Medusa) in the IGPS software (in this case, the “use live wind” information check box, must be unchecked from all clients and the MUMM_LOG_PC). The issue can be checked after flight.

SOP 2.33. Troubleshooting ARINC

1. After full shutdown: disconnect the Arinc connecter and reconnect the connector on both the sniffer as the ASP connector panel (ASP-CON-6) (use pressure)

2. Reboot the system and avionics
3. During the next flight: check if data is available in ARINC-Freq tab under settings of the IGPS software and on the MEDUSA system on the console during flight or with all avionics enabled
4. If no data available on the MEDUSA system, the issue is related to the avionics or wiring, and has to be solved by ASP
5. If no data is available on the AIS present but on the MEDUSA system, check wiring from ASP-CON-06 to J251
6. If cabling is correct, use Realterm to check if data is available
    a. Open Realterm on MUMM_LOG_PC
    b. Go to Port
    c. Select port 192.168.1.121:9760
    d. Select “Change”
7. In case not data is available
8. Demount sniffer, turn sniffer upside-down and open Sniffer cover (see 6.1 Internal sniffer sensor components)
9. Reconnect all cabling and switch on avionics and sniffer
10. Check signal and power wiring and connections visually
11. Read out power to ARINC board
    a. Should be 24 Volt
    b. In case of power issue, replace the power converter (to be done by FluxSense)
12. Read out power to Ethernet converter (should be 5 volt)
    a. Should be 5 Volt
    b. In case of power issue, replace the power converter (to be done by FluxSense)
13. Inspect signal wiring
    a. Connect an external RS232 cable to a PC using a RS232 to USB converter and connect to the ARINC board
    b. Check in device management for the correct COM port (will appear after connecting the USB converter)
    c. Open Realterm, go to “Port”
    d. Select COM port and baud-rate
    e. Select “Change”
    f. Check for incoming data, this will appear in the main window
14. In case no data is observed or the data is scrambled, the ARINC board needs to be inspected or replaced (to be done by FluxSense)
15. In case the data is coming in normally, the issue can be software related or related to the signal cabling
16. Check the Ethernet cable:
    a. Reconnect the RS232 to Ethernet converter
    b. Replace the Ethernet cable from the RS232 converter with standard Ethernet cable to Ethernet port of the PC
    c. Open real term, go to “Port”
    d. Use the port 192.168.1.(port)
    e. Select “Change”
    f. Check for incoming data

17. If no data is received, the problem is related to the RS232 converter and should be replaced by FluxSense
18. If data is received, replace the Arinc Ethernet cable on the Ethernet hub by the external Ethernet cable
19. Reboot the sniffer sensor and check for incoming data using Realterm on the MUMM_LOG_PC and the AIS present software
20. In case data is received on the Realterm window but not on the AIS present, the issue is software related and can be solved by replacing the Hard drives of the MUMM_LOG_PC (see 6.1.5 MUMM_LOG_PC and 7.5 Problems with the MUMM_LOG_PC)
21. In case the data not received on the real term window and the AIS present, replace the Hard drive (see 18), if this does not solve the issue, it is most likely related to a hardware issue with the Ethernet hub, and the Ethernet hub should be replaced (to be done by FluxSense)

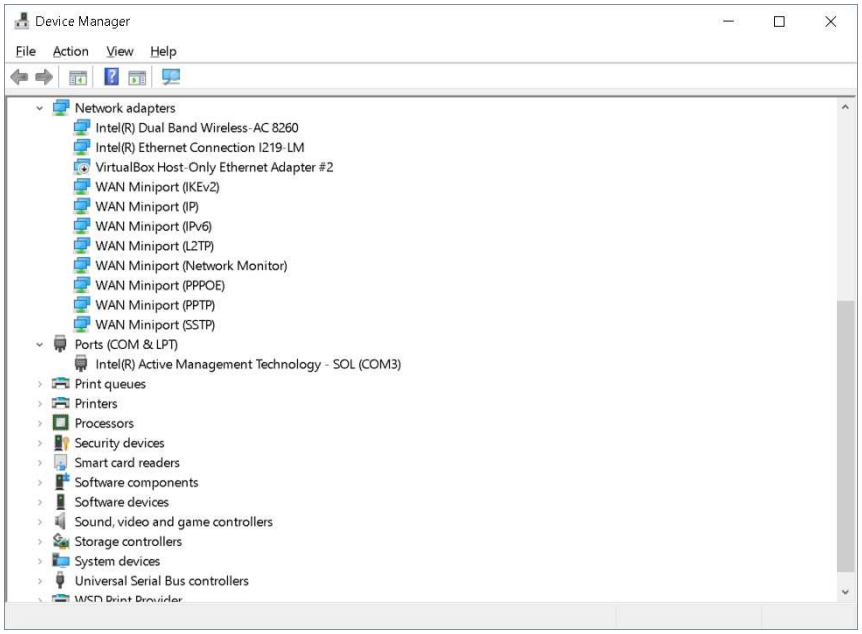


Figure 113 Device manager with COM ports

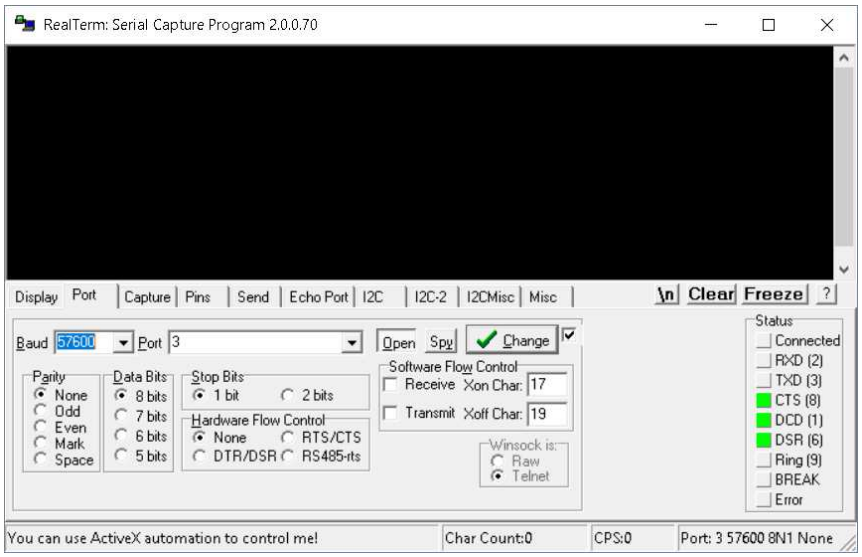


Figure 114 Realterm window

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ANNEX A - PARTLIST

Table 12 Detailed Partlist of internal component

PART	Model/Description	Manufacturer	Serial nr	Voltage	Amp (@28V)	Other specs
Thermo 43i TLE	SO2 sensor head AB9932	Fisher	THE-110838-00 (102311-03)	115 V	5.1 A (real: 1.25 A)	
	Power converter - Model LFWLT150-1003-K	Fisher	EQ1-D-Q227-1433			
	Front panel	Fisher				
	Ribbon cable		32200-000017-RS			
	Motherboard	Fisher				
	Measurement interface board					
	Lamp	Fisher				
	Photoconductor	Fisher				
	HV					
	Input board					
	Pressure sensor	Fisher	102272-03			
		Fisher	?-273-00			
		Fisher	?			
LICOR 7200RS	CO2 sensor U7211	Bioscience	72-1-0822	24 V	1.25 A (real:0.6 A)	
LICOR 7550	Controller	Bioscience				
	Ribbon cable	Bioscience	9972-056			
	Pressure regulator	Bioscience	PZ485			
	Serial cable	Bioscience (Trunck)	392-10268			
	Serial to USB	Bioscience	6400-27			
M50 Archer	Ribbon cable	Harwin	M50-9112042			
HBS 200-3-2,5	Regulator CO2	Airliquide		-	-	200 to 0.1-3 bar
HBSI 200-1-2	Regulator SO2	Airliquide		-	-	200 to 0.05-1 bar
Azote	Flow-meter	Dynaval		-	-	1-15 l/min
	Regulator CO2	Messer				
Rotameter	Overflow	Brooks	2510 A 2A13 S N VT	-	-	0-1 l/min
ARCO Filter	Filter	PAL	4003	-	-	PTFE 1µm, 50 mm

PART	Model/Description	Manufacturer	Serial nr	Voltage	Amp (@28V)	Other specs
T 1/4"	t-connection	Swagelok				
Fitting 1/4"	Ferrule connection SS: Steel,	Swagelok	SS-400-SET			
	NY Nylon		NY-400-SET			
Fitting 3/8”	Ferrule connection	Swagelok	SS-600-SET			
	SS: Steel		NY-600-SET			
	NY: Nylon					
Valve 1/4"		Swagelok				
Feed Through 3/8” to 1/4"	Female-female	Swagelok	SS-400-61-4 or SS-600-61-4			
Reducer 1/4” -3/8”	Female-female	Swagelok	SS-400-R-6			
Straight 1/4”	Male-Male	Swagelok	SS-T6-S-065-6ME			6m
3/8 tube	Steel tubing	Swagelok	SS-T6-S-065-6ME			
1/4 hose	Flexible tubing	Swagelok				
1/4” Straight union	Female-female	Swagelok	SS-400-6			
1/4" Toggle valve	Female-female	Swagelok	SS-1GS4			
1/4" Union Elbow	Female-female	Swagelok	SS-400-9			
1/4" Union T-connection	Female-female	Swagelok	SS-400-3			
1/4" Bulkhead retainer	For feed through	Swagelok	SS-602-61F			
1/4" Nut ferrule SS	Nut for all 1/4" connectors	Swagelok	SS-400-SET			
3/8" Nut ferrule SS	Nut for all 3/8" connectors	Swagelok	SS-600-SET			
3/8" Nut ferrule NY	For removable connection to pito	Swagelok	NY-600-SET			
Buffer	Buffer	Chalmers				PVC tube, Diameter: 10cm length: 10 cm

PART	Model/Description	Manufacturer	Serial nr	Voltage	Amp (@28V)	Other specs
EL-FLOW F-201CV	Flow controller	Bronkhorst	M16206036A	24V	0.21 A (real: 0.2 A)	25ln/min 20ln/min 1000mbar
EL-PRESS P-502C F-004AC	Pressure regulator	Bronkhorst	M12205648E			
			M12205648C			
Inverter	SS120	KGS		28VAC-115VDC	1.10 A (real: 1)	Max 10.3 A output or 50A@28V 87% efficiency
5V Converter	Power converter (5 V)	Traco Power	TMP 15105C	100-240VAC to 5 VDC	Max 0.13 A (real: 0.05)	max 3 A output – 75% efficiency
12V Converter	Power converter (12 V)	Traco Power	TMP 30112C	100-240VAC to 12 VDC	Max 0.21 A (real: 0.03	max 2.5 A output - 79% efficiency
24V Converter	Power converter (24 V)	Traco Power	TMP 30124C	100-240VAC to 24 VDC	Max 0.21 A (real: 0.15 A)	max 1.25 A output - 79% efficiency
PM26726-838	N 838.1 KNDC-B	KNF	9315084	24VDC	2.4A (real: 1.4 A)	Pmax: 50 kPa (0.5 bar)
PJ44313-838.1.2	N 838.1-2 KNDC-B	KNF		24VDC	5A max (real 3.6A)	Pmax: 50 kPa (0.5 bar)
PM32615-N022	N022 ATE	KNF		110VAC	7.8A max (real 5A)	Pmax: 2.5 bar
ZMS100-24	Power converter (24 V)	TDK Lamda		24VDC	100Watt max 4.16A	
Ethernet hub (1)	Ethernet HUB		MXU85A0001	5V	0.17 A (real : 0.09 A)	
Serial to ethernet converter	RS232 to ethernet				0.17 A (real 0.06)	
Serial to USB converter	RS232 to USB			-	-	
SLR 200 NG	AIS/GPS Receiver	Comar	008-403	12V	0.17A (real: 0.05 A)	
Thunderbolt dock	Dock	Startech	TB3DK2DPPDUE	110V		
Thunderbolt cable	2m cable	Startech	TBLT3MM2MA			2m
Fans (large)	Fans (80mm)x3	NMB		115V	1:00 AM	9 W

PART	Model/Description	Manufacturer	Serial nr	Voltage	Amp (@28V)	Other specs
			3610PS-12T-B30-A00		(real: 0.85 A)	
Fans (small)	Fans (40mm)x8	Sunon	MF40060V1-000U-A99	5V	0.05 A (real: 0.04 A)	0.44W
Circuit breaker	Fuse 5A (x4)	Klixon		28V		
ZOTAC	Log PC	Zotac	Zbox Nano ID64	19 V	2 A (real: 0.7 A)	
Arinc Board	-	Olimex (Alta?)	-	12V	0.4A (real: 0.1 A)	
GPU	External power supply	Start Pac	53050	90-240VAC to 28.5VDC	0.2A (@220V)	Max 50A
External battery	2x internal 12V batteries	Sonnenschein	A52A /10S	12v		10Ah
Laptop	Client stations	Lenovo	T460s	20V	2.1A (real: 0.5 A)	
M3x10 T10	Sunken head SS screws casing					
M2.5x10 HEX 2.5	Allen SS screws on connectors					
M5 Locknut	Internal components and wiring					
M7 and M8 locknut	AIS+GPS and LOG_PC frame					
AIS antenna	FM Antenna	Cobham	CI 292-23			135-174 MHz
GPS antenna	LNA GPS receiver	Cobham	CI 401-220	12V	0.035A	
Sniffer power relay	T92 series	TE	T92P11D22-24			

ANNEX B - INTERFACE CONNECTION DOCUMENTATION

Table 13 Interface connection documentation

Connector design.	Signals			Pin	Signal	Connector		Cable type
						Equipment (chassis)	Cable	
J221 J233(4)	Ethernet	Pair Tx1	TX1+	1	Ethernet	RJFTV21G (Mfg. Amphenol)	RJFTV6MG (Mfg. Amphenol)	100 Ohm Shielded twisted pair & Shielded Cable. SPEC55 or ETFE
			TX1-	2				
		Pair Rx1	RX1+	3				
			RX1-	6				
J233(4)	115VAC			A	Pin size 20 115V AC 60 Hz (max 13 A)	D38999/ 20WB5SN (shell 11)	D38999/ 26WB5PN (Mfg. Amphenol, Souriau, other) + Back shell (Mfg. Glenair, other)	SPEC55 or other airframe wire (connections max7.5 A) AWG14 (10ft Max 70 A)
	115VAC return			B				
	DC 5V + Ethernet			C	5V (Ethernet hub)			
	DC 5V Return (DC 20 V + Docking station)			D				
	Chassis Ground (Chassis Ground, Return 5 and 20 V)			E				
J211	DC INPUT +28VDC			A	28V DC (max80 A)	MS3102E24-12P (shell 24)	MS3106E24-12S (Mfg. Amphenol, other)	SPEC55 or other airframe wire AWG12 (20ft max 26A)
	OUTPUT 115VAC			B	115V AC 60 Hz (max 23 A)			
	DC INPUT 28VDC RETURN			C	DC return			
	OUTPUT 115VAC Return			D	AC return			
	Remote ON/OFF (Connect to C for ON/ leave open for OFF)			E	DC (switch on flight deck)			
J231	Signal			Center	162 MHz AIS Antenna	N-Connector R191381000 (Mfg. RADIALL)	N-Connector Depends on cable	50 Ohm ETFE coax.
	Ground			Outer				
J241	Signal /+5V for LNA			Center	1.2-1.6 GHz GPS Antenna	N-Connector R191381000 (Mfg. RADIALL)	N-Connector Depends on cable	50 Ohm ETFE coax.
	Ground			Outer				
J251	ARINC A			A	100kHz ARINC 429	D38999/ 20WF32PN (shell size 19)	D38999/26WF32SN (Mfg. Amphenol , Souriau, other) + Back shell (Mfg. Glenair, other)	Shielded twisted pair. SPEC55 or other airframe wire (connections max7.5 A)
	ARINC B			B				
	Pin 1-2 (J1) Ground			C	Thermo panel remote connection Pin size 20 (max 5 A) max length 1m			
	Screen ARINC			D				
	Pin 3 (J1) LCLK			E				
	Pin 4-5 (J1) Ground			F				
	Pin 6 (J1) LLP			G				
	Pin 7 (J1) LFLM			H				
	Pin 8 (J1) LD4			J				
	Pin 9 (J1) LD0			K				
	Pin 10 (J1) LD5			L				
	Pin 11 (J1) LD1			M				
	Pin 12 (J1) LD6			N				
	Pin 13 (J1) LD2			P				
	Pin 14 (J1) LD7			R				

Connector design.	Signals	Pin	Signal	Connector		Cable type
				Equipment (chassis)	Cable	
	Pin 15 (J1) LD3	S				
	Pin 16 (J1) LCD Bias Voltage	T				
	Pin 17 (J1) +5V	U				
	Pin 18-19 (J1) Ground	W				
	Pin 20 (J1) LCD_ONOFF	X				
	Pin 21 (J1) Keypad Row 2 Input	Y				
	Pin 22 (J1) Keypad Row 1 Input	Z				
	Pin 23 (J1) Keypad Row 4 Input	a				
	Pin 24 (J1) Keypad Row 3 Input	b				
	Pin 25 (J1) Keypad Col 2 Input	c				
	Pin 26 (J1) Keypad Col 1 Input	d				
	Pin 27 (J1) Keypad Col 4 Input	e				
	Pin 28 (J1) Keypad Col 3 Input	f				
	Pin 29-32 (J1) Ground	g				
	Pin 33 (J1) +24 V	h				
	Pin 34 (J1) +24 V	j				
J261 Pumps PWR	28VDC Input	A	28V DC pin size 12 (Max 41A)	62GB12E1402PN (shell 14)	62GB16F1402SN (Shell 14)	AWG12 (6 ft Max 35 A)
	28VDC Return	B				
J271 USB	USB signal (5volt)	USB female	-	Switchcraft EHUSBAABX	USB male (both sides)	Shielded USB
J281 HDMI	HDMI Signal	HDMI female	-	Switchcraft EHHDMI2B	HDMI male (both sides)	Shielded HDMI
J291 Serial BC	RX	1	BC serial to ethernet converter	Serial male	Serial female	AWG20
	TX	2				
	-	3				
	-	4				
	Ground	5				
	-	6				
	-	7				
	5V input BC	8				
	5VDC Return BC	9				
J213 NOx power	115VAC	A	Pin size 20 115VAC (max 7.5 A)	D3899920WA98PN (shell size 9)	D3899926WA98SN Or TV06RW-9-98S (shell size 9) backshell M85049/38-9W	AWG16 (20ft max 40A)
	115VAC return	B				
	Ground not used	C				
Power input AC	DC INPUT +28VDC	A	28V DC pin size 12 (Max 41A)	62GB12E1402SN (shell 14)	62GB16F1402PN (shell 14)	SPEC55 or other airframe wire AWG12 (6 ft Max 35 A)
	DC INPUT 28VDC RETURN (ground)	B				

Connector design.	Signals	Pin	Signal	Connector		Cable type
				Equipment (chassis)	Cable	
Power input GPU	DC INPUT +28VDC	A	28V DC pin size 12 (Max 41A)	62GB12E1402PN (shell 14)	62GB16F1402SN (Shell 14)	SPEC55 or other airframe wire AWG12 (6 ft Max 35 A)
	DC INPUT 28VDC RETURN (ground)	B				
Power output	DC Output +28VDC	A	28V DC pin size 12 (Max 41A)	62GB12E1402SN (shell 14)	62GB16F1402PN (shell 14)	SPEC55 or other airframe wire AWG12 (6 ft Max 35 A)
	DC output 28VDC RETURN (ground)	B				
Battery to EPC	28VDC	A	28V DC pin size 16 (Max 22A)	62GB12E1203SN (Shell 12)	62GB16F1203PN (Shell 12)	SPEC55 or other airframe wire AWG12 (6 ft Max 35 A)
	Unused	B				
	28VDC return	C				
J311 EPC sniffer	28VDC input	A	28V DC pin size 16 (Max 22A)	62GB12E1203SN (Shell 12)	62GB16F1203PN (Shell 12)	SPEC55 or other airframe wire AWG12 (6 ft Max 35 A)
	28VDC output to Pumps	B				
	28VDC return (Ground)	C				
J411 Extern Ethernet hub (power)	DC Input +5V	A	Pin size 20 5VDC (max 7.5 A)	D3899920WA98PN (shell size 9)	D3899926WA98SN TV06RW-9-98S (shell size 9) backshell M85049/38-9W	AWG16 (20ft max 40A)
	(unused)	B				
	DC input Return (ground)	C				

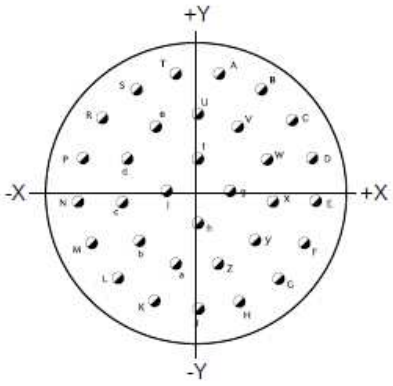
Table 14 Wiring connections

	Connecting Units		Connects to			
Wire #	Unit1	Unit2	Term 1	Term 2	Type of signal	Nom Val
401	J211	Opto Coupler	4	Pin E		28V DC
402	Opto Coupler	Inverter	2	Pin E		28V DC
403	Opto Coupler	50 A Circuit breaker	1	N/A	Control	28V DC
404	50A fuse	Inverter	Pin 1	Pin A	External Power	28V DC
405	J211	50A Circuit breaker	Pin A	Pin 2	External Power	28V DC
406	J211	Inverter	Pin C	Pin C	External Power	GND 28V DC
407	Circuit breaker 1 5A	Inverter	Term 2	Pin B	AC Power	115V AC L
408	Circuit breaker 1 5A	J211	Term 1	Pin B	AC Power	115V AC L
410	Opto Coupler	Opto Coupler	Pin 1	Pin 3		28V DC
411	Circuit breaker 1	Circuit breaker 2	Term 2	Term 2	Power	115V AC L
412	Circuit breaker 2	Circuit breaker 3	Term 2	Term 2	Power	115V AC L
413	Circuit breaker 3	Circuit breaker 4	Term 2	Term 2	Power	115V AC L
414	TMP15105C	TMP30112C	AC	AC	Power	115V AC L
415	TMP15105C	TMP30112C	AC	AC	Power	115V AC N
416	TMP30124C	TMP15105C	AC	AC	Power	115V AC L
417	TMP30124C	TMP15105C	AC	AC	Power	115V AC N
418	Connector Power	Connector Block 1 Row1		422	Power	115V AC N
419	Connector Power	Connector Block 1 Row 3		421	Power	115V AC L
420	Circuit breaker 1	Connector Block 1 Row 3	Term 1		Power	115V AC L
421	TMP30124C	Connector A	AC	419	Power	115V AC L
422	TMP30124C	Connector A	AC	418	Power	115V AC N
423	Ethernet Switch	TMP15105C	+Vout	Term 1	Power	5V DC
424	Ethernet Switch	TMP15105C	-Vout	Term 2	Power	GND 5V DC
425	TMP15105C	Power Bridge	+Vout	431	Power	5V DC
426	TMP15105C	Power Bridge	-Vout	432	Power	GND 5V DC
427	TMP30112C	Power Bridge	+Vout	433	Power	12V DC
428	TMP30112C	Power Bridge	-Vout	434	Power	GND 12V DC
429	TMP30124C	Power Bridge	+Vout	435	Power	24V DC
430	TMP30124C	Power Bridge	-Vout	436	Power	GND 24V DC
431	Power Bridge	Connector D	425	Term 1	Power	5V DC
432	Power Bridge	Connector D	426	Term 2	Power	GND 5V DC
433	Power Bridge	Connector C	427	Term 1	Power	12V DC
434	Power Bridge	Connector C	428	Term 2	Power	GND 12V DC
435	Power Bridge	Connector B	429	Term 1	Power	24V DC
436	Power Bridge	Connector B	430	Term 2	Power	GND 24V DC
437	Connector D	Block 2 Row 2	431	Any	Power	5V DC
438	Connector D	Block 2 Row 1	432	Any	Power	GND 5V DC
439	Connector C	Block 2 Row 4	433	Any	Power	12V DC
440	Connector C	Block 2 Row 3	434	Any	Power	GND 12V DC
441	Connector B	Block 2 Row 6	435	Any	Power	24V DC

	Connecting Units		Connects to			
Wire #	Unit1	Unit2	Term 1	Term 2	Type of signal	Nom Val
442	Connector B	Block 2 Row 5	436	Any	Power	GND 24V DC
449	Olimex Card	Block 2 R3			Power 0V	GND 12V DC
450	Olimex Card	Block 2 R4			Power +12V	12V DC
451	EthernetToRS232	Block 2 Row 1			Power 0V	GND 5V DC
452	EthernetToRS232	Block2 Row 2			Power +5V	5V DC
453	Log computer PSU – L	Block 1 Row 4			AC – Power L	115V AC L
454	Log computer PSU – N	Block 1 Row 5			AC – Power N	115V AC N
455	19V PSU	Log computer			Power 0V	GND 19V DC
456	19V PSU	Log computer			Power +19V	19V DC
457	AIS	Block 2 Row 5			Power 0V	GND 12V DC
458	AIS	Block 2 Row 4			Power +12V	12V DC
477	Connector FAN	Connector Block 1 Row 5	N		Power	115V AC N
478	Connector FAN	Connector Block 1 Row 4	~		Power	115V AC L
479	J291	Connector Block 1 Row 1	B		Power	115V AC N
480	J291	Connector Block 1 Row 6	A		Power	115V AC L
482	J291	Connector Block 1 Row 6	E			GND
485	Licor	Connector Block 2 Row 6			Power	24V DC
486	Licor	Connector Block 2 Row 5			Power	GND 24V DC
502	EthernetToRS232	Bronkhorst	4	4	Gnd	GND
503	EthernetToRS232	Bronkhorst	3	1	RS232 TX	RS-232 type
504	EthernetToRS232	Bronkhorst	6	6	RS232 RX	RS-232 type
560	EthernetToRS232				Gnd	
601	40 mm fan	Fan 2 conn	Black			GND 5V DC
602	40 mm fan	Fan 2 conn	Red			5V DC
603	40 mm fan	Fan 2 conn	Black			GND 5V DC
604	40 mm fan	Fan 2 conn	Red			5V DC
611	Fan 2 conn	Block 2 Row 1				GND 5V DC
612	Fan 2 conn	Block 2 Row 2				5V DC
4771	80 mm fan	80 mm fan				115V AC N
4772	80 mm fan	80 mm fan				115V AC L
4781	80 mm fan	80 mm fan				115V AC N
4782	80 mm fan	80 mm fan				115V AC L

	Connecting Units		Connects to			
Wire #	Unit1	Unit2	Term 1	Term 2	Type of signal	Nom Val
4904	PSU	SO2 Pump	0V	VO-	Power 0V	
4905	PSU	SO2 Pump	+Vout	VO+	Power +	
4906	Bronkhorst	Block 2 Row 5			Power 0V	GND 24V DC
4907	Bronkhorst	Block 2 Row 6			Power +24V	24V DC
4908	SO2 Connector	Block 1 Row 2			AC N	115V AC N
4909	SO2 Connector	Circuit breaker 4			AC L	115V AC L
4910	SO2 Connector	Block 1 Row 6			GND	GND
4911	PJ2	SO2	2	3	Power N	115V AC N
4912	PJ2	SO2	1	1	Power L	115V AC L
4913	PJ2	SO2	3	5	Power GND	115V AC GND
49042	Pump PSU	Block 1 Row 5			Power	115 AC N
49052	Pump PSU	Block 1 Row 4			Power	115 AC L
409A	J211	Block 1 Row1	D			115V AC N
409B	Inverter	Block 1 Row1	B	N/A		115V AC N
A	Interface Board	J251		A		
B	Interface Board	J251		B		

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Ctc	X	Y	Ctc	X	Y
A	+1.68	+8.97	T	-1.68	+8.97
B	+4.80	+7.75	U	0.00	+5.84
C	+7.26	+5.51	V	+3.15	+4.90
D	+8.76	+2.49	W	+5.31	+2.41
E	+9.07	-0.84	X	+5.79	-0.84
F	+8.15	-4.06	Y	+4.42	-3.84
G	+6.15	-6.73	Z	+1.65	-5.61
H	+3.30	-8.51	a	-1.65	-5.61
J	0.00	-9.12	b	-4.42	-3.84
K	-3.30	-8.51	c	-5.79	-0.84
L	-6.15	-6.73	d	-5.31	+2.41
M	-8.15	-4.06	e	-3.15	+4.90
N	-9.07	-0.84	f	0.00	+2.44
P	-8.76	+2.49	g	+2.44	0.00
R	-7.26	+5.51	h	0.00	-2.44
S	-4.80	+7.75	j	-2.44	0.00

Figure 115 J251

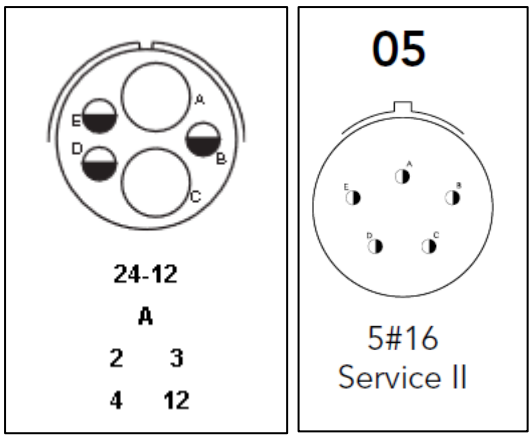


Figure 116 Connector on ASP-CON-06, GPU and external battery (Amphenol 62GB, size 14, 2 pins)

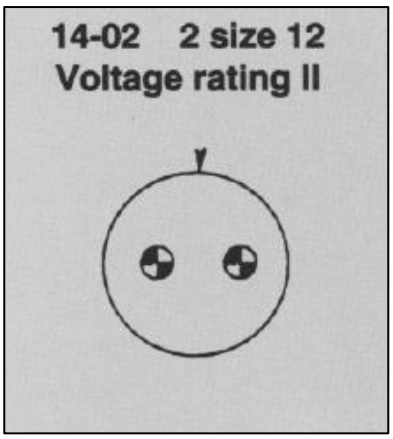


Figure 117 J211 (left) J233 right

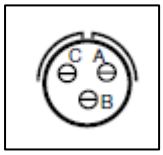


Figure 118 NOx Power connector (Amphenol 38999 series III, shell size 9, 3 pins)

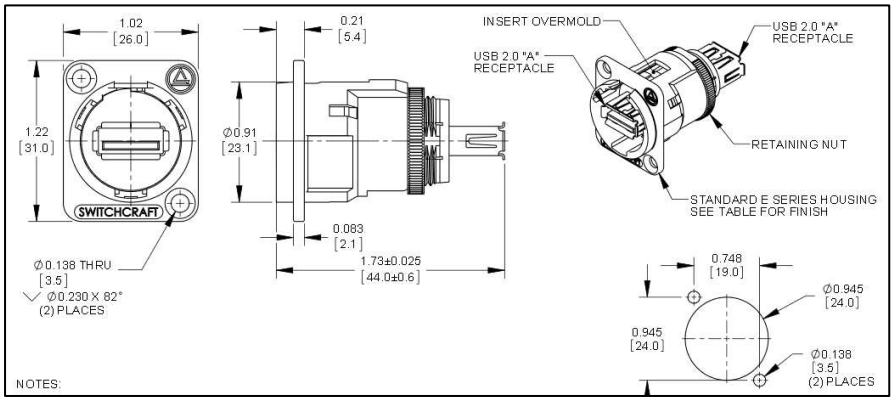


Figure 119 USB and HDMI connectors

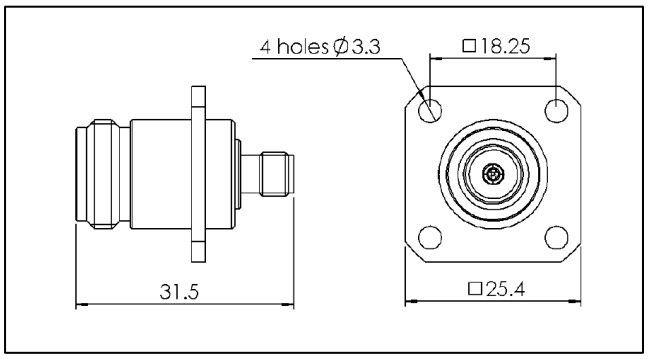


Figure 120 N-connector (RADIALL) used for AIS and GPS antennas (J231 and J241)

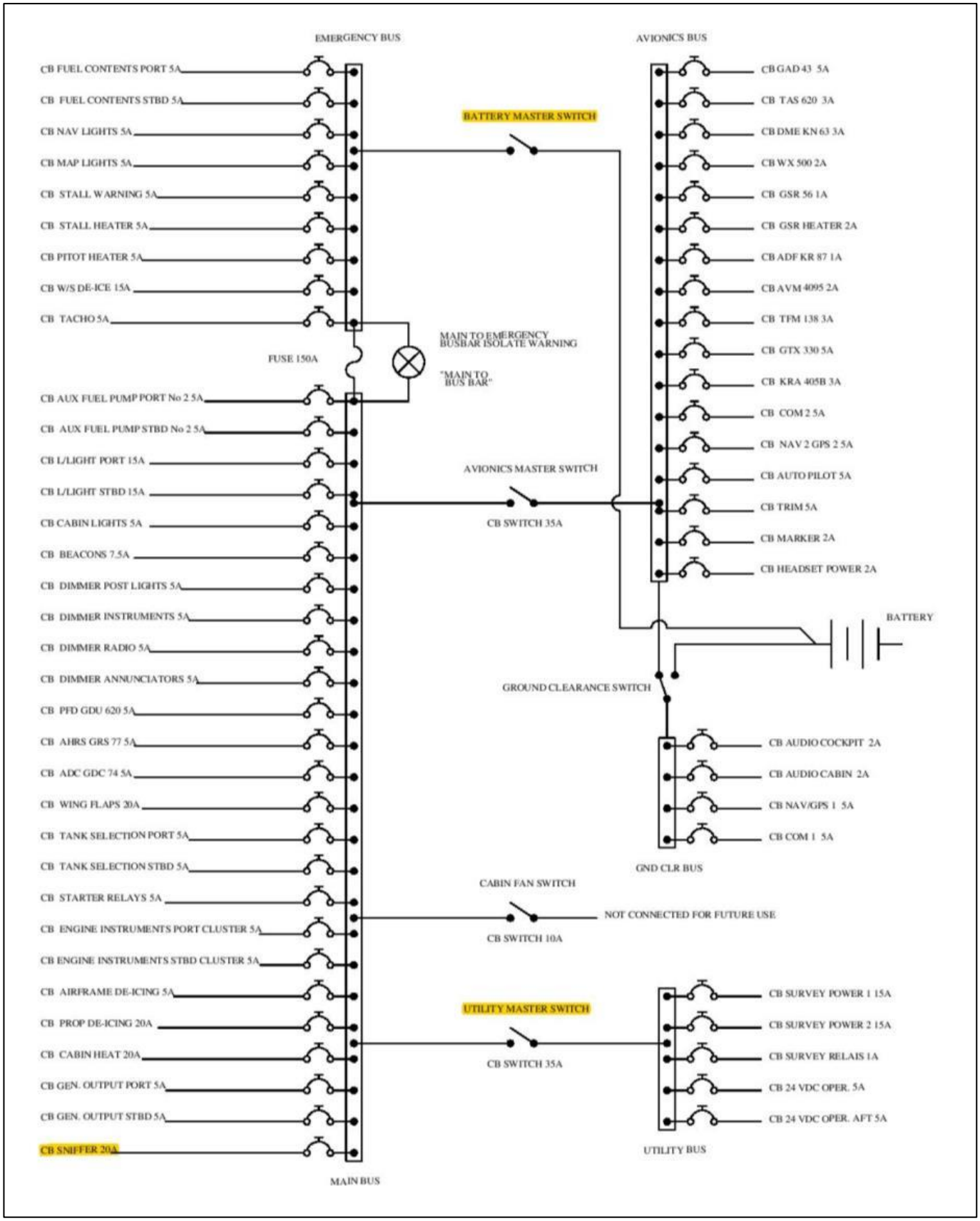


Figure 121 General aircraft power wiring diagrams with Sniffer circuit braker and Master Switch (marked)

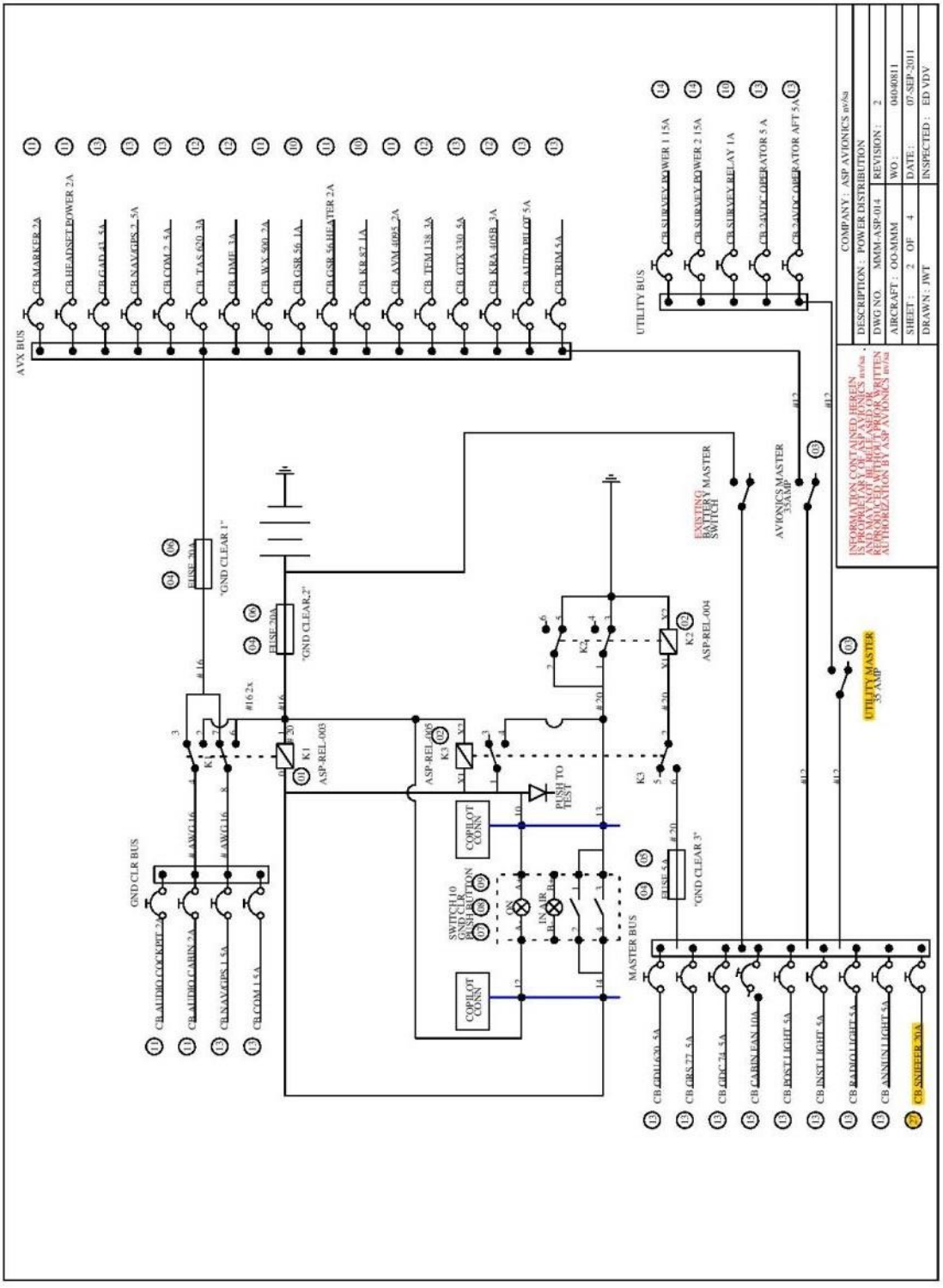


Figure 122 Wiring diagrams Survey Power

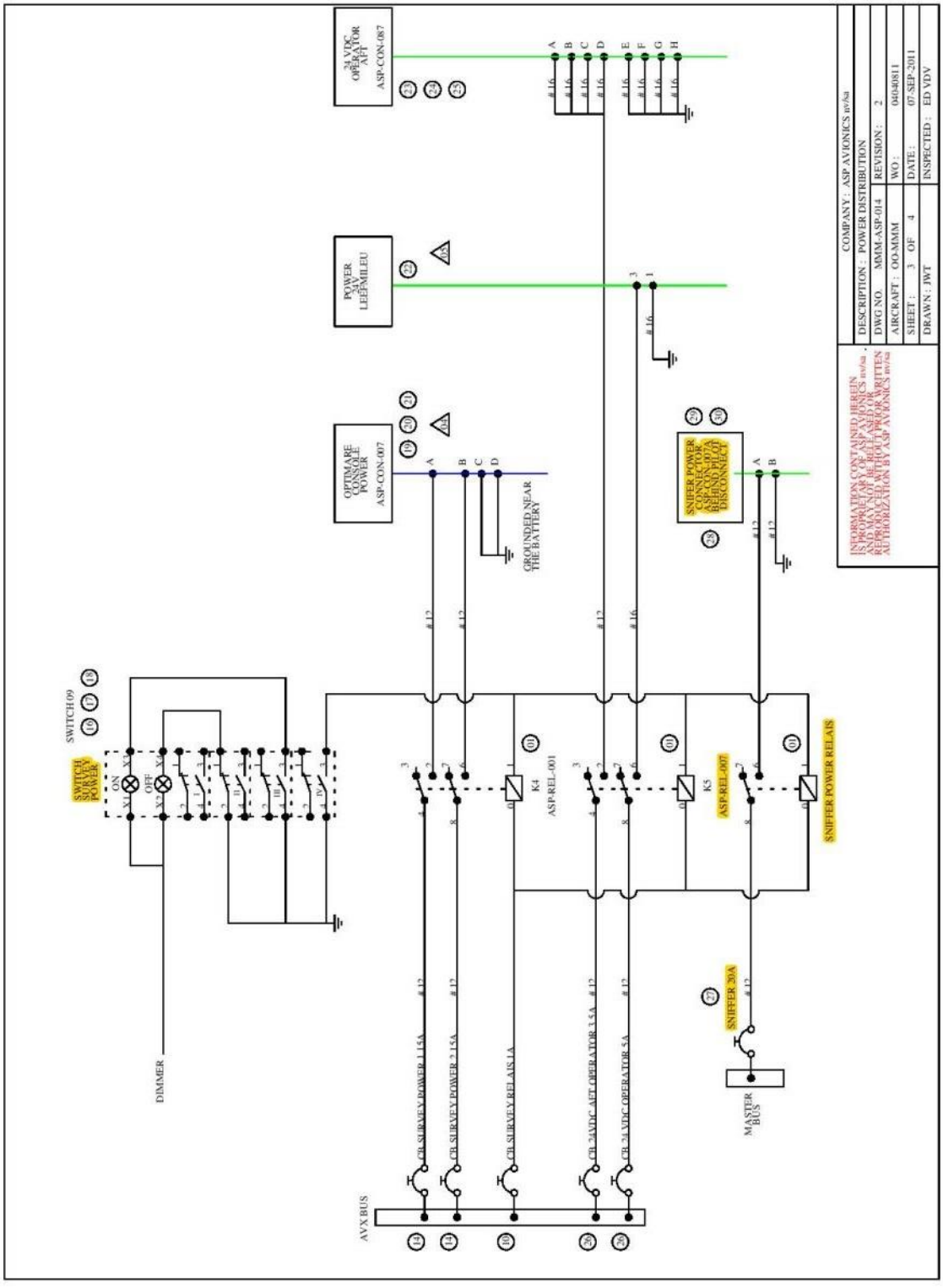


Figure 123 Sniffer Power Relay (T92P11D22-24) wiring

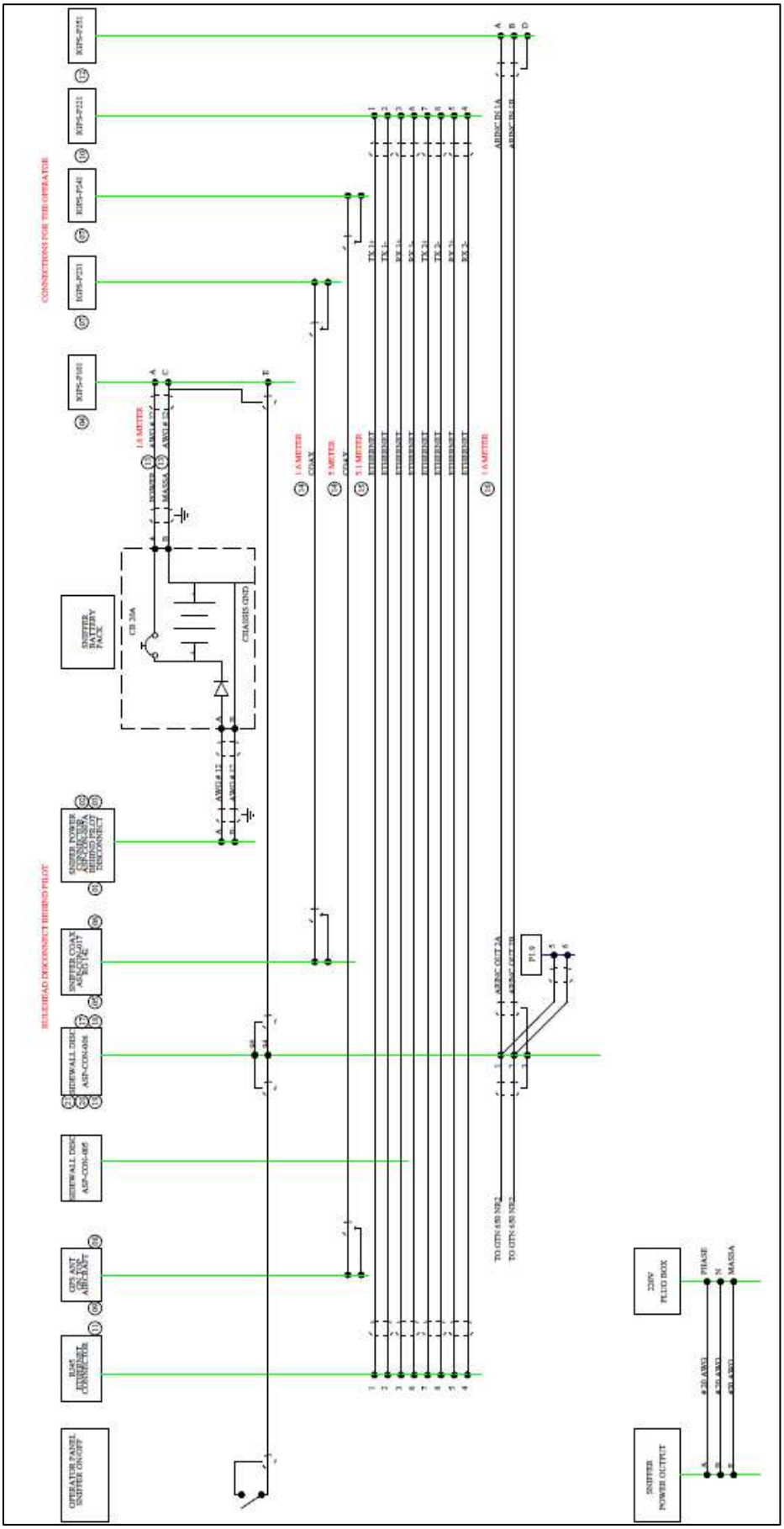


Figure 124 Sniffer battery connection

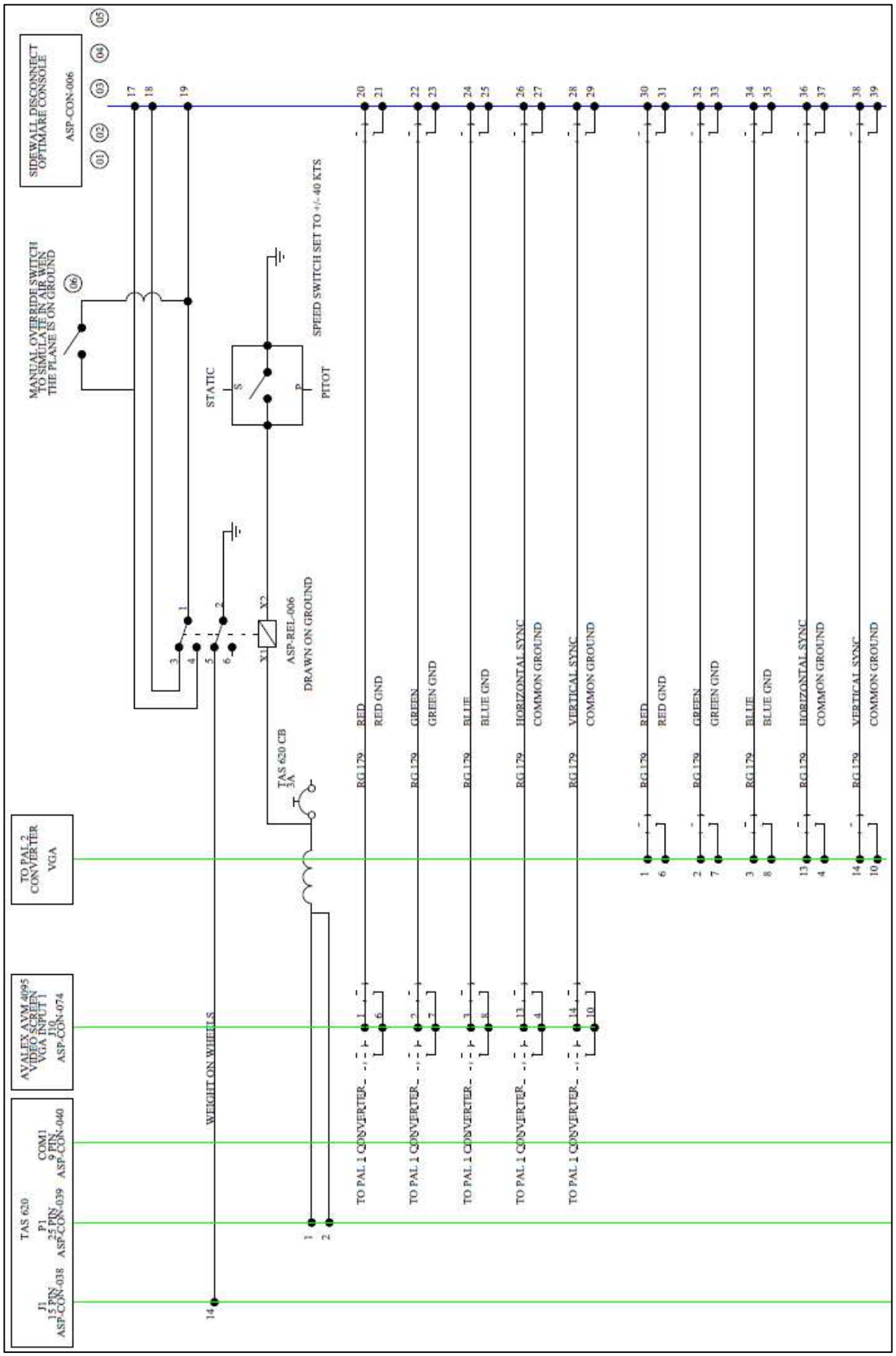


Figure 125 Video signal wiring

ANNEX C - BLOCK DIAGRAMS

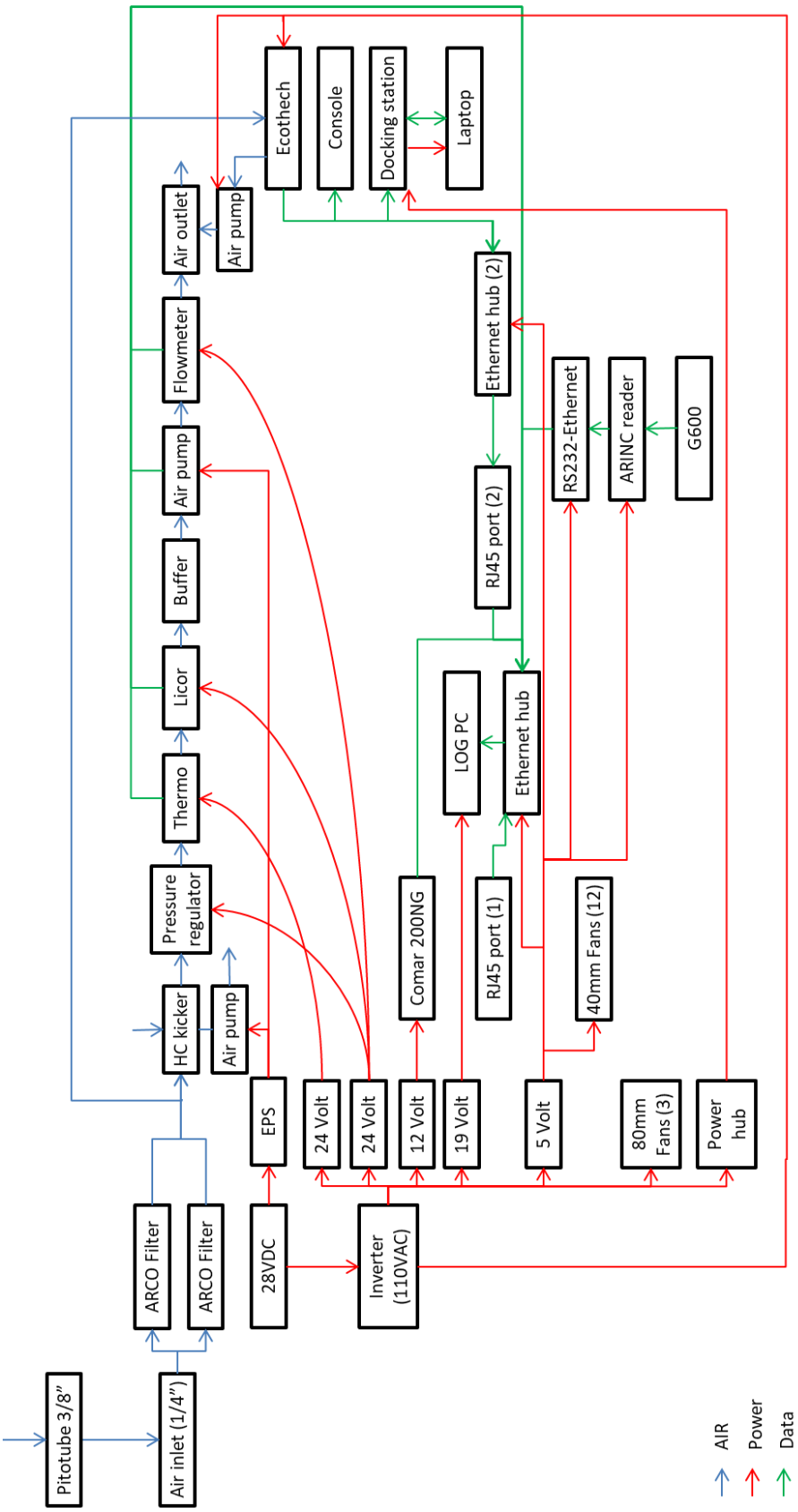


Figure 126 Block diagram Sniffer system

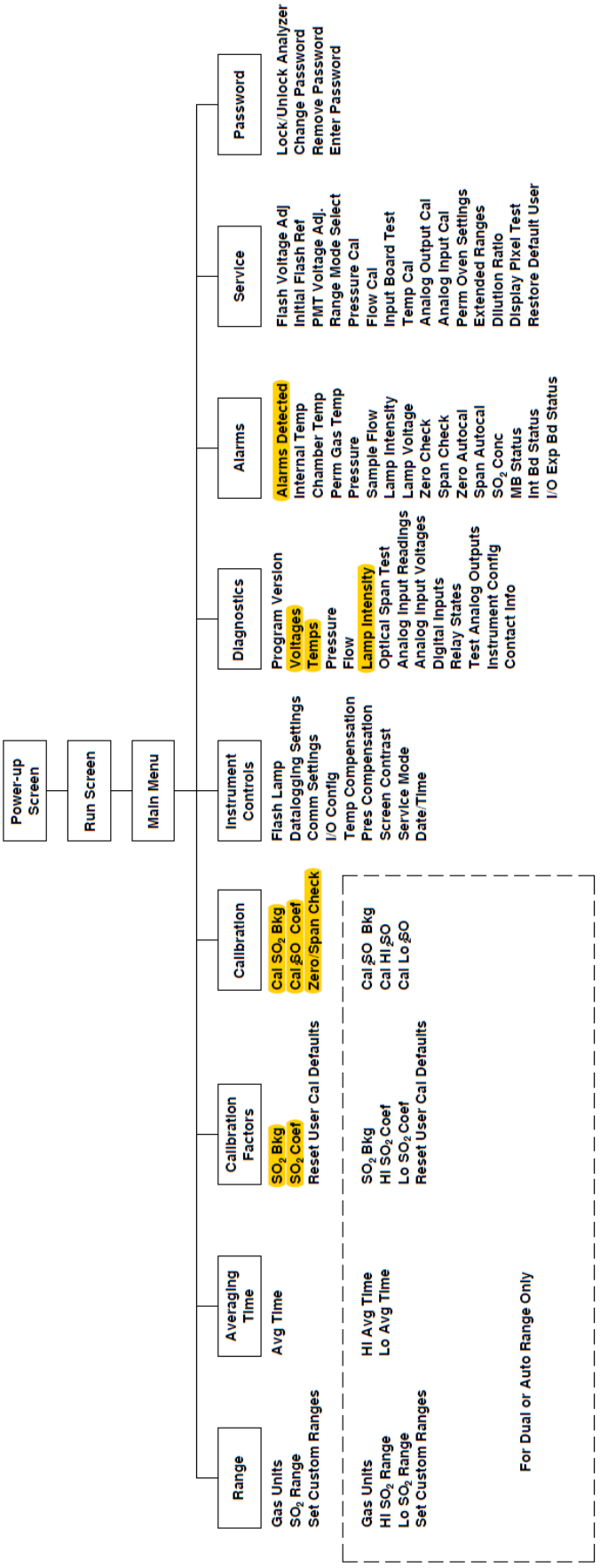


Figure 127 Menu structure Thermo 43i TLE

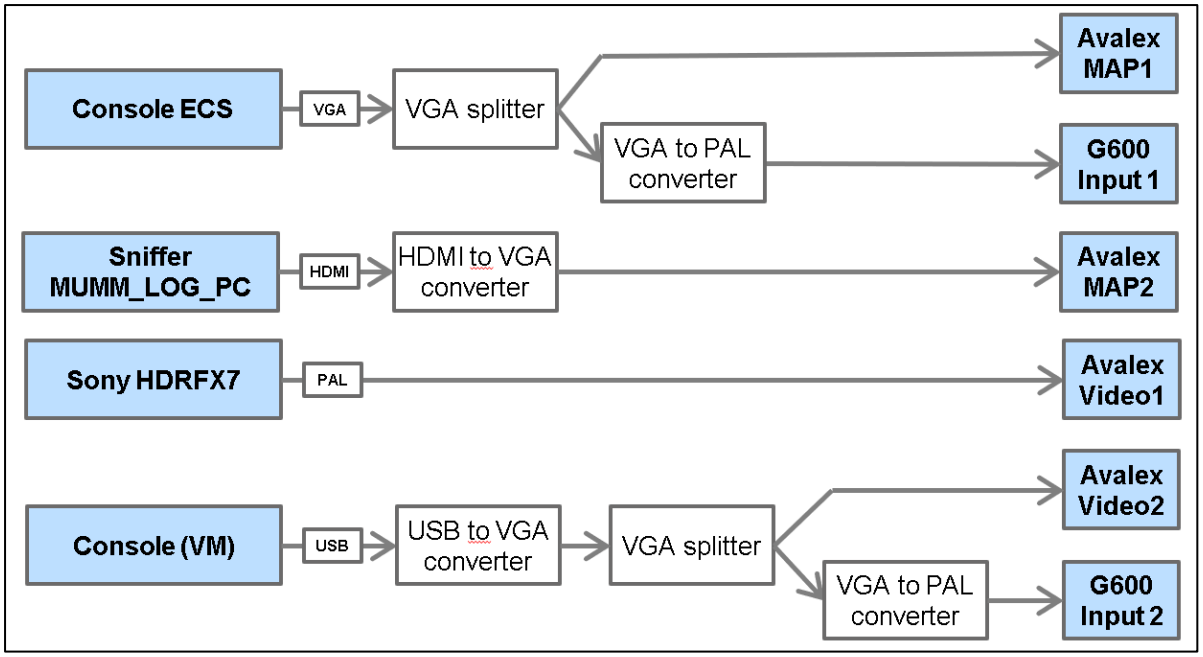


Figure 128 Video signal setup of AVM 4095

ANNEX D - SCHEMES

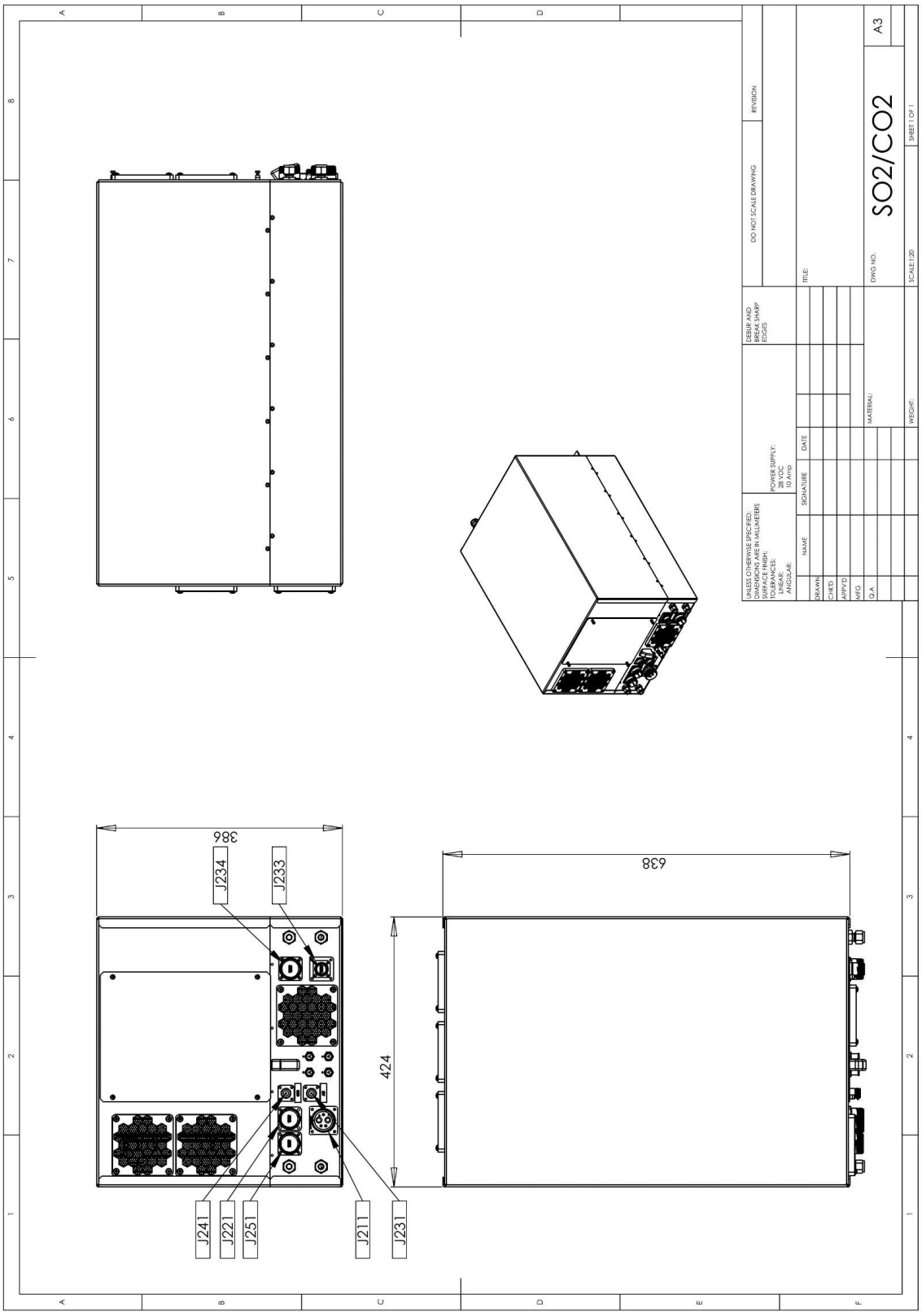


Figure 129 Technical drawing sniffer box

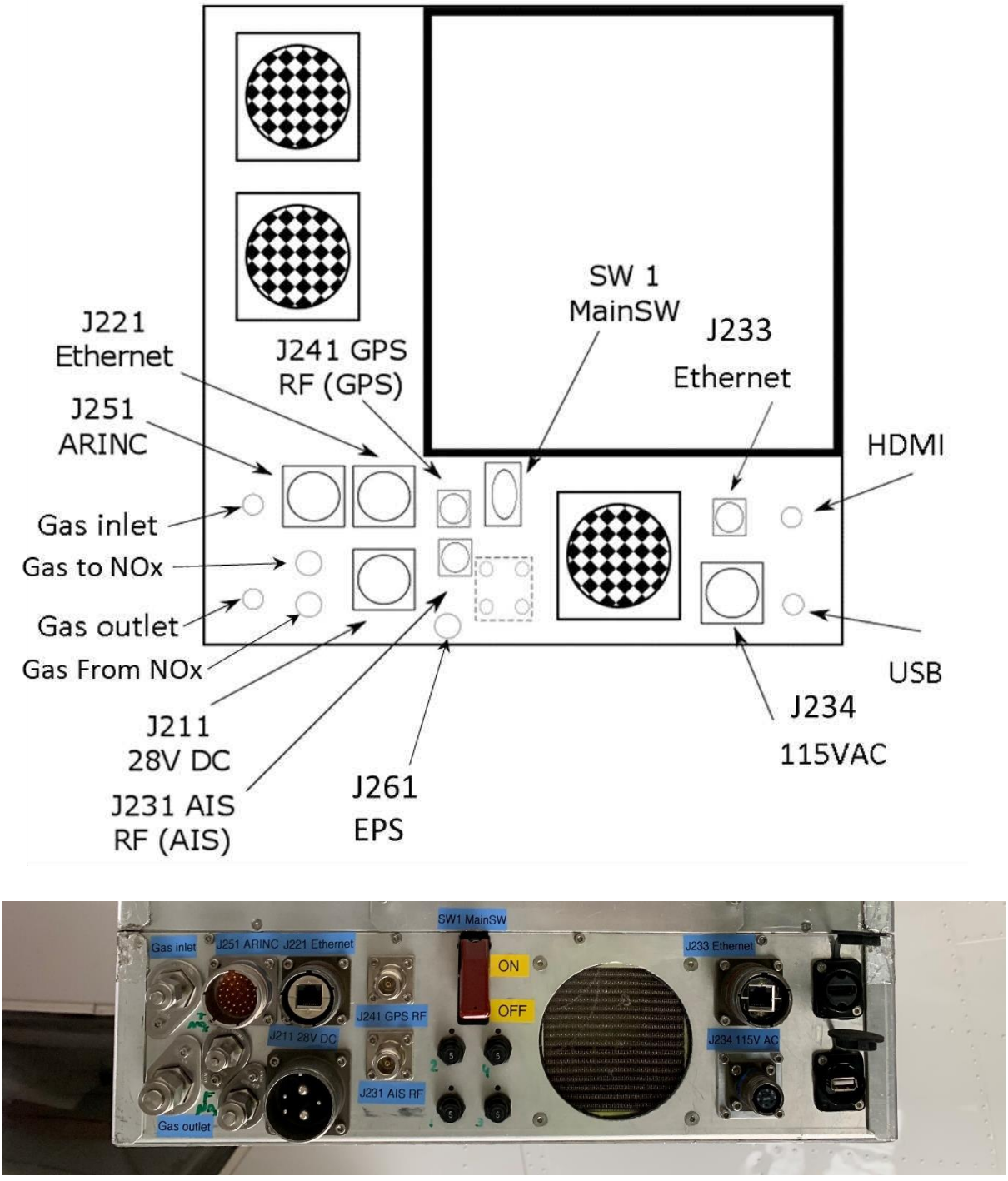


Figure 130 Drawing and picture of the connector panel on the Sniffer sensor (note J261 is missing in the bottom picture)

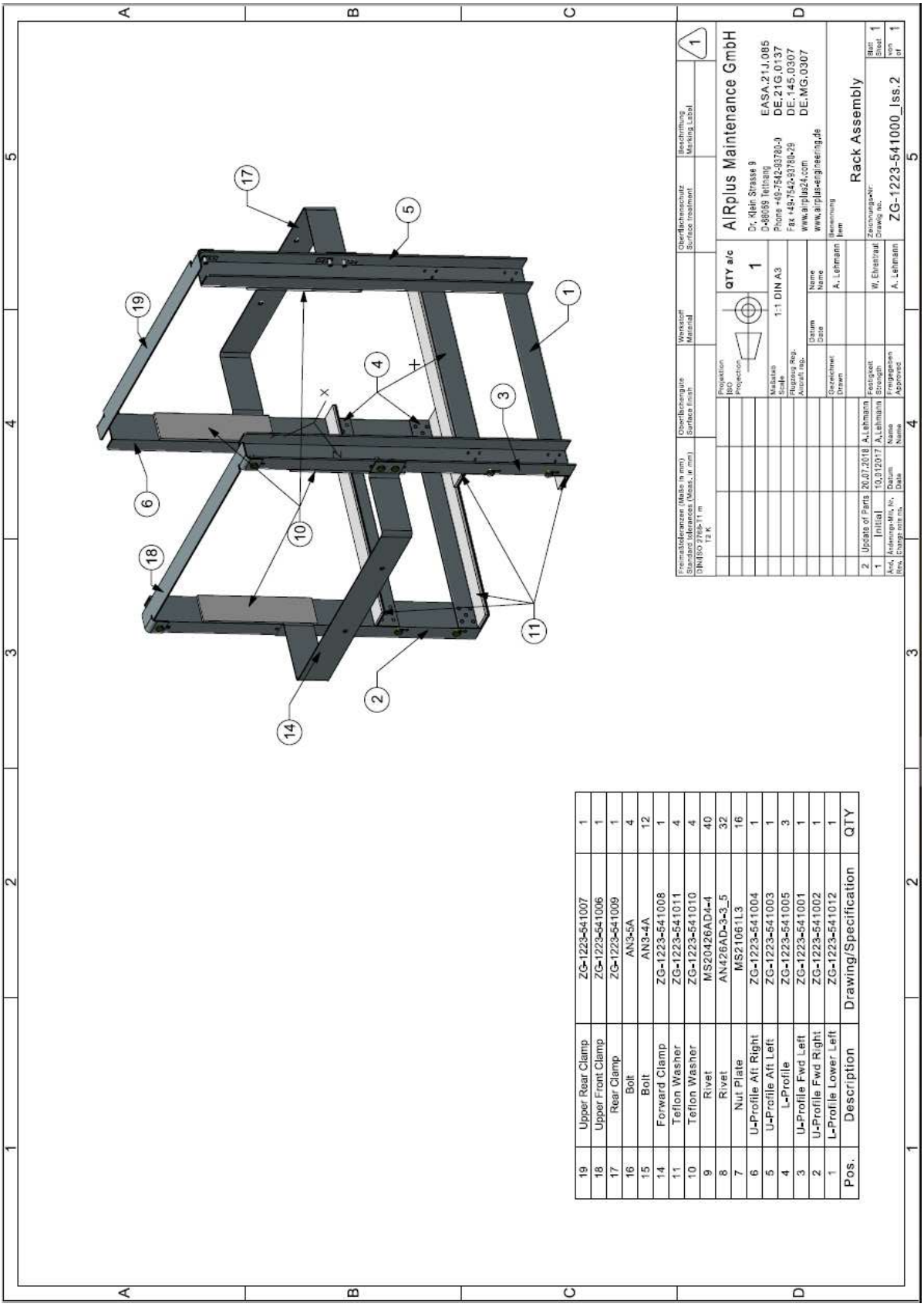
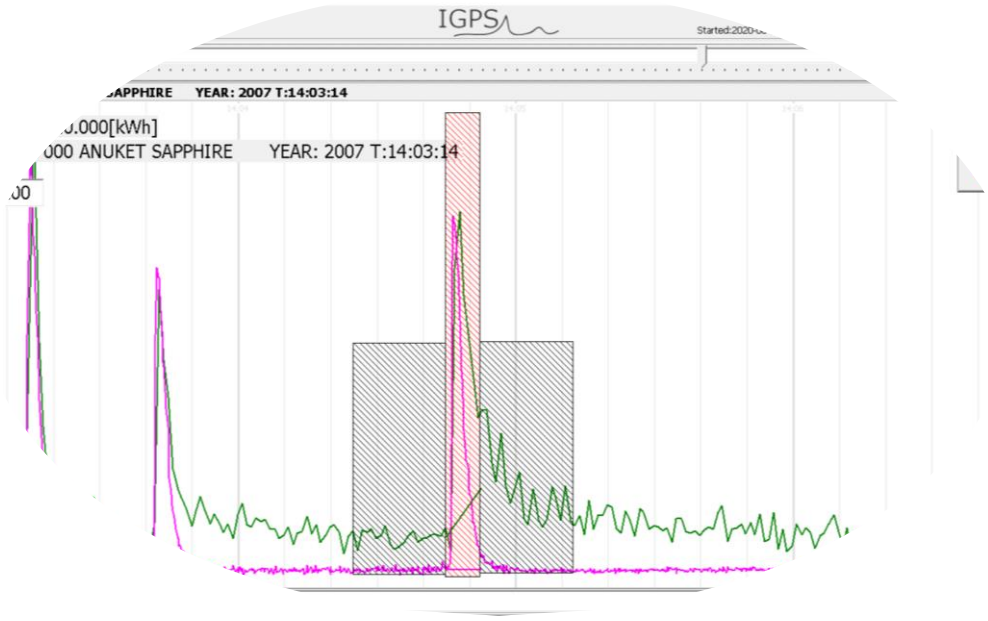


Figure 131 Scheme Sniffer rack

SNIFFER QUALITY MANAGEMENT SYSTEM

SECTION 3.

SNIFFER DATA MANAGEMENT MANUAL



REVISIONS

Revision Date	Chapter - section	Page	Description
17/01/2021	6.4 7.2	7-4	MUMM-LOG-PC moved from Section 2 to Section 3
17/01/2022	All		Adding of NOx
27/07/2022			Adding of FSC bias

ABOUT THIS MANUAL

The Sniffer Data Management Manual was developed by MUMM to be used with the sniffer installation on board of the Belgian Coastguard Aircraft, a BN Islander (BN2A) with call sign OO-MMM. The Data Management constitutes to Section 3 of the Sniffer Quality Management System (QMS). The Sniffer Quality Management System was specifically designed for the Belgian Marpol Annex VI monitoring program entailing the proper functioning of the sniffer system on board of the Belgian Coastguard Aircraft and the provision of accurate and consistent data collection. The Quality Management System consists of in total 3 Sections, Section 1 describes the operational aspects of the airborne monitoring. Section 3 consists of the data management aspects (see Figure 1). For every section a detailed manual is developed and available on the Seafile folder 1. SNIFFER QMS under the Seafile library 05-Instrumentation/05-FluxSense_Sniffer

In this manual, detailed information and step to step instructions are provided about the installation, calibration, and servicing of the sniffer sensor system. The manual is organized in different chapters and annexes to provide direct access to specific information, chapters can be toggled directly. The chapter can also be used as stand-alone guides during the different interventions in the field.

- "**Chapter 1 Internal Data structure**" describes the installation on board of the OO-MMM aircraft and the data structure of Sniffer sensor system.
- "**Chapter 2 Measurement uncertainty**" provides a detailed overview for the calculation of the FSC uncertainty.
- "**Chapter 3 Threholds for reporting**" provide the procedures to determine the thresholds for reporting.
- "**Chapter 4 Reporting of non-compliance data"** provides all information for the reporting of non-compliance data to PSC and Thetis-EU.
- "**Chapter 5 Reporting of compliance data**" describes all practical aspects of the reporting of compliant data to Thetis-EU and for third parties.
- "**Chapter 6 Reporting of annual results**" describes the procedures for the collection of data for the annual reporting.
- "**Chapter 7 Data storage and backup**" describes the procedures for the backup of the data.
- "**Annex A - Block diagram**" provides a blockdiagram of the sniffer sensor system
- "**Annex B - Configuration file**" contains the configuration file of the IGPS system
- "**Annex C - Flight report**" gives an example of a flight report



Figure 132 Sniffer QMS Structure

The sniffer sensor system manufactured by FluxSense (Sweden), consists of a compilation of components from different soft and hardware providers. This manual was composed by the scientific Service MUMM of the Royal Belgian Institute based on the different maintenance provisions of the components, applied on the specification of the sniffer sensor system on board of the Belgian Coastguard Aircraft and the nature of the Belgian North Sea Aerial Surveillance Program, as a result this manual may possibly not fully reflect the official opinion of the manufacturers.

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CHAPTER 1. INTERNAL DATA STRUCTURE

The sniffer sensor system is the complete equipment setup used for airborne Marpol Annex VI monitoring. The sniffer sensor system is installed in a BN Islander type B2-A with immatriculation OO-MMM. The sniffer sensor setup is described in detail in Section 2: Sniffer Quality Assurance manual, an overview is available in **Annex A - Block diagram**.

1.1. Sniffer sensor

The main component of the sniffer sensor installation is the sniffer sensor. The sniffer sensor was developed by Chalmers University and commercialised by FluxSense (Sweden).The sniffer sensor is a collection of different components and sensors that are installed in a custom made casing. The sensors consist of certified equipment used for ambient air quality monitoring that has been disassembled from its original case and reassembled in the sniffer sensor. In 2020 the sniffer sensor was extended with a NOx sensor which is installed in the rear part of the aircraft.

1.2. Measurement principle

The basic measurement principle consist of the measurement of the concentration of SO2 and CO2 for the calculation of the SO2 emission factor and the measurement of the concentration of NOx and CO2 for the calculation of the NOx emission factor.

1.2.1 FSC

To calculate the FSC, the SO_2 emission factor in g SO_2/kg fuel was calculated based on the SO_2 and CO_2 concentration before and in the plume. When passing through the plume, the increased SO_2 and CO_2 compared to the background (bkg) was calculated by looking at the surface area under the respective concentration plots (Balzani Lööv et al., 2014). To calculate the amount of kg burned fuel the amount of C was multiplied with the carbon content in the fuel, for marine fuels a carbon content of 87% was used (Beecken et al., 2014).

$$EF_{SO_2} = \frac{MSO_2 \frac{g}{mol}}{\frac{MC \frac{g}{mol}}{0.87}} \times \frac{10^3 \times \int [SO_2 - SO_{2,bkg}]_{ppm} dt}{\int [CO_2 - CO_{2,bkg}]_{ppm} dt} \left[\frac{g}{kg\ fuel}\right]$$

To find the FSC, this formula was converted by using the molecular weight of S instead of using the molecular weight of SO_2 (Beecken et al., 2015).

$$FSC = 0.232 \times \frac{\int [SO_2 - SO_{2,bkg}]_{ppb} dt}{\int [CO_2 - CO_{2,bkg}]_{ppm} dt} [\%\ Sulphur]$$

1.2.2 NOx

The NO_x emission factor (EF_{NOx}) in g NO_x/kg fuel can be calculated by using the NO_x and CO_2 concentrations. When crossing the exhaust plume, NO_x and CO_2 concentrations will increase and create peaks compared to the background [value] (bkg) before and after the peak. The surface area of these peaks above the background of the respective concentration plots is used for the calculation of the NO_x emission factor. For the calculation of the amount of kg burned fuel, the amount of Carbon

(C) is multiplied with the carbon content in the fuel. For marine fuels a carbon content of 87% is used (Beecken et al., 2014)

$$EF_{NO_x} = \frac{M\,NO_2 \frac{g}{mol}}{\frac{M\,C \frac{g}{mol}}{0.87}} \times 1000 \times \frac{\int [NO_x - NO_{x,bkg}]_{ppb} dt}{\int [CO_2 - CO_{2,bkg}]_{ppm} dt} \left[\frac{g}{kg\ fuel}\right]$$

$$EF_{NO_x} = 3.33 \times \frac{\int [NO_x - NO_{x,bkg}]_{ppb} dt}{\int [CO_2 - CO_{2,bkg}]_{ppm} dt} \left[\frac{g}{kg\ fuel}\right]$$

According to Regulation 13 of MARPOL Annex VI, the molecular weight of NO_2 is used for the calculation of the NO_x emission factor. For the calculation of the NO_x emission in g NOx/kWh, the NO_x emission factor (g NO_x/kg fuel) is multiplied by the Specific Fuel Consumption (SFC).

$$SFC = \frac{kg\ fuel}{kWh\ BHP}$$

$$EF_{P,NO_x} = EF_{NO_x} \times \left(\frac{kg\ fuel}{kWh\ BHP}\right)$$

Based on literature and public engine data, the SFC can generally be found between 0.16 kg/kWh and 0.24 kg/kWh. In the general operations a standard of 0.2 kg/kWh is used.

1.3. Sniffer software

The sniffer system consists of Five main software applications that operate on Microsoft Windows: TCP log, IGPS Present, Watchdogs (WD), IGPS Extract and IGPS Analysis. TCP log runs on the internal computer of the sniffer and manages all communication with the instruments, merges the different data streams from the various instruments to one single data stream that is broadcast on the network to all connected client stations. Figure 133 shows how the information flows in the IGPS sniffer system. The TCP log collects the data and controls the sensors. The information is then forwarded (using the broadcast address of 255.255.255.255) to all computers on the local network. The recorded data is stored to the local disk in files in one hour blocks. IGPS Present is the software run on the operators computer, this software performs the analysis of the measured gases and presents the operator a map with all ships in the area, the watchdogs are making sure TCP Log and IGPS present are always running on the MUMM-LOG-PC. After extracting the raw data with IGPS Extract, IGPS Analysis can be used for further processing either after the flight or during the flight.

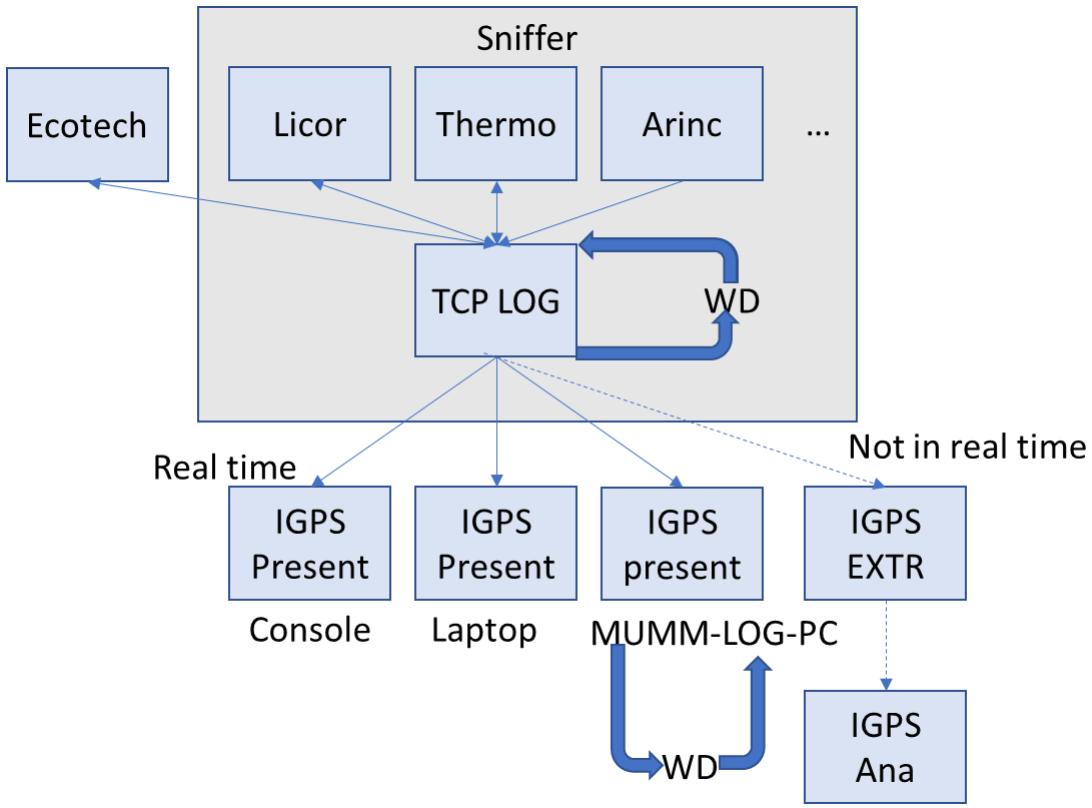


Figure 133 Schematic presentation of the sniffer sensor software

All software is installed on an "IGPS" folder which must be located directly on the "C:" drive, this folder consists of the following data for all stations:

- "Charts" Directory: folder with Open source charts of the world
- "Missions-Data" Directory: folder with generated reports of observations
- "MAIL" Directory: not used by SURV
- "AIS_EX8.exe" program: tool used for extraction of TCP-LOG files
- "AISPresent.exe" program: main software program used in flight and during calibrations
- "IPGSAna44.exe" program: software for post flight analysis (extraction required)
- "AISPresent.ini": this is the settings file for AIS present (can be read and edited using Notepad)
- "IP-configuration-SURV.txt" file: this document contains the used IP addresses for the different clients
- "Emissiondata_xxx.txt" files: are generated by the different clients (ODN-WVR, ODN-KS, ..) and contain the FSC measurements
- "Mail_Sniffer_SO2_Man_Meas.csv" file: contains the evaluation (High/Low/Not detected) of the manually marked ships
- "Comments _xxx.txt" contain the stored comments (old comment files are stored in "Comments" directory
- "wakeuplan.txt" file: contains the Mac address of the MUMM_LOG_PC in the sniffer sensor and can be used to wake up by lan
- "Optical_SO2_Man_Meas.txt" file: not used by SURV
- "STATICSHIPDATA_xxx.txt" file: contains a record of the observed ships per operator

- "borlndmm.dll", "cc32230.dll", "cc32230mt.dll", "Fetchlog.txt", "Logfile.txt", "Memo1-1.txt": are other additions files
- MMSI_Date: This file contains the Keel Laying Dates of tens of thousands of ships

For the IGPS folder on the MUMM-LOG-PC an additional directory is available

- TCP log: This directory includes all log files collected per hour

The IGPS folders of the operator laptops are synched by Seafile. This way all operators use the same software version with the same software directories and files. This is not the case for the IGPS folders on the LOG PC and MEDUSA client station, these folders have to be updated manually when new software versions are configuration settings are available.

The operational use of the software, the measurement data collection, reporting and basic post flight processing are described in Section 1 of the Sniffer QMS. The software aspects for maintenance features, the software troubleshooting and the collection of quality assurance and maintenance data (e.g. calibration data) are described in Section 2.

1.4. IGPS present

This is the main application for the collection of sniffer measurements and may also be referred as IGPS real or AIS Present, all functionalities are described in detail in Section 1 and Section 2. This software has following data-output or will alter following files:

- AISPresent.ini
- Emissiondata_xxx.txt files (one per operator)
- Mail_Sniffer_SO2_Man_Meas.csv
- Comments _xxx.txt (per hour)
- STATICSHIPDATA_xxx.txt (one per operator)

Operators should be aware that when opening the IGPS present software some of these files are used and can be modified by the software, therefore it is advised not to open IGPS presenter on different Operator laptops on the same time or before a synching has been completed. (This does not apply the IGPS software on the Console and MUMM-LOG-PC as they do not have synched libraries).

1.5. AISPresen.ini

The AISPresen.ini (see **Annex B - Configuration file**) contains the configuration parameters for the ASIPresent.exe software. The parameters should be only changed when the IGPS software is closed. For safety reasons it is advised to make a backup of the configuration file before changing it. The ini file can be opened in notepad. Some parameters are changed from the software (eg. Displayed graphs, compass, AIS info box, …), other parameters can only be changed in the software itself. Following parameters might need to be changed manually when deemed necessary:

- NO and NOx Delay (1.5.1)
- NO/NOx ratio (1.5.2)
- MID data (see 7.3.1)

1.5.1 NO and NOx delay

As the NOx is operating in a lower pressure and flow, the airflow is split after passing through the filters (but before the pressure regulator). In addition the NOx sensor is installed at ca 6 m from the other sensors, by using a smaller tube size toward the NOx (1/8") this difference is somewhat reduced. Nevertheless this still results in a different time before the air is passed through the NOx sensor compared to the SO2 and CO2 sensor. In addition the change in flow or pressure in the SO2 and CO2 circuit may also change the time difference between the SO2 and CO2 signal compared to the NOx signal. To correct for these delays 2 parameters have been introduced defining the delay time. To correct for these delay time, the plots on the SNF graph can be used to estimate the delay, by adjusting the delay time iterative one second at a time, the delays on NOx and NO can be removed. This should only be performed when changes are made in the tubing length or in the flow. The NO has currently a delay of 4 seconds and the NOx a delay of 5 seconds (see highlighted section in **Annex B - Configuration file**), the difference is caused by a limited length in tubing between the two modes. In case the delay loop is installed the difference between the two is ca. 5 seconds. Different delays for different operation modes are available in the Delays.xls file on the IGPS folder

1.5.2 NO/NOx ratio

The NO/NOx ratio is used to define the concentration of NO when the NOx sensor is in NO mode and vice versa to estimate the amount of NOx when the sensor is in NO mode. As the ratio is not a fixed constant the sensor is generally operated in NOx mode, only when a possible violation is observed for FSC, the sensor is set to NO mode to calculated the NO interference more precisely.

1.6. TCP log

The software TCPlog has is continuously logging the data from all the available instruments with a sampling period of approximately one second (5hz for the Licor7200). This includes data from the gas analysers, wind information, AIS receiver and GPS. The log program is the only part of the tailored IGPS software that is used to communicate directly to the sensors. TCP-log is only installed on the MUMM-LOG-PC. The log program also handles certain specific sets of commands from the IGPS Present software to the sensors.

TCP-log program is also responsible for the broadcasting of communications entered by any of the users from one client station to all other active IGPS Present windows on other client stations (e.g. comments, targetting or tagging of ships). In this sense, the TCP log avoids user conflicts when multiple operators simultaneously access the sniffer box. The recorded data is storage through text files at regular intervals of 1 hour using the following format: YYYYMMDD-HHMMSS.txt, at ca. 30MB of data per hour. The Storage location typically is C:\IGPS\TCPLog, though this location can be modified by changing the setting of the configuration file (Appendix 2). The TCP Log must be started by loading the executive file: C:\TCPLog.exe this can be done by using a command window, a .bat file, a shortcut, or through the watchdog software (see 1.7 Watchdog). To manually end TCP log, open the program from the task bar and close the program, or end the task using the task management. The watchdog will pop up and must be closed as well, after which the TCP log will open again and must be closed once more.

1.7. Watchdog

A watchdog timer (WDT) software is configured as part of the startup process of the MUMM-LOG-PC. Once the WDT is running it will handle the start of both the TCP Log and the IGPS Present software at the beginning of the measurements, or in case of an unexpected crash of either the TCP log or IGPS Present. If a configuration file must be changed or for updating the IGPS software, the WDT and thereafter the TCP Log and IGPS Present must be manually stopped. The WDT can be manually restarted at the IGPS location:

- TCP Log: C:\IGPS\TCPLog.exe
- IGPS Present: C:\IGPS\AISPresent.exe

1.8. Analysis of LOG files using AIS Extract

The TCP Log software storages all the raw data and calibrations in a semi binary file at regular intervals of 1 hour using the following format: YYYYMMDD-HHMMSS.txt. Every single line of this file contains an individual measurement and a header that includes the GPS-logging time and the instrument network parameters. The IGPS Extract software is a tool that interacts with the raw data in order to generate user friendly individual text files corresponding to each of the logged instruments.

These files can be used of detailed analysis per sensor or for post flight reprocessing with the IGPS Analysis software. Follow the following procedure to extract data. Data can be extracted for individual log files (per hour) or log files can be combined during extraction. Note that when extracting and combining multiple log files, extraction time will be notably longer.

SOP 3.1. To extract log files

1. Open AIS.EX.8.exe
2. Select file(s)
    a. Select start,
    b. browse to LOG directory
    c. select the log file(s) you wish to extract (organized according to date and time),
        - Multiple files can be loaded to create combined extracts, this will lengthen the extraction process time
    d. Select open
3. Select the output directory (create a new one or browse to existing directory)
4. Extraction will begin, when all data is extracted a notification “Done” will be displayed
5. All sensor data will be available in TXT files

The extracted data can either be analysed using the IGPS Ana tool. It is also possible to look into the individual sensor data using Excel or another data or spreadsheet tool (R, Statisitca, …). Following TXT files will be created in the output folder

- EXTR-AIS.txt: these are the altering data of the ships (posting, speed, direction … of moving ships)
- EXTR-AISGPS.txt: these are the GPS coordinates of the sniffer (the track)
- EXTR-AISGPSPos.txt: these are the GPS coordinates of the sniffer (the track)
- EXTR-AIS.txt: these are the static data of the received ships (name, IMO, dimensions…)
- EXTR-ARINC.TXT: This is the ARINC data collected by the Sniffer sensor
- EXTR-CAL.TXT: consist of the software calibration factors
- EXTR-Comments.TXT: are the comments created during flight

- EXTR-Licor7200.TXT: the raw data exported from the LICOR7200 sensor
- EXTR-SO2.TXT: the raw data from the Thermo 43i TLE
- EXTR-Serinus40.TXT: the raw data from the Ecotech Serinus 40
- EXTR-WIND.txt: This is the wind information collected through ARINC

More files are created for other sensors and equipment, but are not used in the sensor setup of the Belgian Sniffer, these files have zero values, but should not be deleted.

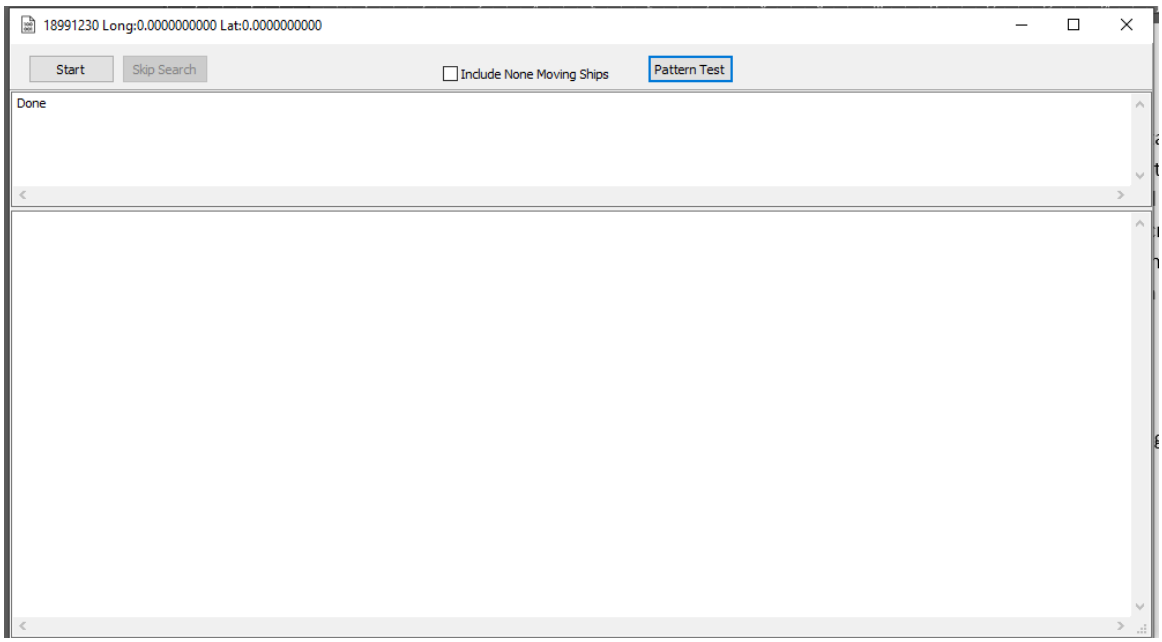


Figure 134 IGPS Extraction software

1.9. Loading extracted data in Excel

Once the data is extracted, the raw data can be imported in a spreadsheet using Excel. For CO2 and SO2 the gas measurements are available in a sperate column, but for NOx a transformation needs to be performed.

SOP 3.2. To import the extracted data

1. Extract the data of the concerned log file (see 1.8 Analysis of LOG files using AIS Extract)
    a. Import the the log file
    b. Open “Calculation T90.xls” file
    c. 05-FluxSense_Sniffer\0. QMS\3. SNIFFER DM\Data analysis\T90
    d. Open Import sheet
    e. Go to Data>Get Data>Legacy Wizards>TXT (legacy)
    f. Select EXTR-SO2.TXT, EXTR-LICRO7200.TXT or EXTR-Serinus40.TXT
    g. Use comma “,” as separator
    h. Select finish
2. Copy the gas and time concentration to selection sheet
    a. For CO2
        - column AX will give the CO_2 in ppm
        - column A will give the time of the sniffer (per second), column L will give the sensor time up to 0.1 sec for T90 calculations use column L
    b. for SO2

- column F will give the SO_2 in ppb
- column A will give the time of the sniffer (per second)

c. for NOx

- column D will give the NO in ppt in scientific values
- column J will give the NOx in ppt in scientific values
- column A will give the time of the sniffer (per second)

SOP 3.3. To transform the NOx data

1. Select the columns D and J and click ctrl+h, write '= and select replace all
2. Split data, use "+" as separator and copy to a new column
3. Split data use "-" as separator
4. Create a new column that either contains the negative values (add -) or positive values for the exponents
5. Combine the value for the measurement with the exponent, devide by 1000 to arrive to the concentration in ppb

Note: excel templates exist for the automatic import of extracted files for NOx, CO2 and SO2 under T90 folder

1.10. IGPS Ana

With this software tool extracted data can be reprocessed, this can be useful for detailed analysis of non-compliant vessels. The advantage of reprocessing the data through the Analysis tool over the replaying the flight with the IGPS presenter tool is that the Analysis tool allows scrolling through the data and maybe therefore more user friendly for reprocessing of large amount of measurements. Another advantage is that the start and end times can be defined for each sensor, which may give a slightly higher accuracy (although the difference is in most cases neglectable).

1.10.1 Visualizing measurement data

After extracting the data with IGPS Extract, the measurement data can be loaded and analysed using the IGPS ANA tool. The user can interactively navigate along the full measurement time or choose to look for a specific plume or ship (Figure 137):

SOP 3.4. To load data

1. Open IGPSAna44.exe
2. Select start
3. Select folder with extracted data
4. Select output folder (use existing or create new)
5. OPTIONALLY: select folder with Emission data (use IGPS folder for recent data)
6. Data will be loaded

SOP 3.5. To scroll through the data

1. Scroll through the mission using the green arrows in the navigation bar
2. Move cursor over one of the two plots
3. When moving the cursor over the plots the aircraft will be moving over the moving map
4. The name and position of the monitored vessels are visual combined with the position of the aircraft on the moving map
5. The plots and moving map can be zoomed either by using the zoom bar, or by a double click on the CO2 plot.

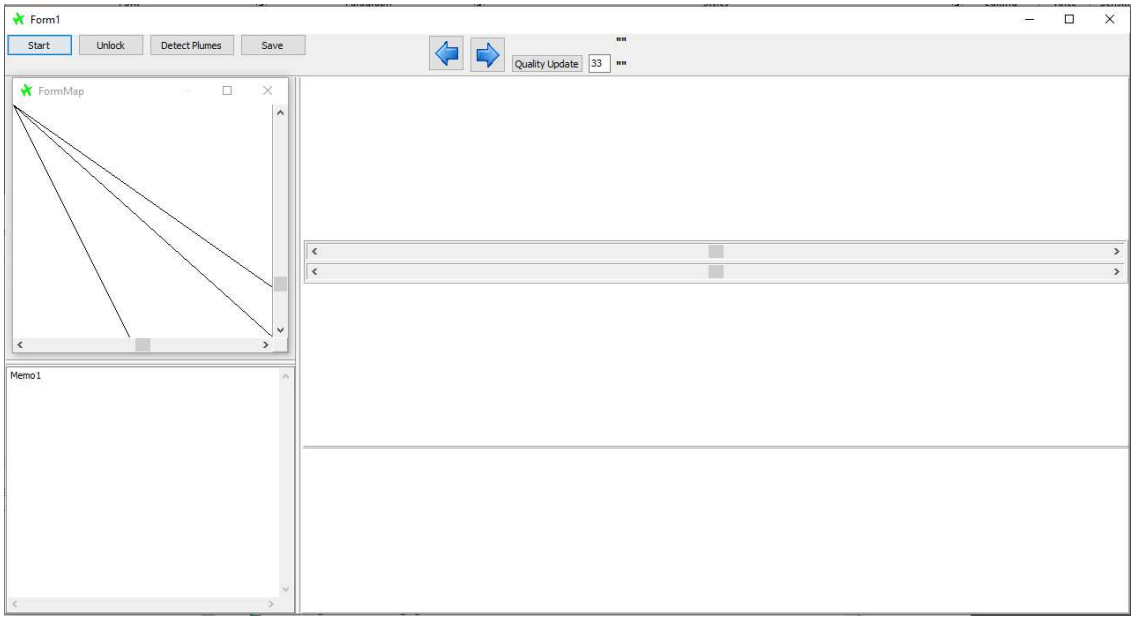


Figure 135 To load data click on start

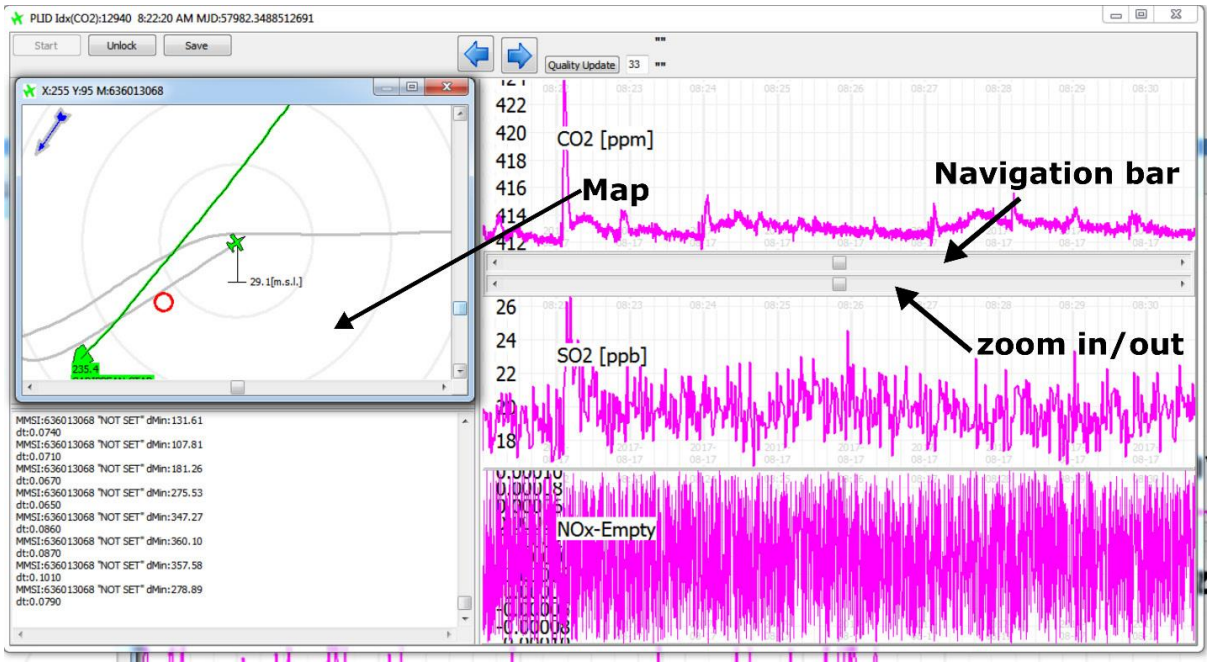


Figure 136 Data view of IGPS ana after loading data

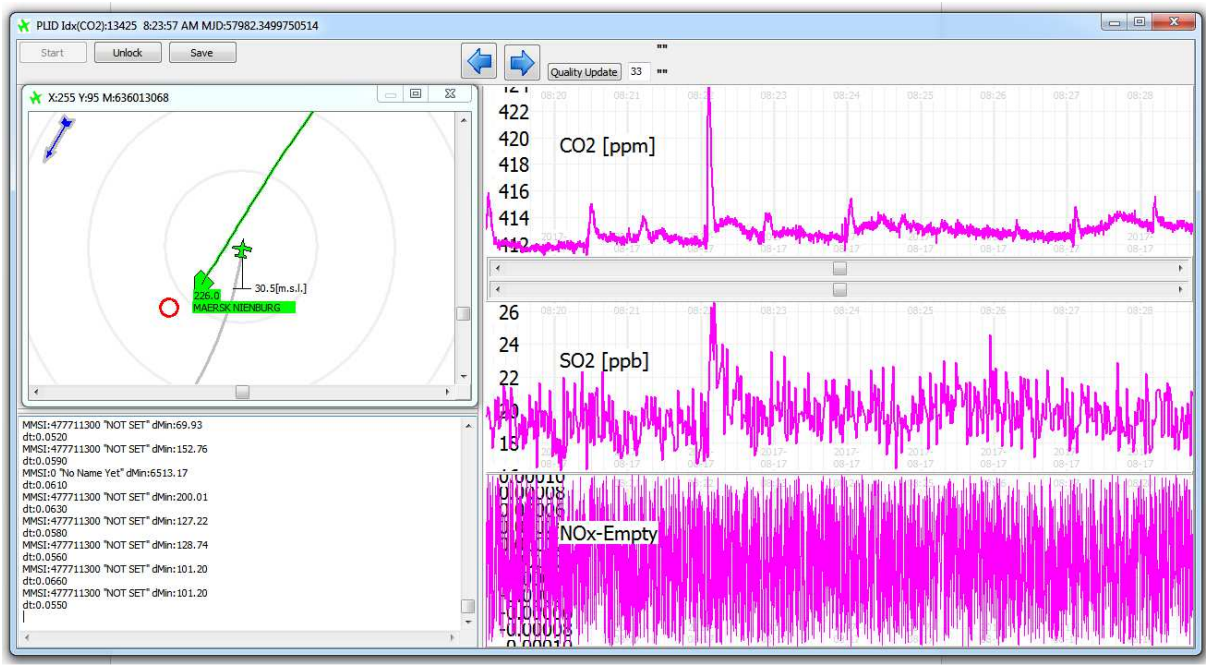


Figure 137 Moving the cursor over the graph will alter the moving map, to show the position of the aircraft corresponding to the time on the graph

1.10.2 Creating new plumes

In addition to analysing the measurement data, new plumes can be measured and assigned to ships.

SOP 3.6. To create a new plume

1. Locate the plume using the cursor and navigation bar
2. Right click on the upper plot
3. A menu appears with following options
    a. New Plume
    b. Zoom Extent (this will reset the zoom to the original state)
    c. Undelete Plume (this will restore a previously deleted plume)
4. Click "New Plume"
5. Go to the map and click right, a window will popup with 3 options
    a. Use This Ship:
        - IGPSAnalys estimates the most likely ship corresponding to the selected plume based on the wind conditions.
        - However, if there are multiple ships available, it is possible to add uncertainties per ship
    b. Unknown Ship: This will Labels the plume as coming from a "No name" vessel.
    c. Cancel: Exit this Menu.

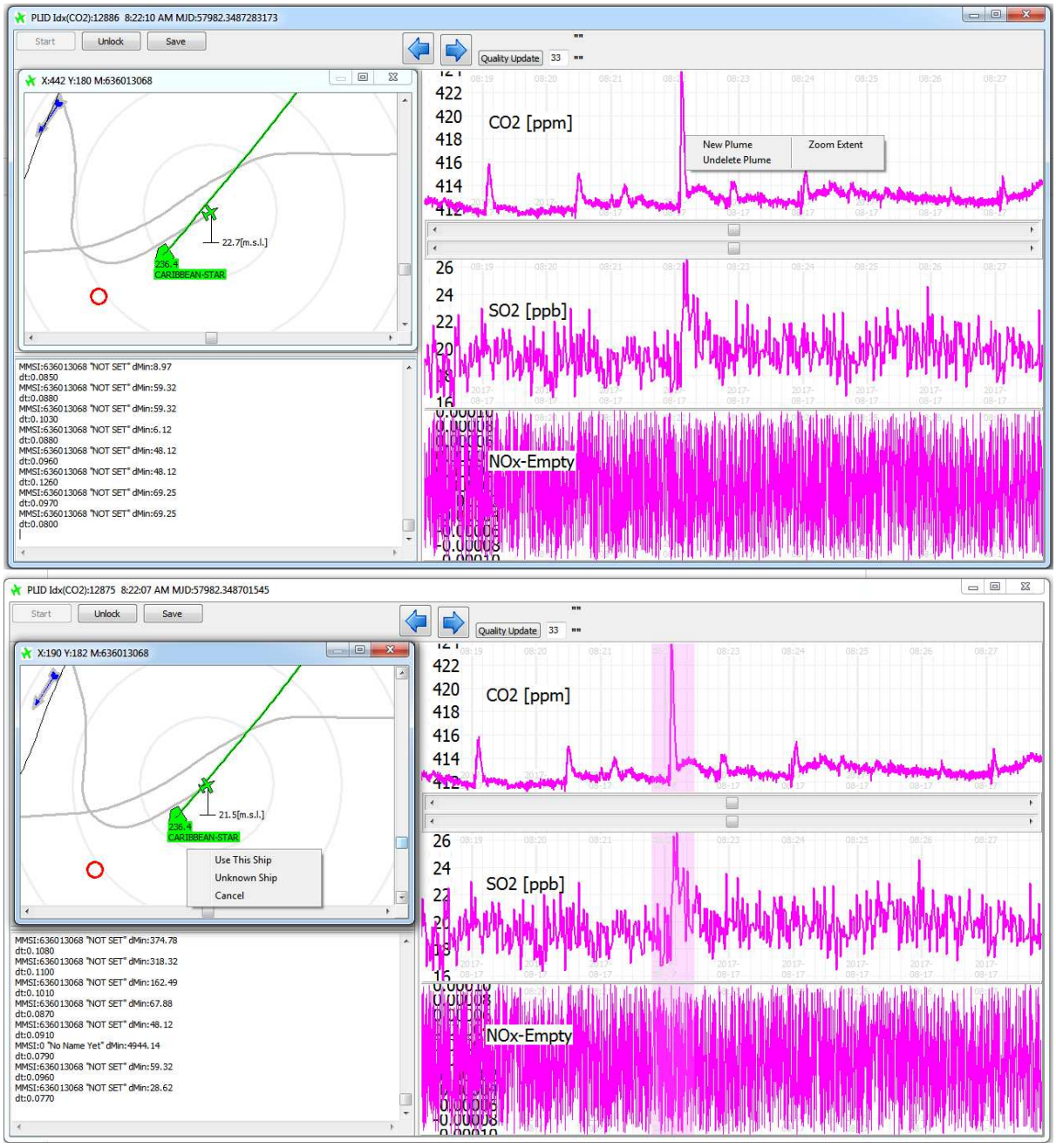


Figure 138 Right-click pop up menu prior to creating a new plume (upper) and assigning the plume to a ship (lower).

1.10.3 Calculating emission factors

After a new plume is created, the base line and the plume start and end limits can be adjusted. This similar to the plume assignment as in IGPS present, but with the possibility to either align the different gasses or to choose different start and end position per gas.

SOP 3.7. To recalculate FSC and NOx

1. Select the start and end position of the SO2 and CO2 plots corresponding to the identified plume
2. Sometimes, this procedure may require to zoom in the plots
3. At the upper panel, the output S[%] is the FSC without NO compensation, the S(NO)[%] is the FSC with NO compensation

4. The FSC and NOx value will be updated when changing the baseline and start and end position of the plumes on the plots
5. An automatic Quality level is assigned
    a. A medium quality level lies between 30 to 66 %
    b. A high quality levels lies between 66 % to 100 %;
    c. otherwise the quality is labelled as low.
6. If the pre-estimated quality flag is not satisfactory, it can also be manually changed by inserting a new value and pressing the button Quality update in the upper panel.
7. The parameter plume index increases every time a new plume is created.

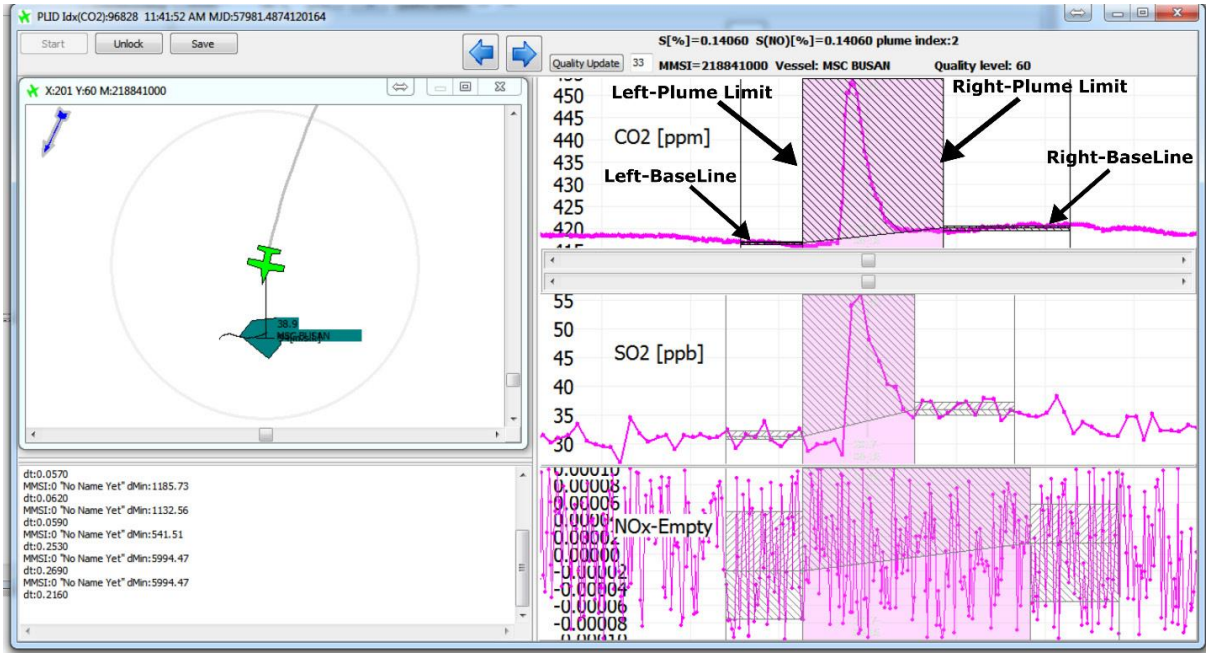


Figure 139 Setting plume delimiters

1.10.4 Checking existing plumes

After the plumes have been created and the FSC and NOx have been calculated for the different plumes it is still possible to adjust plume delimiters and reprocess the emission calculations (in comparison, this is no possible with IGPS Present).

SOP 3.8. To redefine start and end position per gas

1. The buttons with the two arrows allow to move the along the plots following the corresponding plume index
2. A right click on any of the already created plume markers on the SO2 or CO2 plot will pop up a menu with the following options:
    a. Align Left Like This: the other plume marker will be adjusted to the left plume limit and base line
    b. Align Right Like This: the other plume marker will be adjusted to the right plume limit and base line
    c. Align Both Like This: the other plume markers will be adjusted to both baselines and right/left limits
    d. Delete: Only the marker of the CO2 will be deleted, though the plume is not going to be saved. This can be reverted by the previous mentioned option Undelete Plume.

e. Reselect Ship: It allows to assign a different ship to the plume as previously shown.

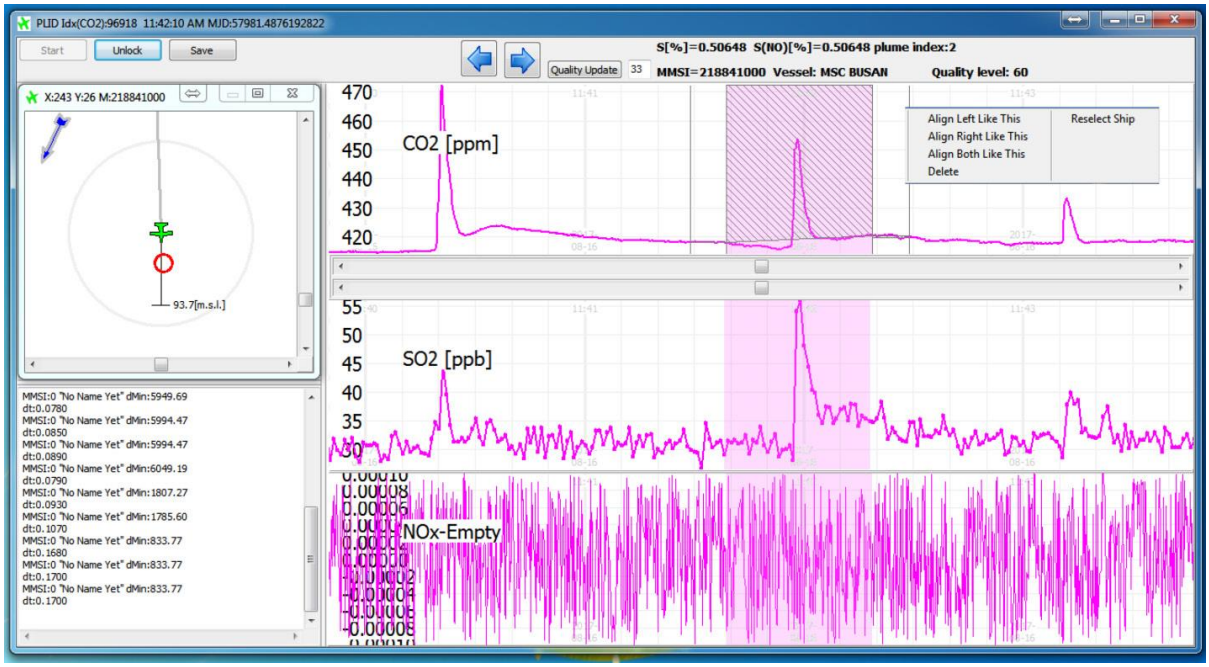


Figure 140 Pop up menu for created plumes

1.10.5 Reanalysis including the plumes emissions file

If the Emissionsdata_User.txt is available, it can be selected during the loading data (step 5 in 1.10.1). If the selected Emission file contains plumes between the time interval corresponding to the loaded extracted files, the plume markers that were created in flight, the corresponding ships and FSCs will be added. It is advisable to double check if the plume delimiters are properly aligned and adjust were necessary.

When the reanalysis is completed, press the button Save and the results will be storage in the previous selected output directory. The result consists of the following files:

- AUTO-EMI-OUT YYYYMMDD-HHmmss.txt: This files contains plume data that the IGPSAnalys can read in order to load a previously saved reanalysis.
- DYYYYMMDD-HHmmss.EMF: This files contains graphic metadata for each plume.
- MAIL-EXTENDED-EMI-OUT YYYYMMDD-HHmmss.csv: This files contains the reanalysis results of all the plume sorted in a CSV format.

1.11. Internal signal wiring

A standard 5VDC 8 port RJ45 Ethernet hub (MXU85A0001) is used to connect all the different Ethernet connectors from the components to the internal computer and client stations. The internal main IP addresses in the sniffer sensor are displayed in Table 7.

A Zotac Zbox Nano ID64 mini pc is installed in the sniffer,this mini pc is further referred as the MUMM_LOG_PC. The MUMM_LOG_PC centralizes the data acquisition and data output to the different client users via Ethernet. One USB port is connected to the external USB connector, this can be used to connect external devices (keyboard, mouse, drives, …) or for troubleshooting. The HDMI

output of this PC is connected to an external HDMI connector and used for the visualisation of the IGPS navigation charts to the cockpitdisplay (VGA2 on Avalex AVM 4095) via an HDMI to VGA converter which is installed outside the sniffer sensor.

Table 15 IP addresses used in the sniffer sensor

IP address	Component	Port
192.168.1.9	MUMM_LOG_PC	
192.168.1. 95	Licor7200	7200
192.168.1.201	Thermo TLE 43i	Command: 9880 Stream: 9881
192.168.1.110	Comar AIS+GPS	10001
192.168.1.102	Bronkhorst Flowbus	1471
192.168.1.130 (CPC-3787) 192.168.1.106 (CPC-3787-RS232)	Bronkhorst pressure control: Ethernet to RS232	23 1470
192.168.1.121	ARINC receiver	9760
192.168.1.213	Ecotech Serinus 4.0	Serial port 97

To access the internal MUMM_LOG_PC, a remote connection can be realized using TeamViewer (V12) or Windows remote desktop. The IP address of the MUMM_LOG_PC is 192.168.1.9 with login name “MUMM” and password “mumm”. To enable this connection the IP configuration of the client stations have to be adjusted. For more information on the configurations and the characteristics of the different sensors and connected equipment, see Section 2.

1.12. External signal wiring

A detailed description of all connection including signal wiring to and from the sniffer is available in Section 2. The Sniffer sensor is connected to the aircraft navigation instrumentation (Garmin GTN-650) using the Arinc protocol information on wind and positioning is provided to the Sniffer sensor.

The sniffer sensor system is a network based system. The means that all sensor data is gathered on the internal LOG-PC and made available for different IGPS software installations on client stations. The client stations are connected with the sniffer sensor via 2 Ethernet connections. 2 clients are used in the aircraft. One on the Mission Management Unit from Optimare on a Virtual Machine and one is connected to a wireless docking station (Lenovo WiGig Dock) that can be used in combination with the Lenovo Thinkpad portable computer (T460). The available IP addresses for client stations to connect to the sniffer sensor are available in Table 1, the subnet mask is 255.255.255.1.

Table 16 IP addresses for external connection to the sniffer sensor

IP addresses	User
192.168.1.230 -239	available
192.168.1.240	Console via VM
192.168.1.241	PC Ward via Thunderbolt
192.168.1.242	PC Kobe via Thunderbolt
192.168.1.243	PC Annelore via Thunderbolt
192.168.1.244	PC Benjamin via Thunderbolt
192.168.1.245	PC Ward via cable
192.168.1.246	PC Kobe via cable
192.168.1.247	PC Annelore via cable
192.168.1.249	PC Benjamin via cable

1.12.1 Operator laptop client stations

3 Lenovo T460 stations have been acquired to be used during sniffer flight. To enable the connection from the Laptop to the sniffer sensor the firewall settings have been adjusted (see Section 2).

1.12.2 MMU client station

The MMU is the main console in the aircraft used for the Medusa system. The MMU runs on a tailored Open Suse Linux Platform and is therefore not suited for the installation of the IGPS software. A Virtual Machine (VM Player) with a Windows XP installation is installed on the MMU to allow to run IGPS on the console, see Section 2 for the correct VM configuration.

The IGPS software is installed on the "C:" drive of this VM XP distribution. The firewall has been deactivated for the IGPS software. TeamViewer V12 has been installed on the VM to enable a remote desktop connection to the MUMM_LOG_PC. To allow sharing of folders with the console the shared folders must be activated in the Virtual Machine Settings and VMWare tools must be installed.

Note: Because of an IP address conflict with the Sniffer, the WiFi connection can currently not be used together with the sniffer sensor (network adapter for WiFi must be disabled when operating the sniffer), in case the FLIR camera is required the sniffer network adapter must be disabled first After connecting the FLIR camera, the sniffer network adapter can be re-enabled.

CHAPTER 2. MEASUREMENT UNCERTAINTY

2.1. Measurement quality

To assess a good quality measurement, the following requirements have to be met:

- plume can successfully be linked to a ship;
- response times of the SO_2 and CO_2 gas sensors are comparable;
- plume sampling time is sufficient;
- a good signal to noise ratio (SNR);
- no interference from land pollution or other sources.

2.1.1 Successful linking of plumes to ships

In the cases when ships are not emitting an AIS signal (e.g., military vessels) or when ships are sailing very close to each other with the same course and speed, it could be challenging to link a vessel to a plume. In some cases when vessels are crossing each other, plumes can be mixed. In those cases it is recommended not to conduct any measurements to avoid cross-linking of ships.

2.1.2 Response times (T90)

To assess the response times for the SO_2, CO_2 and NO_x gas sensors the T90 time can be calculated using the T90.xls file.

SOP 3.9. To compile the raw data

1. Conduct a software calibration (see Section 2)
2. Extract the data of the concerned log file (see 1.8 Analysis of LOG files using AIS Extract)
    a. Import the log file
    b. Open “Calculation T90.xls” file
    c. 05-FluxSense_Sniffer\0. QMS\3. SNIFFER DM\Data analysis\T90
    d. Open Import sheet
    e. Go to Data>Get Data>Legacy Wizards>TXT (legacy)
    f. Select EXTR-SO2.TXT, EXTR-LICRO7200.TXT or EXTR-Serinus40.TXT
    g. Use comma “,” as separator
    h. Select finish
3. Copy the gas and time concentration to selection sheet
    a. For CO2
        - column AX will give the CO_2 in ppm
        - column A will give the time of the sniffer (per second), column L will give the sensor time up to 0.1 sec for T90 calculations use column L
    b. for SO2
        - column F will give the SO_2 in ppb
        - column A will give the time of the sniffer (per second)
    c. for NOx
        - column D will give the NO in ppt in scientific values
        - column J will give the NOx in ppt in scientific values
        - column A will give the time of the sniffer (per second)

SOP 3.10. To transform the NOx data:

1. Select the columns D and J and click ctrl+h, write '= and select replace all
2. Split data, use "+" as separator and copy to a new column
3. Split data use "-" as separator
4. Create a new column that either contains the negative values (add -) or positive values for the exponents
5. Combine the value for the measurement with the exponent, divide by 1000 to arrive to the concentration in ppb

Note: excel templates exist for the automatic import of extracted files for NOx, CO2 and SO2 under T90 folder

SOP 3.11. To import the data in T90 file

1. Select data
    a. With the selection graph, the correct start and end of the concentration peaks can be found
    b. Up to 10 peaks can be calculated at once
    c. Keep minimum 30 measurements before and after the concentration difference(s).
    d. Delete the additional data
2. Go to T90 sheet, T90 times for upper and lower peaks are calculated automatically. A linear T90 is calculated automatically, for non-linear T90 calculation (interpolation between points or by fitting on S-curve) and interpretation a more detailed analysis is required, and should only be done by experienced data scientists
3. The UP and DOWN sheets provide graphs to interpret the linear and non-linear T90 times

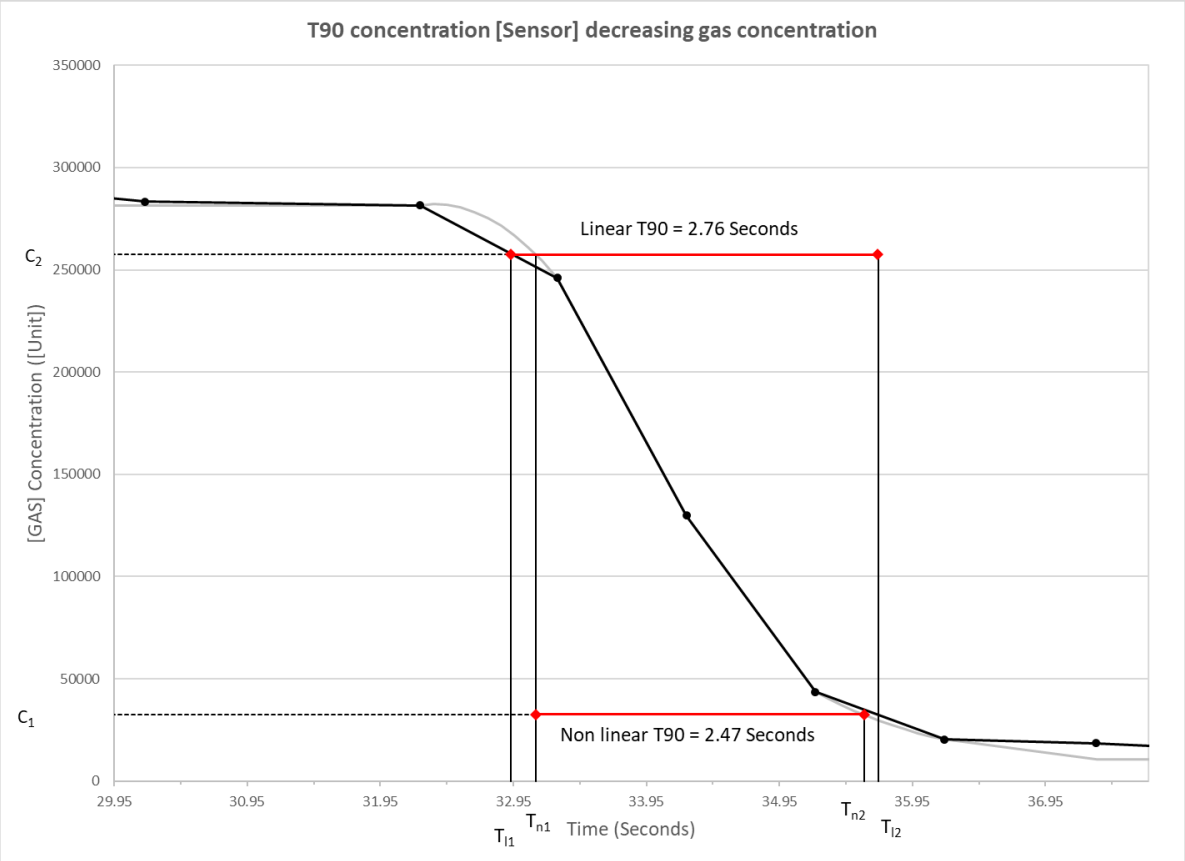


Figure 141 Automatic calculated T90 response time (this example is for decreasing gas concentration

The response time for the three sensors should be the comparable or SO_2 and NOx should be slightly slower than CO_2. (for 2019: T90 of SO_2: 3.52 sec and T90 of CO_2: 2.87 sec were sufficient).

2.1.3 Plume sampling time

To calculate the plume sampling time, the Emissiondata_xxx.TXT can be used, in this file the start and end of each plume is available.

SOP 3.12. To calculate plume sampling time

1. Import data using the IMPORT.XLSM file (See xxx)
2. Go to "Emissions" sheet and copy paste the relevant data (or all data) in a blanco sheet
3. Find plume sampling time
    a. Start time = tEndLeftBaseline
    b. End time = tStartRightBaseline
    c. In a new Colum create a difference between start and end time

The plume sampling time is sufficient when this is half the T90 time, in 2019 this was on average 7-8 seconds.

2.1.4 Noise

Noise is the variation in the gas concentration which is not a result from the measurement of plumes (signal). The noise factor is often expressed as the signal to noise ratio.

$$SNR = \frac{A_{plm}}{A_{bkg}}$$

SOP 3.13. To calculate the A_{bkg}

1. Extract a set of log files (see 1.8 Analysis of LOG files using AIS Extract)
    a. Go to Data>Get Data>Legacy Wizards>TXT (legacy)
    b. Select EXTR-SO2.TXT or EXTR-LICRO7200.TXT
    c. Use comma "," as separator
    d. Select finish
2. Copy the gas and time concentration to selection sheet
    a. For CO2
        - column AX will give the CO2 in ppm
        - column A will give the time of the sniffer (per second), column L will give the sensor time up to 0.1 sec
    b. for SO2
        - column F will give the SO2 in ppb
        - column A will give the time of the sniffer (per second)
    c. for NOx
        - column D will give the NO in ppt in scientific values
        - column J will give the NOx in ppt in scientific values
        - column A will give the time of the sniffer (per second)
3. To transform the NOx data follow the steps
    a. Select the columns D and J and click ctrl+h, write '= and select replace all
    b. Split data, use "+" as separator and copy to a new column
    c. Split data use "-" as separator

d. Create a new column that either contains the negative values (add -) or positive values for the exponents

e. Combine the value for the measurement with the exponent, divide by 1000 to arrive to the concentration in ppb

Note: excel templates exist for the automatic import of extracted files for NOx, CO2 and SO2 under T90 fold

SOP 3.14. To calculate A_{plm}

1. Select a dataset with stable background (over sea) of minimum 60 measurements
2. Calculated the Standard deviation ("STDEV()")

To guarantee a sufficient quality, only plumes with a minimum SNR of 15 are deemed acceptable, for SO2 a lower SNR of 10 can be used as for non-compliant ships always 2 measurements are made. With the A_{bkg} the minimum A_{plm} can be calculated for an SNR of 15 or 10. Based on the data from 2019 a sufficient SNR as achieved from **5ppb CO_2**, for non-compliant ships a minimum peak of **3ppm SO2** is required. (See Section 1)

In some occasions background conditions may be unstable, resulting in more noise. When these conditions are observed and the quality of the measurements cannot be ensured, the Marpol Annex VI mission type should be interrupted and the operators should switch to a general pollution control mission. Main reasons for these unstable background are e.g. land based pollution (close to shore) and smog due to inversion layers. (See Section 1)

The described minimum peak height provide some guidance but ultimately the operators should rely on their experience to assess if the quality of the measurement is acceptable or not, when in doubt it is best to seize the operations.

2.2. Measurement uncertainty FSC

Initially limited information was available on the measurement uncertainty, which was estimated at 50% FSC (Berg et al., 2010). The uncertainty of the Belgian FSC measurements (U) can be defined as a combination of the measurement bias (b) and the standard deviation (u_{tot}):

$$U = |b| + \sigma . u_{tot} \tag{11}$$

To calculate the measurement bias, the median of the airborne emission measurements should be (preferably annually) compared to the median of a set of 30 random fuel sample analysis taken by PSC in a certified laboratory (uncertainty <0.01%). This will give an approximate bias (0.018 +/- 0.005 % FSC).

Note: The bias is actually larger (ca -0.07), but the NO cross sensitivity (+0.05) is partially correcting this bias.

The standard deviation can be calculated based on the intra-assay coefficient of variability and the sum of all additional supplementary uncertainty factors ($u_{sup,i}$). See Table 17 for an overview of these supplementary uncertainty factors.

$$u_{tot} = \sqrt{(CV_{RW})^2 + \sum\left(u_{sup,i}\right)^2} \tag{12}$$

$$CV_{RW} = \frac{1}{\sqrt{2}} \sqrt{\frac{\sum_{i=1}^{n} \left(\frac{x_{i1} - x_{i2}}{0.5(x_{i1} + x_{i2})} \right)^2}{n}} \times 100(\%) \quad (13)$$

The CV_{RW} is calculated on a set of repeated measurements (ships that have been measured twice). The CV_{RW} should be annually updated based on the new data. The CV_{RW} are calculated for 3 different ranges of FSC values. The supplementary uncertainty factors include all additional uncertainty factors. Some were calculated based on the observed values (see. drift values) others, like sensor uncertainty, were based on description from literature or from the sensor manual. In those cases, the used CI is 95%.

The supplementary uncertainty factors are listed in Table 17. The uncertainties of the span gasses should be updated on annual basis. With the bias and total uncertainty values, the combined uncertainty can be calculated for the three FSC levels.

Table 17. Supplementary uncertainty factors and the combined supplementary standard uncertainty.

Supplementary uncertainties	Max
SO_2 span gas drift (3 months)	2.77%
SO_2 span gas concentration*	0.20%
CO_2 span gas drift (6 months)	0.92%
CO_2 span gas concentration*	0.05%
Measurement accuracy SO_2 sensor	0.40%
Measurement accuracy CO_2 sensor	0.05%
Error on FSC correction (offset reference)	2.35%
Error on FSC correction (offset measured)	2.17%
Error on FSC correction (Slope reference)	2.79%
Error on FSC correction (Slope measured)	4.26%
Uncertainty molar mass S	2.49E-06
Uncertainty molar mass O	1.88E-05
Uncertainty molar mass C	0.01%
Uncertainty molar mass N	2.49E-06
Uncertainty C content in marine fuel	0.83%
Combined supplementary standard uncertainty $\sum u_i^2$	3.17%

An additional reason for uncertainty is the sensitivity of the SO_2 sensor to VOCs from marine lubricants in OGV emissions. In standard SO_2 analysers VOCs are filtered out with a hydrocarbon kicker. This kicker restricts the airflow to 0.8 l/min, much lower than the required 6 l/min, and is hence not used in the airborne sniffer system. As a result, in some cases (less than 1 on 20) the SO_2 concentration may not drop back to the background levels together with the CO_2 concentration. This is probably due to an adhesive effect of the VOCs in the measurement chamber of the SO_2 sensor. In those cases the SO_2 level should be cut off together with the CO_2 to avoid an overestimation of the FSC.

2.2.1 Updating FSC uncertainty factors

On annual basis the new uncertainty factors should be calculated to refine the uncertainty calculations.

SOP 3.15. To update the uncertainty factors

1. Open de Accuracy.xls file

05-Instrumentation 0. QMS\3. SNIFFER DM\Data analysis\Acuracy analysis\Accuracy.xls

2. Calculate new bias
    a. Calculate median from 30 Fuel samples (via function: "median()")
    b. Calculated the median from the FSC values from the corresponding period
    c. Copy paste the values in the "Bias" sheet in the Accuracy.xls file
    d. The bias will be calculated and should be copied to the "uncertainty FSC" sheet
3. Open the updated long-term dataset Sniffer long term results 2015-xxx (see xx)
4. 05-Instrumentation\05-FluxSense_Sniffer\0. QMS\3. SNIFFER DM\Data analysis\Belgian Sniffer Campaign 2021
5. Calculate the updated CV_{RW} per alert level
    a. Filter data on colour flag (green+yellow)
    b. Filter data that has 2 measurements (deselect "na" for FSC-2)
    c. Copy paste the filtered data to the correct sheet (man-man <0.2")
    d. Repeat the same with the other colour flags
        - Orange: "man-man 0.2-0.4"
        - Red: "man-man>0.4"
6. Copy paste the updated CVRW to the "uncertainty FSC" sheet in Accuracy.xls file
7. Calculate the supplementary uncertainty factors Go to SQMS follow up.xls
    a. Go to GAS CAL sheet
    b. Calculated the average drift of the SO2 gas mixtures used that year (select values and average is displayed in the bottom)
    c. Fill in this value in the "uncertainty FSC" sheet in Accuracy.xls file (in "min" column)
    d. Do the same for CO2
8. Copy new Bias and FSC uncertainty factors to 0. QMS\3. SNIFFER DM\IMPORT IGPS DATA\Import.xlsm uncertainty sheet (hidden)
9. Save import file

2.3. Measurement uncertainty NOx

Similarly as for FSC the total NOx uncertainty measurement (U) can be described as a combination of the measurement bias (b) and the standard deviation ($\underline{u_{tot}}$):

$$U = |b| + \sigma . u_{tot} \quad (14)$$

In contrast to the FSC, where fuel samples from port inspections were used to calculate the, no reference data is available for NO_x. Nevertheless it can be assumed that there is a negative systematic error for several reasons. The first is the difference between indicated power of the main engine, which is requested through radio communication and the brake power which is used in the NO_x technical code. The brake power is measured at the crankshaft using a brake dynamometer. For conformity and simplification the indicated power is requested when contacting an OGV. As the indicated power is always higher due to friction losses of the shaft and auxiliary systems connected with the main engine. The ratio between indicated power and brake power is expressed as mechanical efficiency (N_m). This efficiency is in the order of magnitude of 95% at full power but can be as low as 75% at rated speed. The use of the indicated power instead of the brake power means an overrating

of the power output in the SFC formula and therefore will result in an underestimation of the SFC and NO_x emissions by ca. 15%.

The next factor is the temperature and a humidity correction. The NO_x Technical Code describes that a correction should be applied for the air intake temperature and humidity.

$$k_{hd} = \frac{1}{1 - 0.0182 \times (H_a - 10.71) + 0.0045 \times (T_a - 298)} \quad (15)$$

In the Belgian part of the North Sea the annual average temperature is 11.9°C, the annual average maximum temperature is 14.5°C with an average humidity of 5.6 g/kg dry air. The corresponding combined average negative correction is 3.4% with a range between 2-4% (see Figure S.10).

The last factor is the impact from auxiliary engines and generators. These are generally 4 stroke engines with a higher ERS and have therefore lower emission limits. As only OGVs that are on-route are measured, the impact of the exhausts of these engines on the emission measurements of the main engine is limited. Nevertheless due to a dilution effect, main engine exhaust with higher NO_x/CO_2 ratios might be mixed with lower auxiliary engine exhaust with lower NO_x/CO_2 ratios and thus creating a negative bias. The part of the auxiliary exhausts in the total OGV exhaust is impossible to determine in flight, nevertheless auxiliary engine(s) can take up to 10-15% of the used fuel on the total journey. This amount can be even higher when the ship is sailing at very low speeds (DNV-GL, 2015; Heywood, 2018). Auxiliary engine emission limit correspond to circa 58-64% of the limit of main engines (ERS ≥ 1000 rpm), the negative bias is therefore estimated to be in the order of magnitude of 4-6%. The combined negative systematic error is therefore estimated to be 15-25%. The NO_x Technical Code provides a margin of 10% to account for the simplified measurement methods as described in Chapter 6 and an additional 10% allowance for the use of non-residual marine (non-RM) graded fuel (ISO8217:2005) such as distillates like Marine Gas Oil (MGO), although the combined allowance should not exceed 15%. For this reason, the negative systematic error was not used to correct the measurement data for reporting to PSC, as this was mostly eliminated by the 15% allowance.

The second part of the uncertainty is described by the standard deviation of the measurements. When comparing the results of repeated measurements, it was observed that in most cases the measurement data correlated strongly (R^2 =0.84). Furthermore no strong relative effect is observed on the difference between both values, although the difference between two measurements is clearly smaller for lower NO_x values than for higher measurement values.

The standard deviation u_{tot} can be calculated based on the intra reproducibility coefficient CV_{RW} and the sum of all additional supplementary uncertainty factors (u_{sup}).

$$u_{tot} = \sqrt{(CV_{RW})^2 + \sum \left(u_{sup,i}\right)^2} \quad (16)$$

$$CV_{RW} = \frac{1}{\sqrt{2}} \sqrt{\frac{\sum_{i=1}^{n} \left(\frac{x_{i1} - x_{i2}}{0.5(x_{i1} + x_{i2})}\right)^2}{n}} \times 100(\%) \quad (17)$$

To calculate the standard deviation, 3 intra reproducibility coefficients have been calculated for 3 different ranges of NO_x emission values: 0-10 g NO_x/kWh, 10-20 g NO_x/kWh and >20 g NO_x/kWh. The CV_{RW} values are displayed in Table S.2. The supplementary uncertainty factors are listed in Table S.1. For the reported indicated power an uncertainty of 6.8% was used and for the provided fuel

consumption 10% was, although this does not include an uncertainty due to human errors during reporting. From the 43 OGVs that were contacted, 16% provided unreliable data, for those OGVs the standard SFOC of 200 g fuel/kWh was used. With the bias and total uncertainty values, the combined uncertainty was calculated for the three NO_x emission levels.

Table 18 Supplementary uncertainty factors NOx

Supplementary uncertainties	Max
NO_x span gas drift (3 months)	1.97%
NO_x span gas concentration*	3.00%
CO_2 span gas drift (6 months)	1.44%
CO_2 span gas concentration*	2.00%
Measurement accuracy NO_x sensor	0.50%
Measurement accuracy CO_2 sensor	1.00%
Uncertainty molar mass N	6.07E-05
Uncertainty molar mass O	1.88E-05
Uncertainty molar mass C	0.02%
Uncertainty C content in marine fuel	1.34%
Uncertainty Indicated power	6.8%
Uncertainty fuel consumption	10.00%
Combined supplementary standard uncertainty	12.97%

** According to gas analysis certificate*

2.3.1 Updating NOx uncertainty factors

Also for NOx the uncertainty should be recalculated on annual basis.

SOP 3.16. To calculated the new uncertainty factors

1. Open de Accuracy.xls file
2. 05-Instrumentation 0. QMS\3. SNIFFER DM\Data analysis\Acuracy analysis\Accuracy.xls
3. Open the updated long-term dataset Sniffer long term results 2015-xxx (see xx)
4. 05-Instrumentation\05-FluxSense_Sniffer\0. QMS\3. SNIFFER DM\Data analysis\Belgian Sniffer Campaign 2021
5. Calculate the updated CVRW per alert level
    a. Filter data on per emission level (smaller than 10 g NOx/Kwh)
    b. Filter data that has 2 measurements (deselect “na” for FSC-2)
    c. Copy paste the filtered data to the correct sheet (man-man <0.2”)
    d. Repeat the same with the other levels
        - 10-20 g NOx/kWh
        - >0.4 g NOx/kWh
6. Copy paste the updated CVRW values to the “uncertainty NOx” sheet in Accuracy.xls file
7. Calculate the supplementary uncertainty factors Go to SQMS follow up.xls
    a. Go to GAS CAL sheet
    b. Calculated the average drift of the NO2 gas mixtures used that year (select values and average is displayed in the bottom)
    c. Fill in this value in the “uncertainty NOx” sheet in Accuracy.xls file (in “min” column)
    d. Do the same for CO2
8. Copy new NOx uncertainty factors to 0. QMS\3. SNIFFER DM\IMPORT IGPS DATA\Import.xlsm uncertainty sheet (hidden)
9. Save import file

CHAPTER 3. THREHOLDS FOR REPORTING

3.1. FSC threshold calculation

Three alert levels (colors) are created. For each color flag an operational reporting threshold (T_{OPS}) is defined. The yellow flag represents the lowest alert level of 0.15% FSC. The orange flag indicates a medium alert level of 0.2% FSC and red flags indicates a high non-compliance alert, set at 0.4% FSC. The actual threshold (T_a) is defined as the FSC for which the difference with the combined measurement uncertainty exceeds a pre-defined sulfur limit (S).

$$S\ (\%FSC) = T_a(1 - U) \tag{14}$$

$$T_a = \frac{S}{1 - U} \tag{15}$$

Different CIs are used per alert level. For the yellow color flag a CI of 68% is used (σ = 1), for the orange color flag a CI of 95% (σ = 1.96) is used, for highest alert level, a CI of 99% is used (σ = 2.576). In addition, different Sulfur limits (S) are used to reflect on the level of PSC follow-up as well. For the yellow flag, a sulfur limit of 0.10% is used. This means that for a yellow alert there is a 68% probability that the FSC value of the OGV is more than 0.10% FSC. For the orange flag, a sulfur limit of 0.11% FSC is used, as this is the limit that can be confirmed by laboratory fuel sampling analysis. This means that an orange alert has an FSC that is more than 0.11% FSC with a CI of 95%. For the red flags, the sulfur limit is set at 0.15% FSC. For red alerts the FSC is more than 0.15% FSC with a CI of 99%. The actual resulting measurement thresholds per color flag are displayed in Table 19. The actual thresholds should be lower than the operational thresholds (T_{OPS}) for an additional margin of error.

3.2. Updating FSC Threholds

The thresholds have to be checked on annual basis (with the updated uncertainty factors and bias), in case the actual threshold exceeds the operational threshold, the threshold should be corrected. In case the actual thresholds would be much lower than the operational threshold, the operational thresholds might be lowered, this should always be approved by FOD Mobility.

To update the Thresholds it suffices to calculate the updated uncertainty factors and bias (See 1.11, the updated threshold are available on the bottom of the sheet and should be when changed updated in the “Threholds and Bias.xls” file on der C:\\IGPS folder

Table 19 Alert flag thresholds 2022 (t values were used instead of σ due to n<30)

Color flag	t	U	CI	Sulfur limit	T
Yellow	0.86	22%	60%	0.10%	0.13%
Orange	2.179	38%	95%	0.11%	0.19%
Red	2.528	48%	99%	0.15%	0.28%

Table 20 Thresholds used in flight (in Thresholds and Bias.xls on C:\\IGPS folder)

Thresholds		CI
Yellow	0.13	60%
Orange	0.2	95%
Red	0.3	99%

3.3. NOX threshold calculation

As for FSC, a color flag system was composed that incorporates the measurement uncertainty, but also reflects on the level of non-compliance. The compliance threshold (T) was defined as the NO_x emission measurement value from which the OGV is considered to be non-compliant and would therefore be alerted to PSC authorities. The Threshold is reached as soon as the NO_x emission minus the measurement uncertainty is higher than the Tier limit (L) plus the NTE.

$$L_{Tier_i} + NTE = T - U_T \tag{18}$$

$$T = \frac{L_{Tier_i} + NTE}{1 - \sigma \times u_{to}} \times (1 + b) \tag{19}$$

For operational use the thresholds are further rounded up to 5 g NO_x/kWh for Tier I and Tier II and to 1 g NO_x /kWh for Tier III. Thus creating operational thresholds, that are convenient for the operators to memorize and apply in flight

3.3.1 Tier I and Tier II

The lowest alert level, the yellow flag color, uses a 68% confidence interval (CI) and a not to exceed limit (NTE) of 15%, corresponding to the 15% margin of the NO_x Technical Code. The medium alert level, the orange flag color, uses a 95% CI with a NTE limit of 20% for Tier I. The red flag is used for high non-compliance alerts, with a CI of 99% and a NTE limit of 50%. The NTE levels for the orange and red flags are higher to take into account a tolerance level for the weighting factors.

3.3.2 Tier III

As no data yet exists for Tier III, the uncertainty for this measurement range could not yet be calculated. Nevertheless it can be assumed that this would be comparable to the uncertainty of Tier I and Tier II. For the Yellow flag a 50% NTE limit was used corresponding to the NTE limit of the NO_x Technical Code. For the Orange and Red flag a NTE of 60% and respectively 65% was used to incorporate an additional tolerance due to the low emission limit and unknown uncertainty.

Table 21 Threholds and uncertainty for different Tier levels

Tier	L_{Tier}	Color flag	NTE	σ	T	T_{ops}
*Tier I**	17	*Yellow*	15%	1	21.2	25
		Orange	20%	1.96	31.8	35
		Red	50%	2.576	53.2	55
Tier II	14.4	*Yellow*	15%	1	17.9	20
		Orange	20%	1.96	26.9	30
		Red	50%	2.576	45.0	45
Tier III	3.4	*Yellow*	50%	1	5.4	6
		Orange	60%	1.96	7.5	8
		Red	65%	2.576	8.9	9

3.4. NOX threshold update

The determination of the initial thresholds was based on test measurements from 2020. The thresholds have to be checked on annual basis (with the updated uncertainty factors), in case the actual threshold exceeds the operational threshold, the threshold should be corrected. In case the

actual thresholds would be much lower than the operational threshold, the operational thresholds might be lowered, this should always be communication with FOD Mobility.

To update the Thresholds it suffices to calculate the updated uncertainty factors and bias (See 1.11, the updated threshold are available on the bottom of the sheet and should be when changed updated in the "Threholds and Bias.xls" file on der C:\\IGPS folder.

Table 22. Updated Thresholds for ERS < 500 RPM

Threholds	Tier I ('01-'10)	Tier II ('11-'20)	Tier III (>2021)	Tier I+II	Tier III	CI
Limit (130xRPM)	17	14.4	3.4	NTE (BE)	NTE (IMO)	
Yellow	25	20	7	15%	50%	68%
Orange	35	30	9	20%	60%	95%
Red	55	45	12	50%	65%	99%

Table 23 Updated Thresholds for ERS > 500 RPM

Threholds	Tier I ('01-'10)	Tier II ('11-'20)	Tier III (>2021)	Tier I+II	Tier III	CI
Limit (500xRPM)	13	10.5	2.6	NTE (BE)	NTE (IMO)	
Yellow	20	15	5	10%	50%	68%
Orange	25	20	6	20%	50%	95%
Red	45	35	7	50%	50%	99%

CHAPTER 4. REPORTING OF NON-COMPLIANCE DATA

This chapters describes the specific reporting procedures for the reporting of non-compliant ships. Chapter 5 describes the reporting procedures for the reporting of all compliance data in bulk, for reporting to Thetis-EU and third parties, hence the reporting for all compliance data also includes the reporting of non-compliance data.

The operational procedures for reporting of non-compliant ships follow the general operational reporting procedures for other violations, these procedures are described under Chapter 3 and Chapter 4 of the OPS manual and can be found on 04-OPS-Manual\OPSMANUAL Draft july19.

It is crucial to provide fast and accurate reporting for non-compliant ships as the airborne monitoring can only be used for targeting ship inspections in port. All crucial steps for the gathering of reliable and high quality data are provided in Section 1. It is important that all quality requirements are fulfilled (see 2.1 Measurement quality) or in case not all requirements are fulfilled that these are documented during the reporting of the non-compliant vessels.

Example in case only one measurement could be made, the alert can still be reported but it should be specifically mentioned in the report.

4.1. Flight report creation

The standard flight report should be used for the reporting of non-compliant ships, see **Annex C - Flight report** for an example of such a flight report for Marpol Annex VI

4.1.1 Data collection

After a non-compliant ship is observed and 2 measurements were made , the measurement data (FSC values, color flag, country, shipname) should be written down on the flight log and the event data should be collected in MEDUSA. Once the data is collected in the event management tool, a flight report needs to be created for every single observed potential violation:

SOP 3.17. To create the pollution event

1. Identify Colour Flag and country in which waters the detection was made
2. Make event on console +
    a. Open AIS INFO (GUI>>ECS>>AIS Info)
    b. Click on the target
    c. Select “Create Target”
3. Select event
    a. Got to event management (GUI>>Control>>Event Management)
    b. Scroll through event list and look for the correct event (last event is displayed on top)
    c. If necessary click on “reset”
4. In the right part of the window in the observation type drop down list select “Pollution”
5. Copy paste comments to further remarks
    a. Cut-paste AIS ship info of polluter to ‘remarks’ in the event manager, keep relevant info:
        - Shipname,
        - IMO number,

- MMSI number,
- Destinations,
- ETA,
- Shiptype,
- Dimensions,
- SOG, COG

b. Check next Port of Call

c. Add 2 FSC values in "Further Remarks", add Colour Flag and "confirmed by second measurement"

6. Fill in polluter name in "polluter observed"

7. For substance, type "SO_2"

SOP 3.18. To create a flight report

1. Generate Flight Report with the MEDUSA Analysis tool

a. GUI>>Control>>Analysis

b. Select flight nr

c. Go to Start>>Generate flight nr

d. Deselect all events and pictures

e. Select the correct event

f. Select "Generate report"

2. Open the report on the Mission folder of the corresponding flight

a. Mission data is stored per flight number on the MSU

b. Per mission a set of folders is created, the flight reports are stored under "Report" folder

c. If multiple reports are generated per flight they will receive an sequence number

3. Open the flight report with calc

4. Following items need to be checked or modified in the report

a. Use Scenario 37

b. Check recipient list

c. Add SIOB email for ships going to SECA ports (others than NL/BE)

d. Make sure PSC (ILT and FOD Mobility are added)

e. Add NFP of affected Coastal State (if measured in FR, NL or UK waters)

f. Add concentration in quantity (add unit % (FSC)

4.2. Communication chain reporting

The flight report should only be send to the MIK. MIK will be responsible for forwarding the flight report to the legal competent authorities. Use preferably the email provider on the console for emailing the flight reports to the MIK (Thunderbird). Special templates have been created for every operator. These templates can be found under the local folders.

SOP 3.19. To send a flight reports to MIK:

1. Open thunderbird (GUI>>Control>>Email)

2. Go to templates under local folder

3. Select your personal operator folder (acronym)

4. Select and double click on the "Flight report XXX Marpol Annex VI XXX Flag XX" email

5. Modify the title

   a. Add Flight number
   b. Add Colour flag
   c. Add Country
   d. Example: Flight report 19148 Marpol Annex VI Yellow Flag FR
6. Add the flight number on XXXs in the email body and send email

```
Dear,

In attachment you can find the Belgian Coast Guard Flight Report of flight
XXX.

This report concerns the observation of a possible MARPOL Annex VI
violation.

MVG
```

Figure 142 Email for reporting Marpol Annex VI violations to MIK

4.2.1 Identities

The Sniffer flight report templates have been created with individual identities per operator. This was done to optimise the communication. As the surv email address is only used as alias it is not possible to add this account to thunderbird, an additional email address was created OO-MMM@naturalsciences.be this email address is for internal use only and should never be used for reporting to external partners. By using identities, it is possible to assign another email address as outgoing email address.

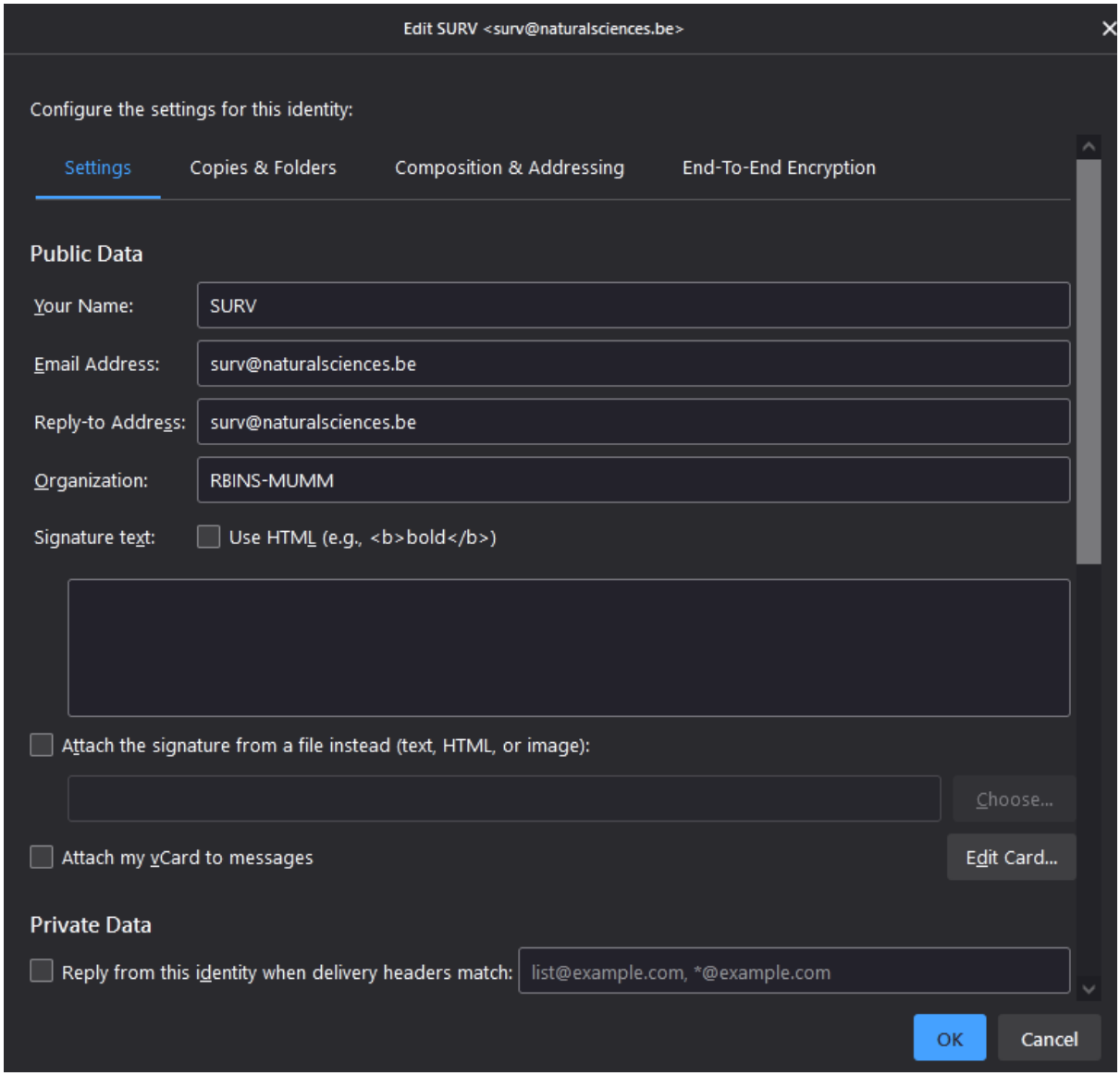
The MIK operator will not only receive all emails as if they were send from the Surv@naturalsciences.be email address but when replying to a flight report not only SURV will be contacted but also the individual email address of the reporting operator will be contacted.

SOP 3.20. To create or modify an identity

1. Go to the account settings of the surv email account (right click on oo-mmm@naturalsciences.be 365)
2. Go to "Manage Identities"
3. A window will appear
   a. Add: to add new identity
   b. Edit: to edit the settings of an existing identity
      - Select identity that needs to be modifed
      - Click edit
4. A window with alle settings will appear following items can be personilised per identity
   a. Name
   b. Email address: surv@naturalsciences.be
   c. Reply to address: surv@naturalsciences.be + optional other addresses
   d. Signature text: eg.:

      --
      Ward Van Roy
      SURV team
      Royal Belgian Institute of Natural Sciences Scientific Service MUMM Rue Vautier 29

1000 Brussels
surv@naturalsciences.be
ward.vanroy@naturalsciences.be
Mobile: 0032 476 94 04 08



CHAPTER 5. REPORTING OF COMPLIANCE DATA

5.1. Reporting to PSC

The sniffer measurement results of non-compliant vessels have to be reported to PSC and the vessels will then be marked in the Thetis-EU database. Therefore the aerial monitoring results on non-compliant vessels should be reported in near real time. For a non-compliant vessel, this means that reporting time is limited to 15 min after landing in order to provide sufficient time for the planning and prioritisation of port inspections. The flight report is send to the national 24/7 coastguard station (MIK), who forwards the flight report to PSC. Measurement results of both non-compliant as compliant vessels are also shared throughout Thetis-EU, this data-export and upload process is largely automated, but some data still needs to be validated manually.

Table 2 PSC-Communication matrix

	Compliant	**Non Compliance**
Reporting Time	<1hr after flight	Near real time (<15 min after landing)
Reporting Means	Thetis-EU web database	Thetis-EU + Flight report

5.2. Import of ship monitoring data

After all sniffer measurements are done, but **before the sniffer is shut down** the emission file and log files from the MUMM LOG PC need to be backed-up by the laptop operator. After which the data can be imported for backup and sharing with Thetis-EU.

SOP 3.21. To backup flight data

1. Copy logs
    a. On laptop go to MUMM-LOG-PC on TeamViewer
    b. Go to C:/IGPS/TCP LOG
    c. Copy recent TCP logfiles (from same day)
    d. On Laptop go to seafile folder 0.QMS\Sniffer DM\Logs\YEAR
    e. Paste the files, in case error message pops up, select “Don’t copy” + “do this for all other x files”
2. Copy the emission file
    a. On laptop go to MUMM-LOG-PC on TeamViewer
    b. Go to C:/IGPS
    c. Copy Emissionsdata_MUMM_LOG_PC.txt
    d. On laptop go to C:/IGPS/
    e. Paste the emission file, select “replace”

SOP 3.22. To import IGPS data

1. Open personal file “IMPORTV22_operatorinitials.xlsm” in “Seafile >> 11-Instrumentatie >> 05-Fluxsense_Sniffer >> SNIFFER DATA >> IMPORT IGPS DATA
2. Import the raw data
    a. The first button will import all data from the C:\IGPS directory
    b. The second button will allow you to import data from a dedicated directory (eg. IGPS POST FLIGHT)

3. Click third button "Calculate Results", the Results sheet will be opened,
4. Check if all ships are present
    a. If all ships are present continue with 5
    b. (if not close import and add measurements, see **5.2** and restart at 1)
5. Edit data in Results sheet
6. Delete double lines
7. Add the number of attempts
8. Check for unknown Keel Laying Years (e.g. use Thetis-EU or Marine traffic);
9. Check the colour flags for FSC
    a. Check if the sequence is correct for NO/NOx
    b. Check the sequence of the emissions measurements
    c. In case a ship has 2 different colour flags use lowest flag
    d. Ungroup the columns right from the emission measurement (blue numbers) change from 1,2,3 to 2,1,3 or accordingly
10. Check the colour flags for NOx
    a. Check the Gross Tonnage for TIER 0 ships with length <150m
    b. check the sequence of the emissions measurements, in case a ship has 2 different colour flags use lowest flag
    c. Ungroup the columns right from the emission measurement (blue numbers) change from 1,2,3 to 2,1,3 or accordingly
11. Recalculate sheet, and check if all adjustments are made correctly
12. Go back to "guidelines" and add start date (if different from the present day) add start/end times in case of multiple flights
13. Add flight number
14. Click apply filter
15. Check the Full data, ILT and EMSA sheets (sheets are read only)
16. Click on all 3 Export buttons
    a. Full data will be exported in the standard YEAR directory,
    b. ILT sheet will be exported in the EXTERN directory
    c. The EMSA file will be exported in the EMSA input files data directory)

Note: For violations check if after 15 min the EMSA file is moved from the "input files" directory to the "imported" directory and the alert is available on Thetis-EU

5.3. Missing data

IGPS present can be used to reload old mission data (from log files), a special IGPS Post flight folder has been installed on the C:\ and shared through seafile, this contains the same software and folders as the IGPS folder, but the advantage is that the data may be deleted. When it is observed during the import step that a ship is missing from the imported list this means that the second operator forgot to assign "LOW"/ "High" / "Not Detected" to the ship after measurements. In case the ship is available in the list but the measurements are missing the measurement needs to be redon

SOP 3.23. To reload flight log data

1. Copy Emissiondata_ODN_XXX.rbins.be.txt from C:\IGPS to C:\IGPS POST FLIGHT folder

2. Open IGPS POST FLIGHT and open LOG file (SNF>>Setting>>load data file>>Select LOG with flight hour)
3. Flight will be loaded (slow) to go faster to the correct time click on the SNF graph (look at timer)
4. When time is right, go to MAP to identify ship and when AC passes through ship plume go to SNF
5. Do measurement and assign measurement to correct ship
6. Data is now added to the emission data under the IGPS post flight folder and be either copied back to the IGPS folder or can be imported from the IGPS Post flight folder in the Import.xls file

SOP 3.24. To add missing ships

1. Identify the approximate time of the missing ship
2. Copy the sniffer file
    a. Go to C:\IGPS\ -Mail_Sniffer_SO2_Man_Meas.CSV
    b. Copy file to C:\IGPS Post Flight, select "Replace"
3. Open IGPS from the IGPS POST FLIGHT (AISPresent63.exe)
4. Load data
    a. Go to SNF>>Setting>>load data file
    b. Select LOG based on flight date and hour from 0.QMS\Sniffer DM\Logs\YEAR
5. Flight will be loaded (slow)
6. To go faster to the correct time click on the SNF graph (look at timer)
7. When time is about right, click cancel
8. Go to MAP and select ship ("LOW, HIGH, Not Detected")
9. Copy paste the sniffer file from C:\IGPS Post Flight back to C:\IGPS

SOP 3.25. To add missing measurements:

1. Identify the approximate time of the missing measurement
2. Copy the local emission file
    a. Go to C:\IGPS\Emissiondata_ODN_XXX.rbins.be.txt (xxx stands for the machine name)
    b. Copy file to C:\IGPS Post Flight, select "Replace"
3. Open IGPS from the IGPS POST FLIGHT (AISPresent63.exe)
4. Load data
    a. Go to SNF>>Setting>>load data file
    b. Select LOG based on flight date and hour from 0.QMS\Sniffer DM\Logs\YEAR
5. Flight will be loaded (slow)
6. To go faster to the correct time click on the SNF graph (look at timer)
7. When time is about right, click cancel
8. Go to MAP and wait until the ship is measured
9. Go to SNF and pause the data flow
10. Click on the CO2 window and conduct the measurement
11. Assign the measurement to the correct ship
12. Go to SNF and stop the pause
13. Close IGPS
14. Copy paste the emission file from C:\IGPS Post Flight back to C:\IGPS

SOP 3.26. To remove a measurement

1. Close all IGPS software
2. Open sniffer file (C:\IGPS\ -Mail_Sniffer_SO2_Man_Meas.CSV) in notepad
    a. Right click on file
    b. Select open with
    c. Select Notepad
3. Identify the line of the wrong ship :
    a. start scrolling from the bottom),
    b. ship names are at the end
4. Delete the line that corresponds to the wrong ship completely
5. Save the CSV file

SOP 3.27. When a measurement is connected to a wrong ship or needs to be deleted:

1. Close all IGPS software
2. Open emission file (C:\IGPS\Emissiondata_ODN_XXX.rbins.be.txt) in notepad
    a. Right click on file
    b. Select open with
    c. Select Notepad
3. Identify the line of the wrong measurement
    a. Start scrolling from the bottom)
    b. Ship names are at the end
    c. Identify the lines that start with “Name_Manual Plume”
4. Delete the line that corresponds to the wrong measurement
5. Save the text file

5.4. EMSA Thetis-EU export tool

All data that is stored in the EMSA folder with the correct format will automatically be uploaded to the Thetis-EU data base. The EMSA folder consists of following subfolders:

- Discarded: non imported files
- Imported: successfully imported files on Thetis-EU
- Inputfiles-data: this folder should be used to copy the EMSA sheet into (see previous section)
- Pending: this folder will contain files with errors that should be checked before they can be imported
- Reporting errors: this file contains all reported errors

A special database tool is created by MUMM, this database will in a first step import the data in a SQL database, in a second step the data will be streamed to the EMSA database.

5.4.1 Problems with import

In case the import is done successfully, no error mail will be send and the csv file will be replaced to the imported folder. In case the system encounters an error during the import an error mail is send to the oo-mmm@naturalsciences.be email address. The records concerning the error will be mentioned with a brief description of the error.

Following errors or commonly reported:

SOP 3.28. In case of invalid IMO number

1. No action required, this is a common error but does not interfere with the import of the data

SOP 3.29. In case of missing data or invalid data:

1. Message code: ['SULPHUR_ContentUncertainty_1=Na NOT VALID']
2. Open xxxx_Sniffer Flight.csv
3. Check which data is missing,
    a. For ship characteristics: go to Marine traffic and look for the correct data

For measurement data, in case measurement data is missing form the Full data sheet, the data should first be recollected (see 5.1)

SOP 3.30. For missing uncertainty in EMSA file

1. Look for comparable measurement in FSC
2. Copy paste the value from another record (e.g. uncertainty for a value of 0.08 is comparable to uncertainty of value of 0.09)

SOP 3.31. For missing Measurement ID in EMSA file

1. Copy paste the ID of the last measurement
    a. Add one number to the last value (e.g. BE20191008ODIN-RBINSOO-MMMR4)
2. For other missing data
    a. Copy paste data from record before the missing record or interpolate for time

SOP 3.32. In case of wrong name or format in EMSA file (wile not using macro)

1. In this case the xxxx_Sniffer Flight.csv was not saved correctly, in this case no error mail will be send and the file will remain in the input folder. This often happens when instead of the EMSA sheet, the ILT sheet was exported to the EMSA directory
2. The incorrect CSV should be deleted
3. The xxxx_Sniffer Flight.csv should be recreated and saved to the EMSA\Inputfiles-data directory
4. In case after 10 min the data is not imported contact should be made with Nabil Youdjou to fix the problem

Table 24 Example of Thetis-EU error message with the concerned record and a description of the error

missionId	Measuren	textlog

19052	BE2021042	{
		"ns0:createOrUpdateEmissionResponse": {
		"@xmlns:ns0": "http://eu/europa/emsa/thetis/integration/ws",
		"@xmlns:ns2": "urn:eu.europa.emsa.thetis.eu.deleteEmission",
		"@xmlns:ns1":
		"urn:eu.europa.emsa.thetis.eu.createOrUpdateEmission",
		"ns1:CreateOrUpdateEmissionResponse": {
		"ns1:Status": "VALIDATION_ERROR",
		"ns1:CreateOrUpdateEmissionErrors": {
		"ns1:ValidationError": {
		"@ns1:Code": "-2",
		"@ns1:MeasurementId": "BE20210427ODIN-RBINSOO-MMMR3",
		"ns1:Message": "Vessel IMO number is not valid"
		}
		}

5.4.2 Updating a record

To update a record with a new value it suffices to reopen the CSV file from the imported folder, change or update the record and save the record in the inputfiles-data directory. The database tool will automatically identify the updated value and will only change the corrected value. It is not required to delete the other records.

5.4.3 Thetis EU Data attributes

The data attributes and the description for the EMSA Thetis-EU database are provided in Table 25. It is very important to respect the formatting and formulas of the EMSA sheet of the xxxx-Sniffer Flight.xlsx file as this might influence the data export, therefore it is best to not change data in the EMSA sheet directly but only in the full data sheet.

Table 25 Attributes for data export to Thetis-EU

Element/Attribute	Comment	Example/Type	
MeasurementId		**BE**20170220112344567	Concatenation of: UNECE LOCODE of the MS (ISO2): 2-digit ISO code of the Member State; YYYYMMDD of the observation: The date of the observation; Local server Id: Identifier of the local server – "UNK" can be used for unknown; Device Id: Identifier of the device that took the measurements – "UNK" can be used for unknown; Source: "R" (stands for Remote); Message Sequence: Integer sequential identifier of each unique recorded measurement. It should be reset for each day of observation.
MemberState	ISO2 Code	"BE"	
MessageSequence	Sequential number	Sequential number: 1, 2, 3, 4, etc	
ServerID	Unique Identification of the transmitting server	Alphanumerical string	
DeviceID	Unique Identification of the used device (e.g. callsign plane, name of RPAS, code of shore based station) ; unique number	Alphanumerical string	
UpdateTime	Date and time (UTC) the msg was sent by the local server to EMSA	2014-03-14T14:15:27Z	
DateTimeOfOBS	Date and time of the observation/ measurement (UTC)	2014-03-14T14:15:27Z	
	A set of info related to the vessel identification, e.g. if the vessel is a ship, this could be the: - IMO,		

	- MMSI, - Ship name, - Call Sign, - Fishing registry and Flag		
ObservationGeoPosition	Geographical - latitude and - longitude of position of ship during the vessel observation (may be an averaged figure for more than 1 measurement)	32.281986 -39.890083	
PositionInSeca	Yes/No		
PositionInEUPort	Yes/No		
VisualObservation	Free text field		
NumberOfMeasurements	Numerical value		
Contents	Derived Sulphur content in the fuel; Percentage, three digits behind comma	1%	
ContentUncertainty	The Sulphur measurement uncertainty	+-0.2%	
Concentrations	A set of gas concentrations as measured; could be SOx, CO2, NOx, etc.		

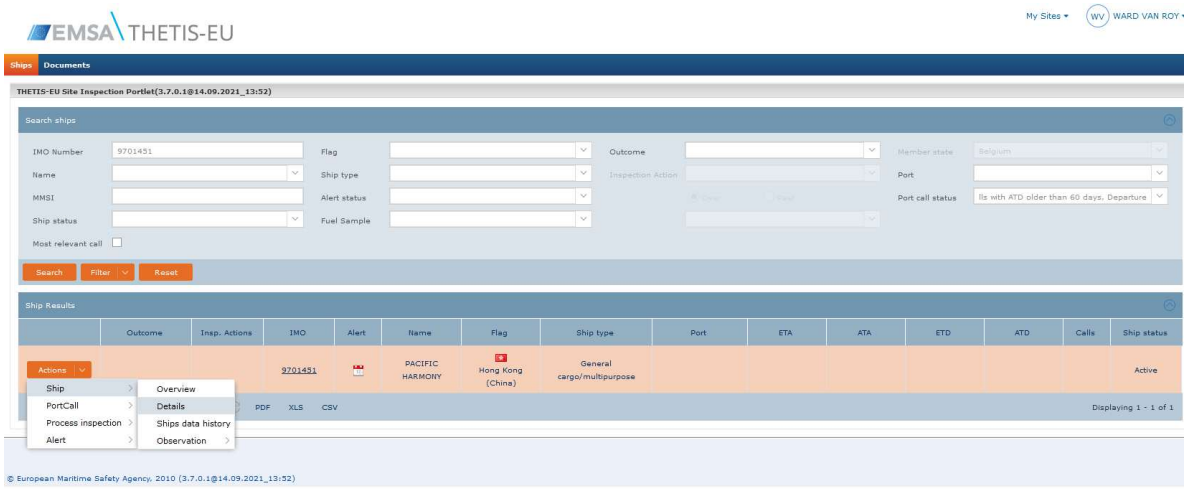
5.4.4 Checking if data upload was successful

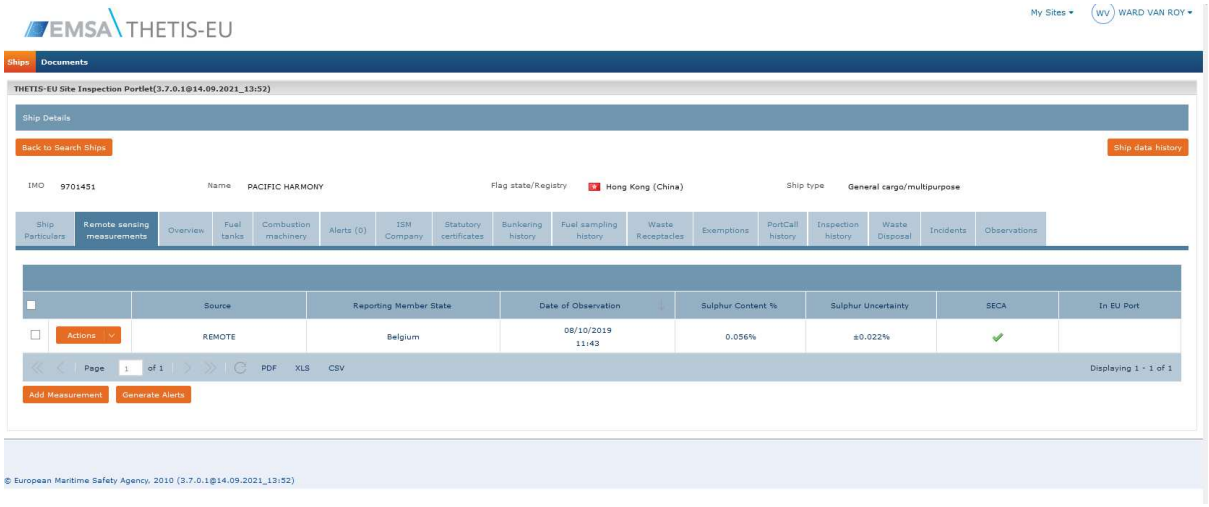
Once the data import process is completed the operator can manually check if the data was imported or not.

SOP 3.33. To check if the data export to Thetis-EU

1. Choose a certain ship
2. Copy the IMO number
3. Login to EMSA portal
    a. Go to https://portal.emsa.europa.eu/home
    b. Login with your EMSA account[6]
    c. Go to Thetis-EU>>Ships
4. Copy paste IMO number
5. Deselect "Most relevant call" checkbox
6. With "Port call Status": select "all"
7. Click search
8. If the ship exists in Thetis-EU the ship will be displayed
    a. Click on Actions (left column)
    b. Go to Ship>>Details
9. Go the "Remote measurements" tab
10. Check if the measurement is correctly available
11. For non-compliant data check if an alert is created

[6] For new users, an authorisation to grant access to Thetis-EU must be requested from the national Thetis-EU responsible (Bart Colaers from FOD Mobiliteit)


EMSA THETIS-EU
My Sites
WARD VAN ROY
Ships
Documents
THETIS-EU Site Inspection Portlet(3.7.0.1@14.09.2021_13:52)
Search ships
IMO Number
9701451
Flag
Outcome
Member state
Belgium
Name
Ship type
Inspection Action
Port
MMSI
Alert status
Port call status
Ils with ATD older than 60 days, Departure
Ship status
Fuel Sample
Most relevant call
Search
Filter
Reset
Ship Results
Outcome
Insp. Actions
IMO
Alert
Name
Flag
Ship type
Port
ETA
ATA
ETD
ATD
Calls
Ship status
Actions
9701451
PACIFIC HARMONY
Hong Kong (China)
General cargo/multipurpose
Active
Ship
PortCall
Process inspection
Alert
Overview
Details
Ships data history
Observation
PDF
XLS
CSV
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EMSA THETIS-EU
My Sites
WARD VAN ROY
Ships
Documents
THETIS-EU Site Inspection Portlet(3.7.0.1@14.09.2021_13:52)
Ship Details
Back to Search Ships
Ship data history
IMO
9701451
Name
PACIFIC HARMONY
Flag state/Registry
Hong Kong (China)
Ship type
General cargo/multipurpose
Ship Particulars
Remote sensing measurements
Overview
Fuel tanks
Combustion machinery
Alerts (0)
ISM Company
Statutory certificates
Bunkering history
Fuel sampling history
Waste Receptacles
Exemptions
PortCall history
Inspection history
Waste Disposal
Incidents
Observations
Source
Reporting Member State
Date of Observation
Sulphur Content %
Sulphur Uncertainty
SECA
In EU Port
Actions
REMOTE
Belgium
08/10/2019 11:43
0.056%
±0.022%
Page
1
of 1
PDF
XLS
CSV
Displaying 1 - 1 of 1
Add Measurement
Generate Alerts
© European Maritime Safety Agency, 2010 (3.7.0.1@14.09.2021_13:52)

CHAPTER 6. REPORTING OF ANNUAL RESULTS

The creation of annual summarizing reports on the measurement results and the dissemination is important as this allows detailed statistical analysis but is also highly important for reporting to policy makers and stakeholders.

6.1. Annual sniffer data

A directory is made per year on the SQMQ directory

0. QMS\3. SNIFFER DM\Data analysis\Belgian Sniffer Campaign "Year"

This folder will contain 2 vital spreadsheets with the annual results

- "year" all data.xlsx
- Sniffer long-term results 2015-xxx

When creating a new annual report, a new folder should be made per year and the 2 spreadsheets should be copied and the title updated to the correct year

6.2. Yearly results

This file consist of all measurement data collected during the last year. This spreadsheet consist of the "full data" sheet, the "ILT Sheet" and the "EMSA sheet".

6.2.1 Compiling the annual data

Only the full data sheet should be updated. The full data sheet has the same format and data structure as the full data sheets of the sniffer measurement files created per flight during the importing of the sniffer data (see Chapter 5). Due to periodic updates in the import procedure it is possible that the format or structure has changed during the year and has to be re-aligned.

SOP 3.34. To compile the data from individual sniffer measurement data

1. Open the directory with the measurement data per flight
2. \0. QMS\3. SNIFFER DM\IMPORT IGPS DATA\"Year"
3. Before data is added it is important that all "xxxx Sniffer Flight.xls" files have the same headers.
    a. Check the headers of first and last flight
    b. In case the headers are not the same check iteratively when headers changed (go each time to the middle of a subset of flights)
    c. Update the headers to the last version (add/move or delete columns)
4. If all data has the same columns, copy paste the "Full data per flight" in the yearly results
5. Add the flight number for every flight in the ILT sheet

6.2.2 Data cleaning

Once all data is added, the full data sheet with the annual results need to be cleaned up.

SOP 3.35. To clean the annual datasheet

1. Remove all redundant "spaces" and @ characters
    a. Ctrl+h, with find what type 20 spaces

   b. Click remove all
   c. Remove a space every time and click remove all
   d. Repeat until 1 space is left
   e. Type "@" under find what
   f. Click remove all

2. Harmonize the Flag states
   a. Use the filter to look for repetitive flag states or flag states that can be combined
   b. E.g. UK and GB
3. Check colour flags
   a. Use the filter both on colour flags and FSC and
   b. Check if all colour flags are correct with the FSC value
   c. Check if colour flags and FSC values match with the HIGH/LOW
4. Check compliance
   a. Use the filter both on Compliance and on Colour flags
   b. Check if all High alerts correspond to a yellow, orange or red colour flag
   c. Check if no FSC measurements are present with "Not Detected"

6.3. Updating Long term data

The long term data sheet consists of all measurement data from the start of the measurements in 2015. The file dates from 2016, at that moment only a limited amount of data was collected, as a result the data structure is much more limited than the data from the full data sheet, and consist of the dame data structure and format from the ILT sheet from the annual data spreadsheets.

6.3.1 Compiling

On annual basis the annual data needs the collected and added to the long-term datasheet

SOP 3.36. To compile the data for the long-term data spreadsheet

1. Open the "Sniffer Long-term results 2015-xxx. Xls" file
2. Go to the 2015-xxx sheet and update the year
3. Open the annual "xxx all data.xls" file
4. Check if the headers from the ILT sheet are the same than the main data sheet (2015-xxx)
   a. Adjust the headers where necessary (add/move or delete columns in the ILT sheet)
5. Copy paste the data from the ILT sheet to the bottom of the 2015-xxx sheet
6. The last columns contain formulas and should be copied to the bottom

SOP 3.37. To add the fight data

1. Go to "Flights" sheet
2. Open the SURV Follow-up On Task "year".xls and open the Flights sheet
3. Select the flights related to Sniffer and ILT (use filter, skip blanks)
4. Copy paste the flight data to the bottom of the flights sheet

SOP 3.38. To add the data from Port State Control follow up and the fuel sampling

1. Update the a list of all reported alerts with the FSC value in the PSC follow up sheet
2. Request all data on fuel sampling from PSC
3. Copy paste the data in the fuel sampling sheet

4. Indicate which fuel samples have been performed after an alert
5. Update PSC follow up sheet
    a. Add the FSC value(s)
    b. add date in the
    c. mark these ships as followed up by BE
6. Update PSC follow up sheet with data from Thetis-EU
    a. Go to EMSA portal, Login and go Thetis-EU/Ships
    b. Lookup which alerts (IMO nrs) were followed up for all reported alerts (see 5.4.4)
    c. Copy paste the FSC content when available (and taken after the alert)
    d. Add the date of the FSC analysis
    e. Mark that the follow up was international and add the country in comments

6.3.2 Data cleaning

Several AIS attributes need to be harmonized to allow annual data compilations.

SOP 3.39. To clean the AIS data

1. Sort on the current year by using a filtering on the date/year
2. Harmonize the destination
    a. Go to destination column
    b. Use filter to see the different values
    c. Sort per value
    d. Values should be cleaned and harmonized with old values
    e. Write the ports in English
    f. Often a 5 digit code is used per port (BEANR is Antwerp)
    g. Use a general terms for “waiting for orders” or “anchorage area”
    h. In case only the country is available use “Na”
3. When updating the Destination from AIS add
    a. Destination country (group the columns between Destination (AIS) and Destination country)
    b. SECA/Out of SECA
4. Add type
    a. Group the columns between the Type (code)
    b. Use the AIS ship type categories
        - 30: Fishery
        - 37: Pleasure craft
        - 60-69: Passenger/RORO
        - 70-79: Cargo
        - 80-89: tanker
        - For military ship, check the name of the vessel (or code 35)
        - All others should get the “others” category
5. Deactivate all filters and do a last filter check on the full data set to remove any remaining doubles
6. For all violations check if the ship was equipped with a scrubber (available on Thetis-EU)

6.3.3 Recalculating FSC data

For harmonization of the data, all measurements can be recalculated using the raw measured data for SO2, CO2 and NOx. Therefore the annual FSC span and offset can be calculated, in addition the NO/NOx ratio and NO sensitivity need to be established.

SOP 3.40. Calculating annual FSC span and FSC offset

1. To get the lower reference value
    a. Collect 30 random FSC measurements from PSC (using XRF scanner)
    b. Calculate Median FSC value from PSC
2. To get the lower measurement value
    a. Recalculate the FSC for all measurements from the raw data
        - FSC = 0.233 x (SO2-NO/NOx ratio x NO CS_{NO} x NOx)/CO2
        - NO/NOx ratio = 0.8
        - NO CS_{NO} = 0.0045
        - The gas data is available in the full data file
            i. SO2 = columns: DI-DK
            ii. CO2 = columns: DL-DN
            iii. NOx = columns: DO-DQ
    b. Calculate the unbiased FSC data
    c. Calculate mean
3. To get the higher reference value
    a. Use the average of all the lab measurements of the plume simulation mixture
4. To get the higher measurement value
5. Use the average value for all the highest values of the measurements of the plume simulation mixture
6. With the two reference values and 2 measurement values the spann and offset can be calculated by entering these values in the SQMS_Follow-up.xls file in the CO2-SO2 sheet

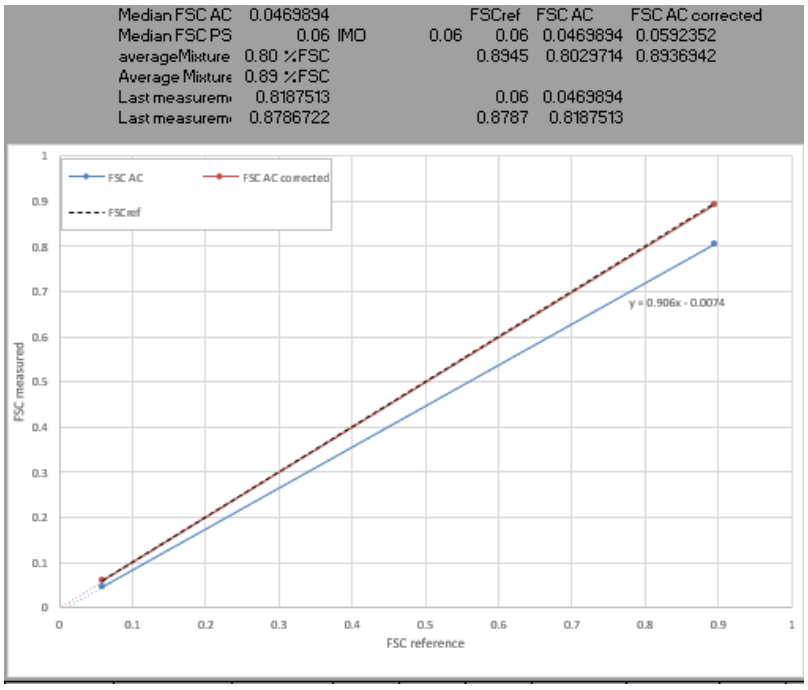


Figure 143 Calculation of annual FSC span and offset

SOP 3.41. Calculating NO/NOx ratio

1. The standard ratio is 0.8
2. To update the standard ratio measurements with both NO and NOx are used
3. Filter data with both NO/NOx measurements
4. Copy paste full data to new sheet
5. Use CO2 to calculate the NO/NOx
    - $NO/NOx = NO_i/CO2_i \ / \ NOx_I/CO2_I$
    - Calculate average NO/NOx

SOP 3.42. Calculating cross sensitivity to NO

1. The last measured NO CS is 0.0045
2. To measure the NO CS the sniffer needs to be demounted and moved to the lab of the BIM
3. Install filter box at the air inlet of the sniffer
4. Install caps on the NOx tube connectors
5. Power on the sniffer using the GPU and the clip for ground operation
6. Connect the sniffer with laptop using an ethernet cable
7. Connect Thermo panel to the sniffer
8. Set Thermo on averaging time of 30 sec
9. Use gas mixing device to provide a mixture of NO in synthetic air with different intervals between 0 and 2000 ppb
10. Write down the SO2 measurement data per step once the measurements are stable
11. Make a graph and do a regression or trendline (with intercept = 0)
12. The slope is the NO CS factor
13. Update the NO CS in the AIS-Present ini file (see Annex B - Configuration file)

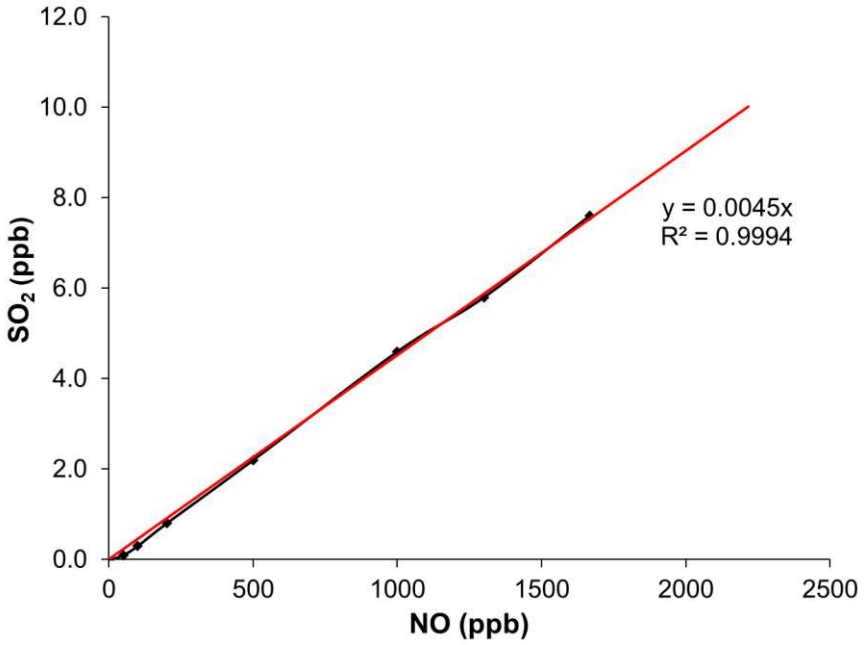


Figure 144 Calculation of NO CS

SOP 3.43. Recalculating annual data

1. With the updated NO/NOx ratio
2. With the updated NO-CS
3. With the annual FSC span and offset
4. The FSC values can be recalculated
    a. FSC = Spann x 0.233 x (SO2-NO/NOx ratio x NO CS_{NO} x NOx)/CO2 + Offset
    b. The gas data is available in the full data file
        - SO2 = columns: DI-DK
        - CO2 = columns: DL-DN
        - NOx = columns: DO-DQ

6.3.4 NOx data

In addition to the data compilation for the creating of the results on FSC. Some specific data processing is needed for the NOx data.

SOP 3.44. To clean, update and harmonize the NOx data

1. Check if all Tier levels are available and have a KLY if not add KLY
    a. Add KLY based on Thetis-EU
    b. Add KLY based on Built year from IMO/Marine traffic
2. Add maximum speed and check if for all possible violations have entered the engine parameters if not add data from following websites
    a. Thetis-EU
    b. https://www.fleetmon.com/
    c. https://ships.jobmarineman.com/
    d. https://shipnext.com/
    e. ..

6.4. Compilation of annual results

Once the data is cleaned, the summarizing table must be modified to include the new results

SOP 3.45. To update the overview sheet with the total results:

1. Go to the overview sheet
2. Add a column between the results per year and the total column
3. Copy paste the formula for each cell from the previous year updating the start and end of the rows for the new year
4. Modify the end row for the formulas in the total column

6.4.1 Updating graphs

Several graphs need updating, for those graphs either the data for the graphs needs to be update, a metadata table need to be updated, or the pivot table needs to be updated. As a full description for each graph would be too much time consuming this job needs to be done by an experienced data-analyst or under guidance of trained operator.

CHAPTER 7. DATA STORAGE AND BACKUP

This chapter described the tools that were developed to ensure a failproof data sharing system of vital sniffer data and the efficient archiving of backups.

7.1. Seafile

At this moment the sniffer data is not integrated in the SURV database. To make sure that the sniffer data is properly archived all data is regularly backed up on the Seafile cloud service either through an automatic synchronization process or by manual backups.

7.1.1 IGPS folders

IGPS folders on the laptop client stations are synchronized through seafile this makes sure that all operators have access to all measurements and use the same software versions and configuration during flight. Although some files are personal like the emission files and the collected AIS data. This means that for every user a separate file is made (naming is done based on the name of the machine on which the software is running).

7.1.2 SQMS

The SQMS folders include all aspects of operations of the sniffer and is shared through seafile. The structure is in line with the sections in the Sniffer Quality Management system:

- Sniffer OPS: The main content is the sniffer operational manual
- Sniffer QA: The main content is the SQMS Follow up and Sniffer Quality Assurance manual, this folder also includes the Technical reference docs and relevant manuals
- Sniffer DM: this includes all data analysis, LOG data, Imported data and the this Data Manual

7.1.3 Datastore folders

The datastore is a network location provided by RBINS, a folder of 4 TB was provided for surv and consists of the SURV mission archive. For long term safekeeping the raw data from IGPS folders should be annually backed up on the Datastore (see 7.3). The \surv location on the Datastore is shared through seafile through the laptop of Ward Van Roy and consist of following subfolders:

- 20-SURV-Flight-Reporting
- 21-SURV-Pictures
- 22-SURV-Movies
- 23-Mission Database Backup
- 24-International-Missions-Polex
- 25-Sensor data
- …
- 30-CSN Data

Note: although shared on Seafile these folders contain a high amount of data and should not be physically synchronized on the hard drives of the operator laptops.

To access the data-store a VPN connection is required. The Sophos SSL VPN client 2.1 application needs to be used to create a VPN connection. In some cases the software needs to be reinstalled due to issues with the initial installation.

SOP 3.46. To install the VPN software

1. Download and install Sophos SSL VPN Client 2.1 application from
2. 0. QMS\2. SNIFFER QA\Technical Reference Docs\VPN\OLD_VPN\
3. Download your configuration file
    a. Go to https://proxy.naturalsciences.be/userportal/webpages/myaccount/login.jsp
    b. and log in using your RBINS credentials (same Primetime)
    c. Download configuration for Other Oss from SSL VPN Client area.
4. After the installation go to "C:\Program Files (x86)\Sophos\Sophos SSL VPN Client\config" folder;
5. Delete the OVPN file
6. copy your xxx@rbins.be__ssl_vpn_config.ovpn file into
7. "C:\Program Files (x86)\Sophos\Sophos SSL VPN Client\config" folder

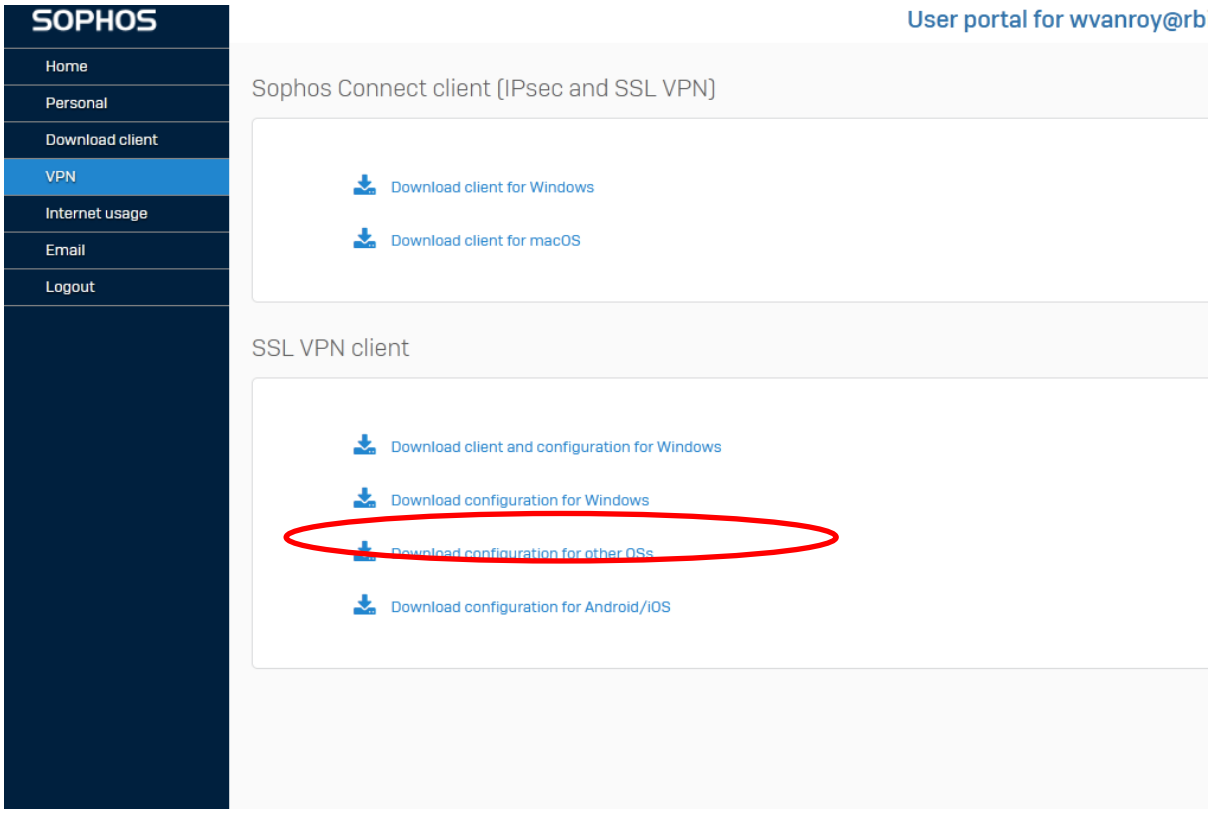


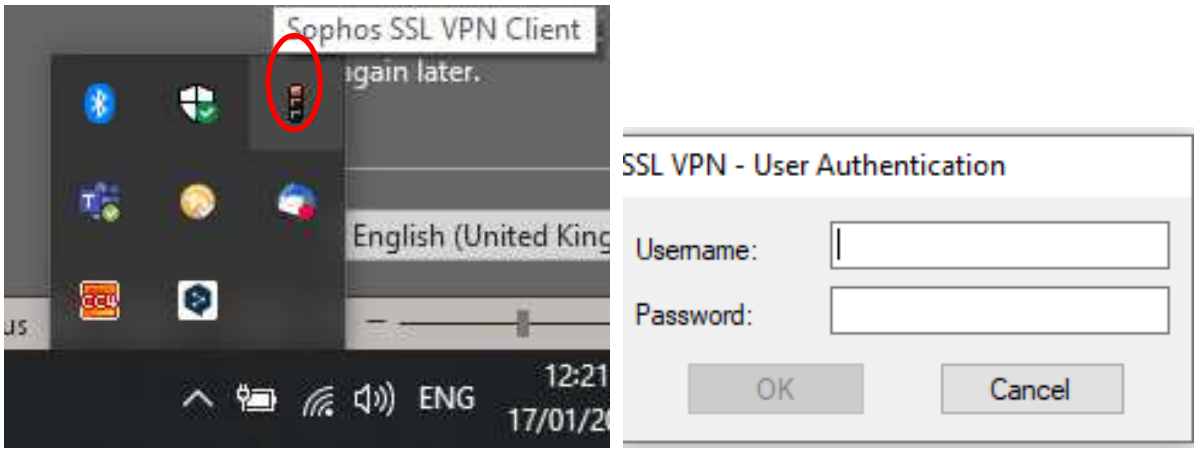
Figure 145 Sophos configuration file

SOP 3.47. To re-install the VPN software after reinstallation

1. Go to "C:\Program Files (x86)\Sophos\Sophos SSL VPN Client\config" folder
2. Delete all OVPN files
3. Uninstall Sophos SSL VPN Client 2.1 application;
4. Repeat the steps 1-5 from SOP 3.47

SOP 3.48. To connect to the RBINS network

1. Launch the Sophos Open VPN software (location from start or search)
2. Right-click on the traffic light symbol in the right taskbar
3. Select “Connect”
4. A popup window appears for Authentication
5. Use your RBINS credentials and select “Ok”
6. The traffic light will become green once connected to the RBINS network



SOP 3.49. To access the datastore

1. Go to “This PC” in Windows Explorer
2. Right click and select “Map network drive”
3. Enter the “\\Datastorew\surv” path
4. The location will be opened, to create a shortcut, use ctrl+d or add to quick access or start

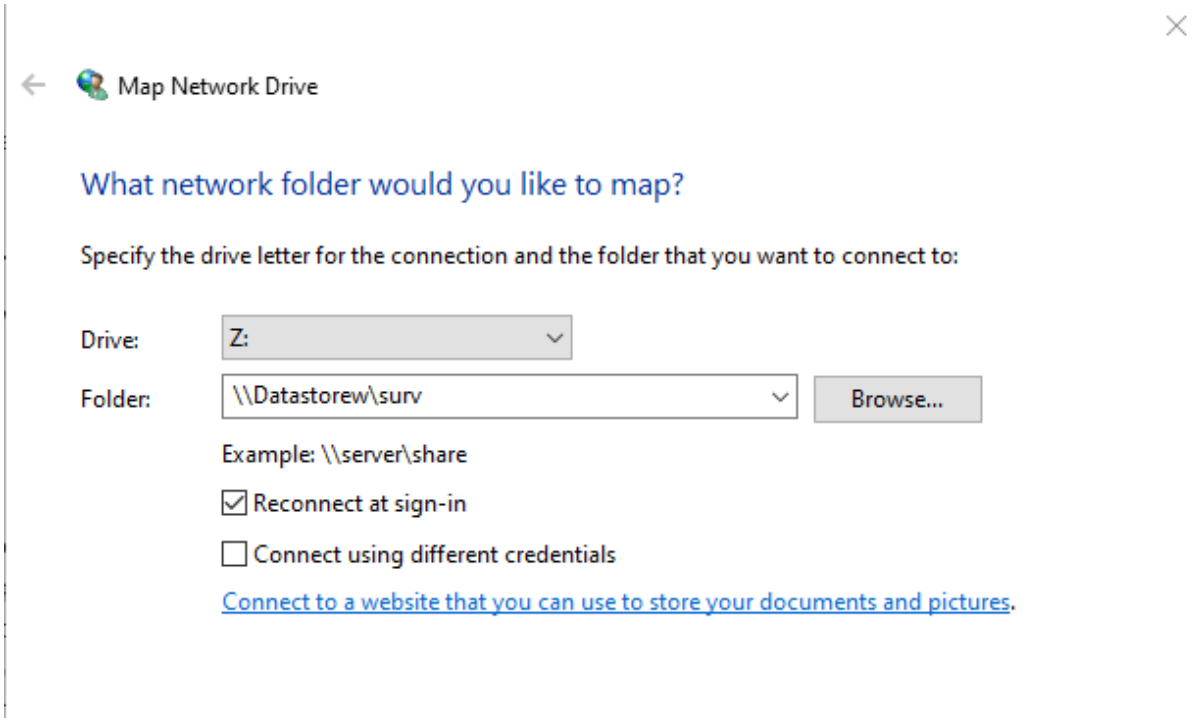


Figure 146 Map network drive to access Datastore

7.2. MUMM-LOG-PC

7.2.1 Software update

The IGPS software on the MUMM-LOG-PC does not undergo a regular updating cycle, but will only occasionally be upgraded e.g. when new features or sensors are requested from FluxSense/Chalmers. In addition it is important to perform an annual software backup.

SOP 3.50. To update the MUMM-LOG-PC

1. When:
    a. Update: as soon as a new stable version is available from FluxSense
    b. Backup: Every 12 months
2. General Equipment:
    a. Ground Power UNIT (GPU)
    b. Optional power cord to bypass AC power
3. Methodology
    a. Connect GPU to the AC
    b. Close the Watchdogs, TCP log, IGPS present, and all other files and programs
    c. Make a backup of the program files, log files and emission files from the IGPS folder from the LOG_PC (to 25-Sensor-Data/Sniffer/MUMM_LOG_PC Seafile)
    d. Copy the latest IGPS software to the IGPS folder on MUMM_LOG_PC
    e. Remove or rename the old “AISPresent.exe” version
    f. Rename the new version to “AISPresent.exe”
    g. Shut down the MUMM_LOG_PC
    h. Power off the sniffer, wait 10 seconds and power on the sniffer
    i. Reboot the sniffer

7.2.2 Annual SSD cloning

It is important to perform an annual back up of the SSD installed in the MUMM-LOG-PC, this will allow a last resort solution for serious software malfunctioning.

SOP 3.51. To Clone SSD

1. **When**: Every 12 months
2. General Equipment:
    a. Ground Power UNIT (GPU)
    b. Optional power cord to bypass AC power
3. Methodology:
    a. Connect GPU to the AC
    b. Close the Watchdogs, TCP log, IGPS present, and all other files and programs
    c. Make a backup of the program files, log files and emission files from the IGPS folder from the LOG_PC (to 25-Sensor-Data/Sniffer/MUMM_LOG_PC Seafile)
    d. Place SSD-2 in Kingston drive case and connect to USB port on the back of the sniffer
    e. Power on the Sniffer sensor
    f. Connect to the MUMM_LOG_PC using TeamViewer
    g. Close all programs and files
    h. Open Samsung Data-Migration software

i. Run the cloning software, make sure both drives area visible, select start (cloning will take 30 min)
j. Shut down the Sniffer sensor
k. Disconnect the SSD

In case of SSD failure or significant software issue, the SSD1 can be replaced with SSD2. To replace the SSD see Section 2.

Note: Do not override the original HDD, this should be kept for safekeeping,

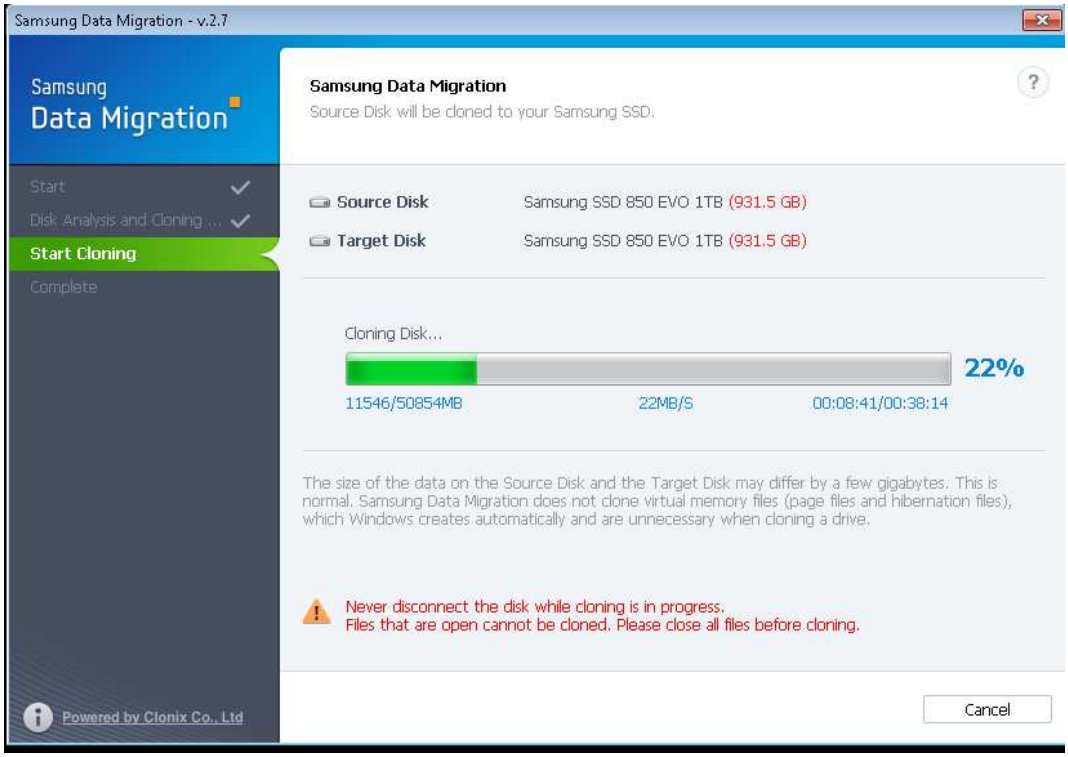


Figure 147 Samsung data migration software

7.3. IGPS directory maintenance

The IGPS folder contain all software data and data reference files for the proper functioning of the IGSP software. On annual or bi-annual basis a cleaning and update of the data reference files should be executed to continue to proper functioning of the software and data import tools. The IGPS folders for the operator laptops are synched through seafile, so for these folders maintenance needs to be performed only on one PC. For the MUMM-LOG-PC the same maintenance needs to be repeated with in addition a backup of the log files, the MEDUSA PC is not used for measurements but for uniformity it is advised to update the data reference files and clean the IGPS directory together with the MUMM-LOG-PC.

7.3.1 MIDs

The MID data is used by the IGPS software to identify the flag state of the ships based on their MMSI number. The MMSI MID country codes should be updated on annual basis or when crashes or commonly observed. The official list of MIDs can be found in a document called “Table of Maritime

Identification Digits" and can be found at ITU (https://www.itu.int/en/ITU-R/terrestrial/fmd/Pages/mid.aspx).

SOP 3.52. To update the MID data

1. Open the file AISPresent.ini, located in the same directory as AISPresent63.exe
2. Search for the tagg MIDS (see **Annex B - Configuration file**)
3. Scroll down to the appropriate location of the list, eg. 259 if a country code for MID 260 should be inserted.
4. Add a new row with the following content [new MID] =[new MID], [two char territory abbreviation],[three char country abbreviation],,[name of territory]

E.g, for a ship from Ursa Minor with a MID of 260 the line would be: 260=260,UM,URM,,Ursa Minor

Note that the ini files on all client station need to be updated, to avoid errors with other configuration settings it is recommended to do this procedure for the Laptops, Console and MUMM-LOG-PC separately.

7.3.2 Update MMSI-Keel Laying Date

Keel Laying Date (KLD) is used to identify the Tier level of ships. KLD information is made offline available to the operators during flight.

SOP 3.53. To update KLY dataset (MMSI_Date.csv)

1. Open the last keel laying data import file
    a. Go to 0. QMS\3. SNIFFER DM\Data reference files\Keel laying date\"YEAR"
    b. Copy IMO_Keel-laying-date.xls to a new "Year" folder
2. Go to GISIS Website: https://gisis.imo.org/Public/Default.aspx
3. Go to Login
    a. Type: Member state/ Authorization
    b. Country: Belgium
    c. Login using your credentials
4. Go to Ship particulars
5. Go to Advance search
    a. Select start year
    b. Select Length overall (>70)
    c. Select status Keel laid

REMOVE EDIT Year of build is in or after (previous year)
REMOVE EDIT and Length overall (m) is more than or equals 70
REMOVE EDIT and Current status of the ship is Keel Laid

6. Select download
    a. Do the same but select in service/commission
    b. Select start year
    c. Select Length overall (>70)
    d. Select status In Service/Commission
7. Select download

8. Combine both results
9. Do cross reference with old data (remove doubles that are already present)
    a. Keel-laying-dates IMO-MMSI-Vx-x-x-202x.xls
10. Add non doubles with information (IMO number, name, flag, GT, type, status, year of build, registered owner) to the end of the list in the SHIPS sheet (Keel-laying-dates IMO-MMSI-Vx-x-x-202x.xls)
11. Create **list nr 1** with all IMO numbers (including the old data)
    a. This list will be updated by EMSA to provide updated MMSI numbers: Celia.CACIONES@emsa.europa.eu
    b. Once the list is updated the updated MMSI data should be copied replacing the old numbers, in case the data is missing, the old MMSI numbers should be kept
12. Create **list nr 2** with IMO nr and Year built of new ships
    a. This list will be updated by EMSA to provide keel laying years: Celia.CACIONES@emsa.europa.eu
    b. all ships that had status keel laid at GISIS in 2020, but without the provision of an exact keel laying date from EMSA should have a keel laying year of 2020
    c. Copy the new ships to the xls file, keep the additional data on GT, …
13. Create a new CSV file
    a. Go to the sheet “CSV manual”
    b. Copy past the MMSI to the first column (as values)
    c. Copy paste the Keel Laying Dates to the second column (as values)
    d. Save excel file first
    e. With the “CSV manual” sheet open, save as “MMSI_Date.csv”
    f. Copy and replace the new csv file to IGPS folder
    g. keep backup of the old file with date in title in the

7.3.3 Cleaning IGPS data

The IGPS folders will collect the measurement data, to free up space and to speed-up the importing procedures the IGPS folders on each client station should be backed up and cleaned. The full content of the IGPS folders (except the charts) should be copied every year and stored on the Datastore network location Surv-Disk\25-Sensor-Data\04-SNIFFER DATA\Backup Emission and LOG data\”Year”. Following folders should be created per year

- IGPS folder shared on Seafile (client stations)
- IGPS folder from MEDUSA
- IGPS folder from MUMM-LOG-PC

After copying the following files should be deleted from the different IGPS folders:

- All content from the “Missions-Data” Directory
- All content from the “MAIL” Directory
- All “Emissiondata_xxx.txt” files
- “Mail_Sniffer_SO2_Man_Meas.csv” file
- “Comments _xxx.txt” and “Comments” directory content

For the IGPS folder on the MUMM-LOG-PC the content from the TCP log folder should also be deleted.

CHAPTER 8. REFERENCES

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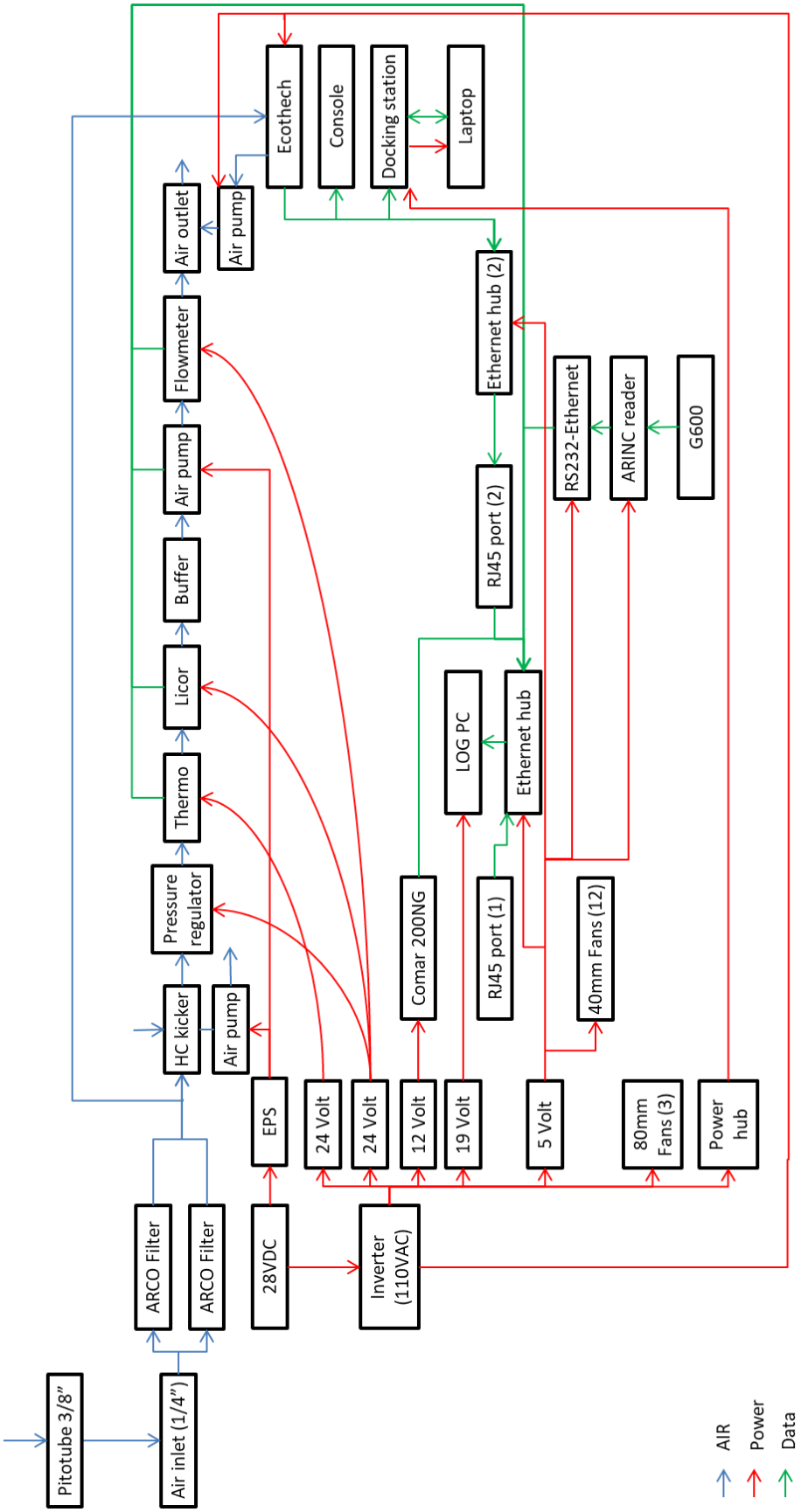
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https://www.bronkhorst.com/products/pressure/el-press/p-502c/

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https://www.itu.int/en/ITU-R/terrestrial/fmd/Pages/mid.aspx

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ANNEX A - BLOCK DIAGRAM



ANNEX B - CONFIGURATION FILE

```
#[
#MAC_SNIFFER=00012E4D9E04
[GASES]
#DEPRICATED=DATA now in section [SITE-GASES]
[SETTINGS]
InfoBalloon=0
InfoBalloonFontSize=8
CompassFontSize=8
MY-MMSI(EXCLUDED)=-1
CompassFontBlackOnWhite=1
CompassSimple=1
APPERENT_WIND=0
UPDATE_SO2CO2_DIAGRAM=1
SHOW_MY_TRACK=1
SHOW_SHIP_TRACK=1
LIVE_WIND=1
SHOW_LANDMASS=1
GPS_HEADING=1
WIND_FILTER=1
SHOW_COMPASS=1
IS_AUTO_CALIBRATOR=0
LOG_TO_FILE=0
ALLWAYS_CONNECT_TO_REMOTE_ON_START=0
TRANSP_LABELS=1
SHOW_COMMENTS_IN_DIAGRAM=1
SAVE_LOCAL_TCPDATA=0
SHOW_NOXCOMMANDS=0
CO2_OFFSET=381
SO2_GAIN=30
SHOW_BEARING=1
HIGH_SENSITIVITY=0
PlotFontSize=9
CURSORLATLONGFORMAT=1
ShowAllWindArrows=0
PlotShipsRegardlessOfPosQuality=1
ShowShipInfoBalloon=1
SHOW_START_AND_UP_TIME=1
ALWAYS_CONNECT_TO_REMOTE_ON_START=0
WindArrowAlongWind=1
[SITE-GENERAL]
SLOW-SO2=0
NORMAL-SO2-ORDER=0
[SITE-WIND]
AIRMAR_WIND_SELECTION=3
AIRMAR_WIND_DO_ADJUST=0
AIRMAR_WIND_OFFSET=0
DirLeft(lower)LimitDeg=-1001
DirRight(upper)LimitDeg=-1001
DirLeft(lower)LimitWideDeg=-1001
DirRight(upper)LimitWideDeg=-1001
[SETTINGS_META]
TILE_DIR=C:\IGPS\Charts
XMLCONFIG=default
BASE-OUTPUT-DIR=C:\IGPS\
[NOX_params]
MMSI_DATE_DIR = C:\IGPS\MMSI_Date.csv
KWH_Factor = 0.2
NO_Delay = 4
```

```
NOx_Delay = 5
NO_Interference = 0.45
NONOx_Ratio = 0.8
FSC_Span = 1.2571
FSC_Offset = 0.0007


[E-MAIL-SFC-ALERT]
MailAbove=100
[E-MAIL-QUEUE]
CONTAINING-FOLDER=C:\IGPS\
[MIDS]
-111=-111,IM, IOM,,Isle of Man
201=201,AL,ALB,,Albania
202=202,AD,AND,,Andorra
203=203,AT,AUT,,Austria
204=204,PT,PRT,PT-20,Azores
205=205,BE,BEL,,Belgium
206=206,BY,BLR,,Belarus
207=207,BG,BGR,,Bulgaria
208=208,VA,VAT,,Vatican City State
209=209,CY,CYP,,Cyprus
210=210,CY,CYP,,Cyprus
211=211,DE,DEU,,Germany
212=212,CY,CYP,,Cyprus
213=213,GE,GEO,,Georgia
214=214,MD,MDA,,Moldova
215=215,MT,MLT,,Malta
216=216,AM,ARM,,Armenia
218=218,DE,DEU,,Germany
219=219,DK,DNK,,Denmark
220=220,DK,DNK,,Denmark
224=224,ES,ESP,,Spain
225=225,ES,ESP,,Spain
226=226,FR,FRA,,France
227=227,FR,FRA,,France
228=228,MT,MLT,,Malta
229=229,MT,MLT,,Malta
230=230,FI,FIN,,Finland
231=231,FO,FRO,,Faroe Islands
232=232,GB,GBR,,United Kingdom
233=233,GB,GBR,,United Kingdom
234=234,GB,GBR,,United Kingdom
235=235,GB,GBR,,United Kingdom
236=236,GI,GIB,,Gibraltar
237=237,GR,GRC,,Greece
238=238,HR,HRV,,Croatia
239=239,GR,GRC,,Greece
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242=242,MA,MAR,,Morocco
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529=529,KI,KIR,,Kiribati
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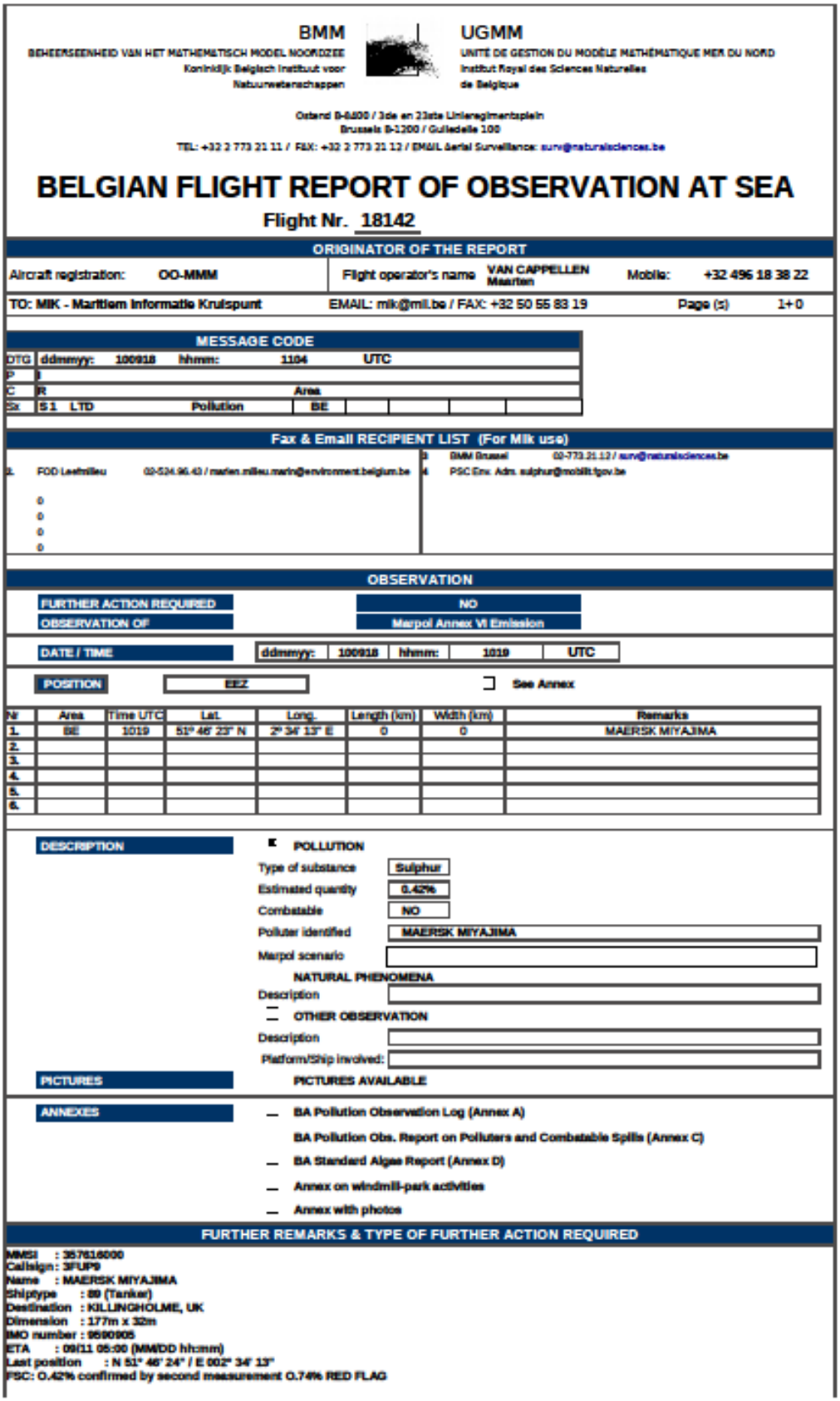
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765=765,SR,SUR,,Suriname
770=770,UY,URY,,Uruguay
775=775,VE,VEN,,Venezuela
[SITE-CAL_COEF]
CO2b_ValueOfRefGas=1
CO2b_MeasuredRef=1
CO2b_MeasuredZero=0
SO2_ValueOfRefGas=264
SO2_MeasuredRef=291.8
SO2_MeasuredZero=0
NOx_ValueOfRefGas=1
NOx_MeasuredRef=1
```

```
NOx_MeasuredZero=0
[CAL_COEF]
#DEPRICATED=DATA now in section [SITE-CAL_COEF]
[SITE]
PlatformID=MUMM
PositionLatDeg=48.9300150
PositionLonDeg=-5.5955283
FilterEnabled=0
FilterLengthPost=0.0
FilterLengthPre=5.0
CO2_FilterEnabled=0
SO2_FilterEnabled=0
NOx_FilterEnabled=0
CO2_MeanFilterLength=0.5
SO2_MeanFilterLength=0.5
NOx_MeanFilterLength=0.0
[POLY]
1=SECA_W_HATCHED,CLOSED;0x008F8CC5,0,0x008F8CC5,bsFDiagonal;48.5,-5.0; 50.0,-5.0; 50.0,-4.9; 48.5,-4.9
2=SECA_W_LINE,OPEN;0x008F8CC5,2,0x008F8CC5,bsClear;48.5,-5.0;50.0,-5.0
3=SECA_NW_HATCHED,CLOSED;0x008F8CC5,0,0x008F8CC5,bsFDiagonal;58.5,-4;62.0,-4;62.0,5;61.95,5;61.95,-3.9;58.5,-3.9
4=SECA_NW_LINE,OPEN;0x008F8CC5,2,0x008F8CC5,bsFDiagonal;58.5,-4;62.0,-4;62.0,5
101=BE_EEZ_HATCHED,CLOSED;0x008F8CC5,0,0x008F8CC5,bsBDiagonal;51.067181,2.466578;51.26917,2.290278;51.5577
8,2.138333;51.61306,2.153333;51.805,2.381667;51.94,2.536;51.55167,3.181389;51.433362,3.407997;51.378627,3.45258
8;51.372891,3.463;51.391547,3.441897;
51.368981,3.366396;51.372891,3.363;51.378627,3.352588;51.433362,3.307997;51.55167,3.081389;51.87611,2.539333;5
1.805,2.481667;51.61306,2.253333;51.55778,2.238333;51.26917,2.390278;51.089876,2.544952
102=BE_EEZ_LINE,OPEN;0x008F8CC5,2,0x008F8CC5,bsClear;51.089876,2.544952;51.26917,2.390278;51.55778,2.238333;5
1.61306,2.253333;51.805,2.481667;51.87611,2.539333;51.55167,3.081389;51.433362,3.307997;51.378627,3.352588;51.3
72891,3.363;51.368981,3.366396
;100=# Usage:
;101=#
nnn=name,PolyType;PenColor,PenWidth,FillColor,FillStyle;LatDeg1,LongDeg1;LatDeg2,LongDeg2;..;LatDegN,LongDegN
;102=#    nnn              unique integer number
;103=#    name             A symbolic name for this path/region ( Only _ | A..Z | a..z | 0..9 )
;104=#    PolyType         CLOSED|OPEN
;105=#                     CLOSED  A closed region given by the lat/long-pairs
;106=#                     OPEN:   A line through the give lat/long-pairs
;107=#    PenColor/FillColor   An integer ex. 0x00bbggrr
;108=#                         b,g,r: 0..9|A..F
;109=#                         b:blue,g:green,r:red
;110=#    FillStyle        bsSolid|bsClear|bsHorizontal|bsVertical|bsFDiagonal|bsBDiagonal|bsCross|bsDiagCross
;111=#                     applies only to CLOSED polys
;112=#                     dont care for OPEN polys
;113=#    LatDeg/LongDeg       Floating point number in DEG (decimal point)
[VISIBLE-TABS]
TabARINC_FRQ=1
TabSheetGas=1
TabSheetGlobalMap=1
TabSheetComments=1
TabSheetAnalogValues=0
TabSheetEEPSStatus=0
TabSheetNOx2Diagram=0
TabSheetNOx1Status=0
TabSheetIK=0
TabSheetDev=1
TabSheetAirmar=0
TabSheetPicarro=0
TabMailSetup=0
Tab2=0
TabSheetPlotsConf=1
TabSheetOPT=0
TabSheetGlobalWEB=0
[PLOTCO2.VISIBLE-TRACES]
```

```
1=0
0=1
2=0
6=1
7=0
8=1
3=0
4=0
5=0
9=0
10=0
11=1
12=0
13=0
14=0
[UNITS]
WindSpeed=kt
ShipSpeed=kt
SensorSpeed=kt
[PLOTNOX.VISIBLE-TRACES]
19=1
0=0
1=0
2=0
3=0
4=0
5=0
6=0
7=0
8=0
9=1
10=1
11=0
12=0
13=0
14=0
15=0
16=1
17=0
18=0
20=0
[PLOTSO2.VISIBLE-TRACES]
0=1
1=0
2=0
3=0
4=0
5=0
6=0
7=0
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9=0
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12=0
13=1
[SITE-GASES]
GAS0=0,0,0,0,0,0,0,0,0,0,1,60
GAS1=0,0,0,0,0,0,0,0,0,0,2,60
GAS2=0,0,0,0,0,0,0,0,0,0,3,60
GAS3=0,0,0,0,0,0,0,0,0,0,4,60
GAS4=0,0,0,0,0,0,0,0,0,0,5,60
CurrentGas1=0
```

```
CurrentGas2=1
CurrentGas3=2
CurrentGas4=3
CurrentGas5=4
```

ANNEX C - FLIGHT REPORT



BMM
BEHEERSEENHEID VAN HET MATHEMATISCH MODEL NOORDZEE
Koninklijk Belgisch Instituut voor Natuurwetenschappen

UGMM
UNITÉ DE GESTION DU MODÈLE MATHÉMATIQUE MER DU NORD
Institut Royal des Sciences Naturelles de Belgique

Oostend B-8400 / 3de en 23ste Linieregimentsplein
Brussels B-1200 / Gulledelle 100
TEL: +32 2 773 21 11 / FAX: +32 2 773 21 12 / EMAIL Aerial Surveillance: surv@naturalsciences.be

BELGIAN FLIGHT REPORT OF OBSERVATION AT SEA

Flight Nr. 18142

ORIGINATOR OF THE REPORT

Aircraft registration:	OO-MMM	Flight operator's name	VAN CAPPELLEN Maarten	Mobile:	+32 496 18 38 22
TO: MIK - Maritiem Informatie Kruispunt		EMAIL: mik@mil.be / FAX: +32 50 55 83 19		Page (s)	1+0

MESSAGE CODE

DTG	ddmmyy:	100918	hhmm:	1104	UTC			
P	I							
C	R			Area				
Sx	S1 LTD		Pollution	BE				

Fax & Email RECIPIENT LIST (For Mik use)

1.	FOD Leefmilieu	02-524.96.43 / marien.milieu.marin@environment.belgium.be	3	BMM Brussel	02-773.21.12 / surv@naturalsciences.be
			4	PSC Env. Adm. sulphur@mobilit.fgov.be	
	0				
	0				
	0				
	0				

OBSERVATION

FURTHER ACTION REQUIRED		NO			
OBSERVATION OF		Marpol Annex VI Emission			
DATE / TIME	ddmmyy:	100918	hhmm:	1019	UTC
POSITION	EEZ		☐ See Annex		

Nr	Area	Time UTC	Lat.	Long.	Length (km)	Width (km)	Remarks
1.	BE	1019	51° 46' 23" N	2° 34' 13" E	0	0	MAERSK MIYAJIMA
2.							
3.							
4.							
5.							
6.							

DESCRIPTION

☒ POLLUTION
Type of substance: Sulphur
Estimated quantity: 0.42%
Combatable: NO
Polluter identified: MAERSK MIYAJIMA
Marpol scenario:

NATURAL PHENOMENA
Description:

☐ OTHER OBSERVATION
Description:
Platform/Ship involved:

PICTURES
PICTURES AVAILABLE

ANNEXES
☐ BA Pollution Observation Log (Annex A)
BA Pollution Obs. Report on Polluters and Combatable Spills (Annex C)
☐ BA Standard Algae Report (Annex D)
☐ Annex on windmill-park activities
☐ Annex with photos

FURTHER REMARKS & TYPE OF FURTHER ACTION REQUIRED

MMSI : 357616000
Callsign : 3FUP9
Name : MAERSK MIYAJIMA
Shiptype : 89 (Tanker)
Destination : KILLINGHOLME, UK
Dimension : 177m x 32m
IMO number : 9580905
ETA : 09/11 05:00 (MM/DD hh:mm)
Last position : N 51° 46' 24" / E 002° 34' 13"
FSC: 0.42% confirmed by second measurement 0.74% RED FLAG