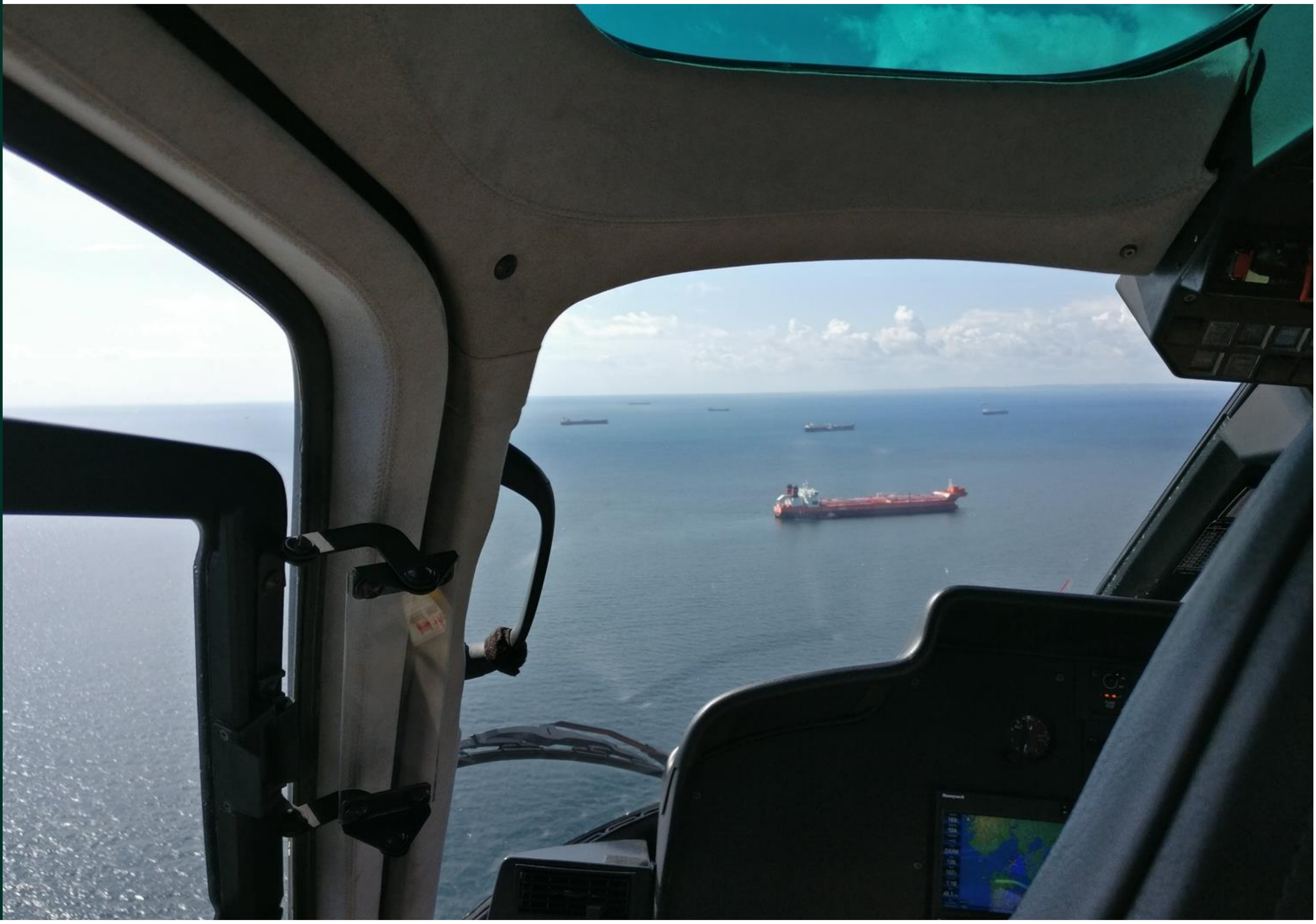
Ministry of Environment and Food of Denmark
Environmental Protection Agency

Airborne Monitoring of Sulphur Emissions from Ships in Danish Waters

2017 Campaign Results

Environmental Project no. 2001

April 2018



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Contents

Acronyms / Definitions

2017 Campaign	DEPA 2017 Airborne Sulphur Monitoring Campaign
AIS	Automatic Identification System
ANNEX VI	MARPOL Annex VI for the Prevention of Air Pollution from Ships
CEMS	Continuous Emissions Monitoring System
DEPA	Danish Environmental Protection Agency
EASA	European Aviation Safety Agency
EC	Electrochemical
EEZ	Exclusive Economic Zone
EMSS	Explicit Mini Sniffer System
EMSU	Explicit Mini Sniffer Unit
FSC	Fuel Sulphur Content
IMO	International Maritime Organization
IPR	Intellectual Property Rights
MARPOL	International Convention for the Prevention of Pollution from Ships
MEPC	IMO Marine Environment Protection Committee
NDIR	Non-dispersive infrared
PSC	Port State Control
RSD	Relative Standard Deviation
SECA	Sulphur Emission Control Area

Summary

Since June 2017, Explicit ApS has been contracted by the Danish Environmental Protection Agency (DEPA) to conduct airborne monitoring of sulphur emissions from ships in Danish waters. The aim of the monitoring has been to determine individual vessel compliance with the international sulphur regulations as outlined by the International Maritime Organisation in MARPOL Annex VI. The regulations impose a strict 0.10 % limit on permitted sulphur in the bunker fuel being burned for all vessels operating within the North European ECA including all Danish waters.

This report outlines the technology used, the operational setup, as well as the compliance findings of the 2017 Campaign. With regards to the latter, the report finds that:

- Of the 404 ships measured during the period July-December 2017, 22 ships (5.4%) were found to have substantially elevated fuel sulphur content levels at or above 0.15 %, the limit at which the instrumentation with 95 % confidence can detect a breach of the 0.10 % threshold. This finding – corresponding to approx. 1:18 ships not complying with sulphur regulations by burning fuel with min. 50% higher sulphur content that the law allows – is in line with reported results from previous airborne surveillance campaigns in Danish waters.
- The campaign found no clear geographical pattern in the compliance behaviour. Various degrees of non-compliance are found throughout Danish waters with the exception of the Great Belt were non-compliance levels appear to be generally lower.
- Similarly, there is no clear type pattern observed. Both cargo ships and tankers (the two dominating vessel types in the dataset) displayed equal levels of compliance.
- The data also shows no apparent directional patterns with similar levels of compliance found for both inbound and outbound ships as well as ships operating locally.

The 2017 Campaign marked the first instance in which micro sensor technology in the form of a Mini Sniffer System has been officially used by an authority to monitor maritime sulphur compliance. The report describes in detail what this new technology entails and how it is applied, including the use of Multiple Parallel Sampling to improve measurement uncertainty; a technique developed by Explicit. The report also outlines principles for navigating vessel exhaust plumes using a manned helicopter in combination with a Mini Sniffer System, including the Smart Flight navigational approach developed and patented by Explicit. Various advantages and challenges of the technology are also discussed.

By and large the report finds that both the technology and overall approach to airborne measurement demonstrated in the 2017 Campaign shows an attractive way forward for airborne emissions surveillance of ships. Overall, the campaign was able to demonstrate a consistently satisfactory quality level with 97 % of all measurements classified as ‘high quality’. This is significantly above what other similar campaigns / technologies have been able to achieve. In conclusion, the robust performance of the Mini Sniffer System and approach adds another important tool to the arsenal available to authorities when they design their sulphur enforcement strategies.

1. Introduction

This report has been prepared by Explicit ApS for the Danish Environmental Protection Agency (DEPA). It outlines the methods, operations, and results of the airborne monitoring activities conducted in Danish waters in 2017 from July through December as part of the Agency's maritime sulphur enforcement effort (the 2017 Campaign).

Since June 2017, Explicit has been contracted by DEPA to conduct airborne monitoring of sulphur emissions from ships in Danish waters to determine individual vessel compliance with the international sulphur regulations as outlined by IMO in MARPOL Annex VI.

Currently, all vessels operating within the North Sea and Baltic Sea Emissions Control Area for SO_X (SECA) of which the Danish EEZ is part, have to comply with a maximum 0.10% restriction on the permitted level of sulphur in the bunker fuel being burned. As an alternative, a ship may use equivalent means to obtain compliance, i.e. an exhaust gas cleaning system (scrubber).

Since the new regulations came into force on 1 January 2015, the DEPA has used various innovative methods to monitor compliance. One of those methods, applied by Explicit, includes direct gas sampling of vessel emissions by way of sniffer instrumentation mounted on a manned helicopter (or remotely piloted drone) flying into a vessel's exhaust plume to measure the sulphur emitted. Both the instrumentation and the approach to navigating the plume used in the 2017 Campaign is based on unique micro sensor technology and methods developed by Explicit specifically for the purpose of monitoring vessel sulphur compliance from the air.

By applying airborne monitoring, it has been the aim of DEPA to gain a comprehensive geographical picture of vessel compliance behaviour as well as identify individual violations that may be targeted for fuel inspection by PSC or sulphur inspectors.

Since 2015, in additional to national enforcement efforts, DEPA has shared compliance data collected from their airborne sulphur monitoring programme with other EU Member States via the THETIS database, allowing other EU authorities to act on this information. Similarly, it is the intention of this report to share relevant findings and experiences gained from the airborne surveillance effort, so others may learn from the Danish maritime sulphur monitoring initiatives and enforcement programme.

2. Methodology and technology

Measuring sulphur compliance levels in vessel exhaust plumes from the air is a complex task. The low regulatory threshold (0.10% FSC), the composition and dynamics of the exhaust plume itself, and the operational conditions and constraints under which air sampling has to be performed, all set a high bar for how technology can be applied.

The following chapter outlines the methodology and technology used by Explicit in the 2017 Campaign to monitor vessel sulphur compliance from the air. The overall solution is based on a combination of established measurement methodology; innovative micro sensor technology and advanced software for intelligent plume navigation and emissions analysis which, when mounted on a rotary aircraft, enables a stable, consistently high-quality measuring output.

The use of micro sensor technology in particular, to conduct airborne measurements of vessel exhaust gasses, constitutes the first instance globally in which these types of sensors have been officially applied for sulphur enforcement purposes by a national authority.

The use of micro sensor technology has several advantages, all of which were key drivers behind the development of the solution:

- Micro sensors are readily available in the market, they are low-cost and easy to replace making any micro sensor-based system comparatively easy to scale and maintain. Sensors can even be multiplied to build additional supportive evidence and improve system uncertainties.
- The small size and light weight of the sensors enables the whole measuring system to be miniaturized and operated as a standalone system, drastically reducing or completely eliminating the need for expensive host aircraft integrations and/or modifications.
- Because the instrumentation is scaled down, it can be easily fitted on a rotary aircraft (manned or unmanned drone) leveraging the ability of these platforms to navigate precisely in the plume and optimize gas sampling.
- The standalone setup also allows the operator to easily move or replace the equipment should the operation require this, awarding important redundancy to the overall operation and enabling the same equipment to be used on multiple platforms.
- Finally, the size also means the instruments themselves can easily be subjected to controlled laboratory testing and validation as part of a future broader quality assurance and standardization schemes for air sampling in shipping.

The monitoring system used in the 2017 Campaign, the Explicit Mini Sniffer System (EMSS), is a culmination of more than four years of intense development. Part of this development has been supported by funding from the Danish Ecoinnovation Programme (MUDP), the Danish Innovation Fund, and the Horizon 2020 SME Instrument.

Both the methodology and technology used in the 2017 Campaign has undergone extensive testing and validation by FORCE Technology, the Danish Government Reference Lab for Air Emissions. Prior to use by DEPA, the EMSS was scale-tested on more than 400 vessels in both Dutch and Danish waters. For more on validation, see section 2.4.

2.1 Establishing the sulphur content in the bunker fuel

As described in detail by International Maritime Organisation[1] and documented by several scientific studies[2], the Fuel Sulphur Content (FSC) (%) in the bunker fuel can be determined by:

(a) Measuring the ratio between SO_2/CO_2 gasses in the vessel exhaust; and
(b) Subsequently converting this ratio value to an FSC percentage using the exhaust emission factor also established by IMO.

As established by science, the ratio between sulphur and carbon in the exhaust plume is the same as the ratio in the bunker fuel. The ratio is unaffected by the distance to the emission source and so in principle, any position sufficiently within the plume will return the correct FSC value. For more on how to evaluate the position and navigate the plume, see 2.4.2 and 3.4.

The methodology may be expressed as follows:

$$FSC = \frac{SO2_{measured}\,[ppm]}{(CO2_{measured} - CO2_{background})[ppm]} \cdot 10^5 \cdot 0.02308$$

The EMSS applies the same formula with the only difference being that the input values for SO_2 and CO_2 used by the system are applied post adjustment for sensor calibration, cross interferences, and other sensor dependencies such as temperature. See section 2.2 for further.

Note, a minor percentage of the sulphur is not emitted as SO_2 but is instead converted to sulphuric acid or emitted in particle form. This fraction has however, through comparative studies, been found to have immaterial impact on the ratio calculation in this case (see 2.4), in part due to the close proximity to the emissions source and the resulting high gas concentrations.

All measured values are derived from a baseline established in free air before and after entering the plume. As shown in the FSC formula, to get the right ratio, the measured CO_2 value is further offset by the corresponding CO_2 value in the background (usually approx. 400 ppm).

Note, in the EMSS all sensor signals are in fact corrected for background levels using a baseline approach, as shown in Figure 1. But since it is only the CO_2 background level that has a material impact on the SO_2/CO_2 ratio, for the sake of simplicity, this is the only offset value included in the formula above. Ambient gas levels for SO_2, NO2 and NO only fluctuate a few ppb.

The baseline principle is illustrated in Figure 1 for all sensors (next page):

[1] IMO MEPC 2015 Guidelines for Exhaust Gas Cleaning Systems.

[2] See for example: Lööv et al. (2014): Field test of available methods to measure remotely SOx and NOx emission from ships. Atmos. Meas. Tech., 7, 2597-2613.

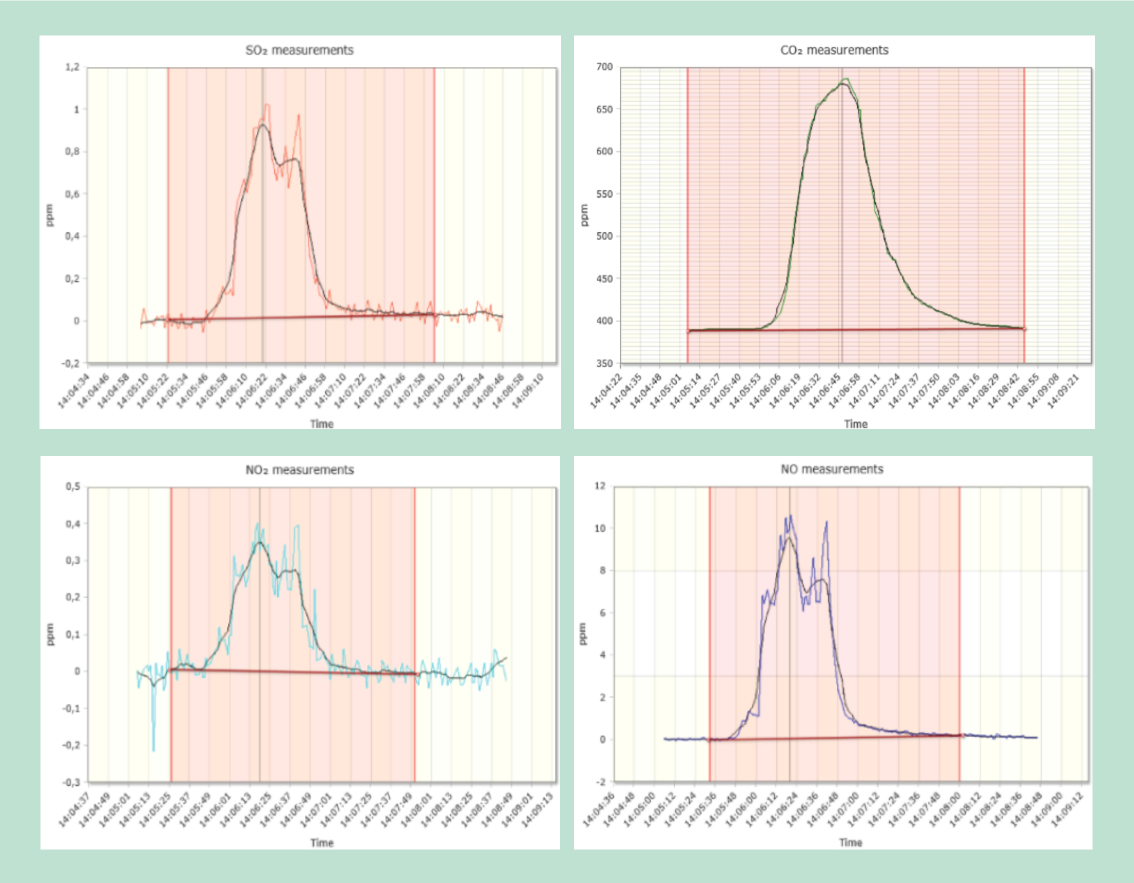

FIGURE 1. Baseline establishment on sensor feeds from the plume of a non-compliant vessel.

As illustrated by the sensor feeds in Figure 1 above, with the measuring approach used in the 2017 Campaign, gas concentrations are in fact measured in the *ppm range* and not in the ppb range as has otherwise been the case with other remote and/or airborne surveillance campaigns monitoring vessel plumes. Typical measuring ranges observed in the plumes are as follows:

- CO_2: 200 – 600 ppm over background
- SO_2: 0.5 – 1 ppm
- NO_2: 0.5 – 1 ppm
- NO: 2 – 10 ppm

The ability to measure in the ppm range is a direct outcome of using a rotary aircraft. Rotary platforms can manoeuvre in the plume for longer periods of time enabling the system to capture more gasses to measure on. Higher gas concentrations are a requirement in order to make micro sensors work, but the closer distance and/or longer time spent in the plume also has the added value of materially reducing the risk of slight fluctuations in background levels impacting the ability to correctly establish the SO_2/CO_2 ratio.

2.2 Measurement instrumentation

The measuring instrumentation used for the 2017 Campaign were made up of a proprietary system of hardware and software components developed by Explicit. Contrary to remote monitoring technologies that rely on optical instrumentation, the EMSS uses direct *in situ* sampling of the gasses themselves, otherwise referred to as “sniffing”.

2.2.1 Sensors

To measure the gasses in the exhaust, the EMSS uses low-cost EC and NDIR micro sensors for measuring SO2, CO2, NO and NO2. Although not relevant to the SO2/CO2 ratio directly, NOx sensors are included in the system for cross interference reasons (see below) as well as to enable the system to also measure NOx and estimate the emissions in g/kWh.

All sensors used in the system are state-of-the-art micro sensors commercially available from leading industry manufacturers. No modifications have been made. Instead sensor performance has been enhanced through advanced algorithm design derived from extensive performance testing and validation under both lab and real-life conditions, including direct comparisons against vessel fuel samples and CEMS. The algorithms are part of Explicit's IPR.

2.2.2 Corrective measures

Built into the sensor algorithms are various corrective measures designed to mitigate known issues with EC sensors of cross interference, other dependencies, and noise. In particular, the sensors have been found to have (primary corrections):

- One-way cross interference NO_2 → SO_2 (but not the other way).
- A dependency on temperature and humidity.

In addition, the system applies various measures to reduce the impact of potential noise on the sensor signals.

2.2.3 The Explicit Mini Sniffer Unit and Snifferbox

All sensors are built into small, specially designed mini sniffer units (EMSUs, see Image A) each weighing approx. 500g in total including pump system. Small in size and light in weight, the EMSU forms the core of the EMSS.

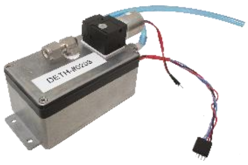

Image A: The EMSU
The Explicit Mini Sniffer Unit weighs approx. 500g.

Each EMSU is built as a continuous airflow system with a unique air chamber designed to ensure a steady and satisfactory exposure of all sensors. Each unit is assembled by Explicit and tested and calibrated by FORCE Technology before deployment. See section 2.3 for further on calibration and replacement routines.

During operation, the EMSU(s) are housed inside a sealed instrument cabinet – a so-called 'Snifferbox' (see Image B and C). The Snifferbox is EASA approved for mount on a helicopter carrying arm. Equipped with its own power supply and additional controls for GPS positioning and data communication storage and relay, the Snifferbox operates as a standalone measuring instrument. Communications with the sensor operator ground control is done via radio link.

Image B and C
The snifferbox mounted on an AS355NP equipped with a carrying arm.

Note, the forward position of the Snifferbox and its inlet tube (in front of the air speed indicators on the aircraft), in combination with the slightly tilted forward motion of the helicopter when airborne, means the air intake is effectively placed free of any material downwash from the rotors during measuring. Also helping ensure this is the wind factor. All measurements are done upwind to capture the drifting plume, and so the wind itself also pushes the downwash away from the forward-placed inlet. This impact is even more pronounced when the helicopter is measuring cruising vessels and thus moving with the vessel while measuring.

The placement of the Snifferbox relative to the downwash is illustrated in figure 2.

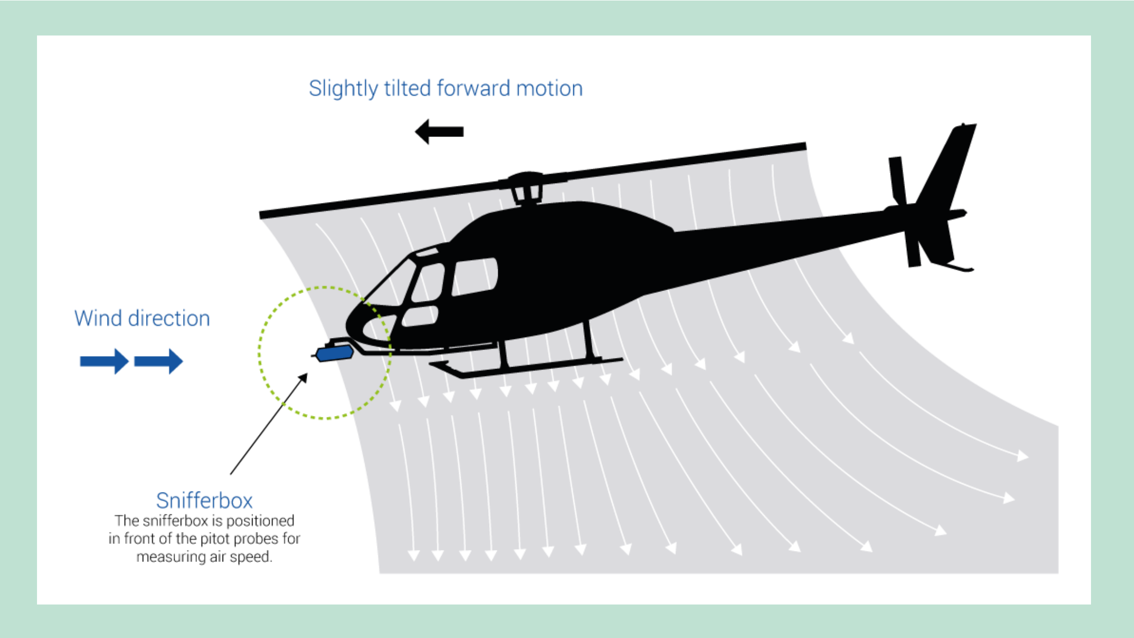

FIGURE 2. Placement of the Snifferbox relative to the downwash.

2.2.4 Multiple Parallel Sampling

Whenever weight restrictions allow, Explicit applies Multiple Parallel Sampling, i.e. multiple independent EMSUs are operated in parallel to lower measuring uncertainty, ensure system redundancy, and secure additional evidence. This was also done in the case of the 2017 Campaign where the Snifferbox was equipped with a dual unit configuration.

The use of multiple units helps increase data integrity and supports system reliance. Each doubling of units corresponds to a reduction in the measurement uncertainty by the magnitude of $\sqrt{2}$. When using Multiple Parallel Sampling, the final FSC results is presented as a consolidated average over all unit measurements. See section 2.4.1 for further on the system uncertainties.

The use of Multiple Parallel Sampling is unique to the EMSS. All other airborne or fixed remote monitoring technologies are single feed setups, largely because of system costs and logistical restrictions.

2.3 Pre-deployment performance testing and calibration

To ensure the functionality of the sensors, Explicit has established the following test and calibration protocols:

Each EMSU is performance tested and calibrated before deployment. Testing and calibration is done by FORCE Technology in accordance with ISO-standard EN ISO 6145-1[3].

Each calibrated unit is subsequently issued with a certificate of calibration. Units that do not meet the performance standard inherent in the system (i.e. perform comfortably within the established uncertainties) are rejected.

Because of EC sensor signal decay over time, each EMSU must be replaced at appropriate intervals, or as a minimum once a year, to ensure functionality. Through drift and performance tests before and after campaign operations, the maximum durability of a unit has been conservatively assessed to be approx. 100 hours of powered operations. Explicit has built-in system logs to keep track of usage and will replace units in due time before their duration expiry.

The above test, calibration and replacement procedure was also followed during the 2017 Campaign.

2.4 Validating measurement accuracy and assessing quality

To assess the applicability and performance of the selected micro sensors for the purpose of monitoring SO_2 and CO_2 in ship exhaust plumes, FORCE Technology and Explicit during 2014-2016 conducted a series of laboratory and field tests on both the 4 individual sensors and the final EMSU design. Those tests include, but are not limited to:

- Linearity
- Detection range
- Precision
- Response time
- Cross interferences
- Signal drift over time
- Temperature dependency
- Humidity sensitivity

Many of the lab tests were conducted in a simulated plume environment in which the sensors were exposed to gasses, concentrations and humidity levels resembling the composition in a ship exhaust plume, in a pulsed pattern to imitate the highly shifting gas concentrations experienced when measuring at sea.

The sensors have further been tested under harsh real-life conditions, including conditions of up to 95% humidity and in temperatures ranging from -5 to +35 degrees Celcius.

On the bases of the tests, FORCE Technology has independently established an uncertainty budget applicable to system. The budget is summarized in section 2.4.1 below. In-field verification of the budget has subsequently been done by Explicit by comparing EMSS air sample results collected from vessels in operation against onboard fuel samples, or – in the case of scrubber vessels – ship CEMS data, all correlated in time. In the case of the fuel samples, these were subsequently analysed in independent labs to established their FSCs.

[3] EN ISO 6145-1 describes the calibration methods involved in the preparation of gas mixtures by dynamic volumetric techniques.

The comparative samples have been coordinated in collaboration with shipowners Maersk Line and DFDS at different occasions in both Dutch, Danish and Norwegian waters during both at-sea operations and at harbour entry and manoeuvring.

In total, 16 comparative datasets have been collected during 2016-2017 from 7 different vessels; 5 non-scrubber and 2 scrubber vessels. In all cases, except 3 scrubber measurements in which the vessel FSC was ≤ 0.01 %, the comparatives samples have been found to be within the system assigned uncertainties. See Figure 3.

While the comparative dataset is still small, the relatively close correlation between the FSC values supports a conclusion that micro sensors are applicable for airborne sulphur enforcement. Explicit is continually working to expand the comparative dataset and thus improve the real-life documentation available on sensor performance.

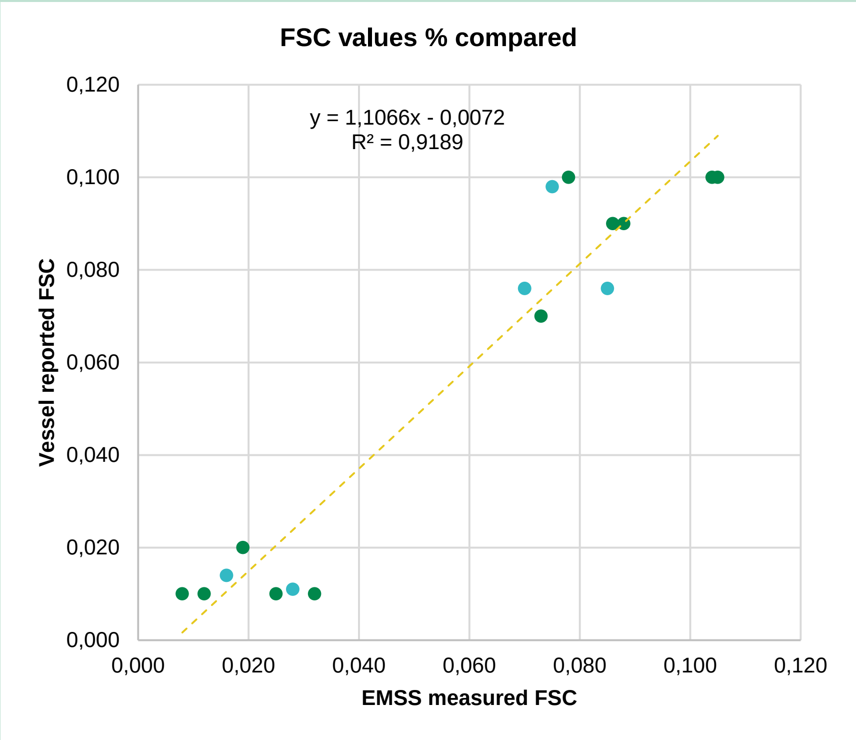

FIGURE 3. FSC values compared. Comparatives marked in green are based on a dual sensor configuration, while comparatives in blue were collected using a single configuration.

2.4.1 Uncertainty budget and detection thresholds

Based on the validation an uncertainty budget for the measured EMSS results was established by FORCE Technology. From this, detection thresholds for determining non-compliance at various RSD levels can be derived.

All measuring systems have uncertainties, and it's important to know what those margins are in order to assess how much reliance can be put on a given result. Uncertainties are expressed in RSD. The higher the RSD applied, the bigger the certainty that the measured FSC is in fact above a given threshold.

The EMSS system uncertainties for a dual configuration at different levels of FSC and RSDs, including corresponding detection thresholds (cuf-offs), are presented in Table 1.

TABLE 1. System measuring uncertainties at difference FSC thresholds.

FSC threshold	**1 x RSD** (68% coefficient)		**2 x RSD** (95% coefficient)		**3 x RSD** (99.7% coefficient)	
	Uncertainty	FSC cut-off *	Uncertainty	FSC cut-off *	Uncertainty	FSC cut-off *
0.10 %	± 25 %	0.13 %	± 50 %	0.15 %	± 75 %	0.18 %
0.15 %	± 20 %	0.18 %	± 40 %	0.21 %	± 60 %	0.24 %
0.25 %	± 15 %	0.29 %	± 30 %	0.33 %	± 45 %	0.36 %
0.50 %	± 15 %	0.58 %	± 30 %	0.65 %	± 45 %	0.73 %
1.00 %	± 16 %	1.16 %	± 32 %	1.32 %	± 48 %	1.48 %

* FSC cut off = The level at which the measured FSC minus the uncertainty is above the FSC threshold.
The green row indicates the regulatory threshold applicable to the SECA.

2.4.2 Quality scoring

While the measurement uncertainties can be used to express something about compliance, it doesn't say anything about the quality of the air sample, i.e. the extent to which the captured gas sample was sufficient to satisfy the performance requirements of the sensors.

In the case of airborne monitoring, the sample quality can also be said to express the ability of the pilot to navigate and get into the best possible position in the plume. At the end of the day, both uncertainty and quality are key measures to assess the robustness of a measurement.

In particular two criteria are important when evaluating quality in this context:

(c) Was the position good enough to reach sufficient gas concentration levels?
(d) Was the time in the plume sufficient to satisfy the response time on the sensors?

Because there is no agreed standard on how to measure these quality criteria in the context of airborne sulphur monitoring, Explicit has developed its own quality scoring protocol based on the validated performance profile of the micro sensors. In particular, the NO and CO_2 sensors have been found to be strong indicators of sample quality, either because the sensor (NO) reacts fast to determine the best position in the plume, or because it reacts slow (CO_2) to indicate how long to remain.

The quality scoring protocol is tightly linked to the patented *Smart Flight* concept developed and used by Explicit to navigate intelligently in the exhaust plume. See section 3.4 for further.

Each measurement is given a quality score between 0.00 - 10.00, calculated automatically by the system according to the criteria outlined in Table 2.

TABLE 2. Quality scoring criteria applied

Parameter	Threshold criteria	Used to evaluate
CO_2 concentration	150 ppm above background	Plume position (a)
NO concentration	1 ppm above background	Plume position (a)
Integrated CO_2 concentration	10,000 ppm * s	Time in plume (b) Example: 666 ppm over 15 minutes.
Integrated NO concentration	100 ppm * s	Time in plume (b) Example: 6.6 ppm over 15 minutes.

Any values below the threshold criteria will impact the quality score negatively from a top score of 10.00 down to zero. The quality scores may be grouped as follows:

- Low quality: 1.00 – 3.00
- Medium quality: 3.00 – 6.00
- High quality: 6.00 – 10.00

Note, any quality score below 1.00 will be rejected in quality control as a failed attempt at measuring. Explicit also advises to treat any measurement with a quality score below 3.00 with appropriate caution.

While the quality scoring protocol has been proven in real-life operations to be a valuable indicator on the reliability of a measurement, the protocol has one inherent weakness relating specifically to vessels with selective catalytic reduction systems (SCR) or other NO_X-reduction technologies designed to comply with IMO Tier III NO_X regulation. In those instances, the exhaust will only contain very low levels of NO, resulting in a falsely low quality score. The mitigating response to this is to adjust the score based only on an evaluation of the CO_2 criteria. This is done as part of the manual quality control procedure.

Ships equipped with SCRs or other NO_X reduction technologies are still very rare. Explicit has only encountered 2 cases so far after having measured more than 800 ships. However, as low NO_X-emitting vessels become more common, the automatic quality scoring protocol may easily be adapted to identify the low levels and correct the scoring.

3. Operation

Measuring vessel exhaust plumes from the air is classified as a special aerial work operation. Due to the low altitudes and close proximity to the observed targets, the mission is considered high risk emphasising the importance of pilot and sensor operator experience. This being said, sulphur missions share traits with other similar special helicopter operations requiring precision flight, such as powerline inspections and other mapping tasks.

This chapter outlines the operational framework applied during the 2017 Campaign, including aviation considerations and data processing.

3.1 Team

All flights conducted during the 2017 Campaign were carried out in collaboration between Explicit (responsible for all sensor operators, analysis and reporting) and Charlie 9 Helicopters (responsible for aircraft and piloting). Both parties have extensive experience in flying sulphur missions from previous (test) campaigns.

3.2 Aircraft and safety measures

All flights were conducted using an Airbus AS355NP twin-engine helicopter equipped with an AFSP-1 carrying arm (airfilm single pole mount) for mounting the Snifferbox. The AS355 is a modern light-weight twin-engine helicopter known for its reliance, safety and performance.

A secondary aircraft, an Airbus AS350B3 single-engine helicopter was also available to the campaign but was never used. Similarly, due to air space and other operational restrictions, this year's campaign did not utilize drones.

All flights were carried out in accordance with the Special Operational Procedure (SOP) for sulphur missions prepared by Charlie 9 and approved by the Danish Transport Authority.

While operations were not announced in advance, to clarify intent when approaching vessels, the helicopter was equipped with appropriate markings (see Image D and E). The helicopter was further equipped with inflatable floats and life rafts as part of the safety procedures.

Image D and E
To signal intent to the vessel, the helicopter was equipped with side markings. Markings on the front nose further instructed vessels on how to communicate with the pilot team, if needed be.

3.3 Operational conditions

Prevailing weather conditions in Denmark allow for measuring of vessel plumes to take place all through the year. Seasonal shifts are not a prohibitor for mission operations, although there might be fewer days in the winter season with optimal flight conditions.

Image F: Plume positioning and Smart Flight
Often the wind conditions are such that measurement has to be done at an angle to the heading of the ship in which case the pilot must navigate sideways to keep the sensors in the line of the drifting plume. The ability of the helicopter to maneuver and stay long enough to capture a robust air sample is a crucial, key advantage of using a rotary platform. The picture also shows how plumes are often invisible, making it absolutely imperative to have guidance tools such as Smart Flight.

This being said, there are both limitations on the measuring conditions and safety of the aircraft, vessel and crews which have to be taken into account when flying sulphur missions. For this reason, the operational team has developed its own operational guidelines which were also followed during the 2018 Campaign. Those include, but are not limited to:

- *Maximum recommended wind speeds: Approx. 30 knots gusting.*
  Higher wind speeds may affect the integrity of the plume, effectively tearing it apart leaving insufficient gas concentrations to enable a good measurement. Similarly, high wind speeds can create conditions of turbulence around the vessel which are difficult to navigate.
- *Recommended no-fly zone: <30° on either side of the vessel heading as well as over the vessel itself.*
  See image F and Figure 4. The no-fly zone is self-imposed for safety reasons and prevents measurement under conditions where the plume is positioned directly over the vessel. This scenario can however, in most cases, be prevented through flight planning.
- *Conditions with precipitation: No flight.*
  Any rain or snow will impact the composition of the plume, effectively “washing out” the sulphur, which increases the risk of incorrect measurement results.

In addition, normal safety considerations for helicopter special operations are observed.

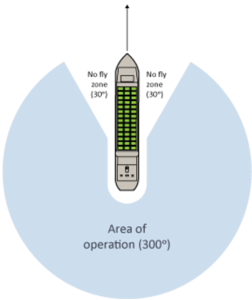

FIGURE 4.
The helicopter has a 300° operational area around the vessel to conduct measurements.

3.4 Plume positioning

Contrary to what some believe, exhaust plumes are not clearly visible; not even when they contain high amounts of sulphur and other pollutants. Locating and navigating the plume is therefore a critical aspect of airborne monitoring of vessel emissions.

To assist plume positioning, Explicit has developed a set of software pilot assist tools (part of the Sensor Operator Ground Control Station software package) which allow the operations team to identify the best position in the plume for measuring the exhaust gasses, also known as the plume's 'sweet spot'.

The sweet spot is most often located along the centre line of the plume in reasonable distance from the ship stack, see Figure 5. The exact distance will depend on the size of the ship. The smaller the vessel, the closer the distance. The typical position of the sweet spot ranges from 25-100 meters, 40-60 meters above sea level. The relatively close proximity to the emissions source, also means the risk of contamination from other plumes is in practice non-existent.

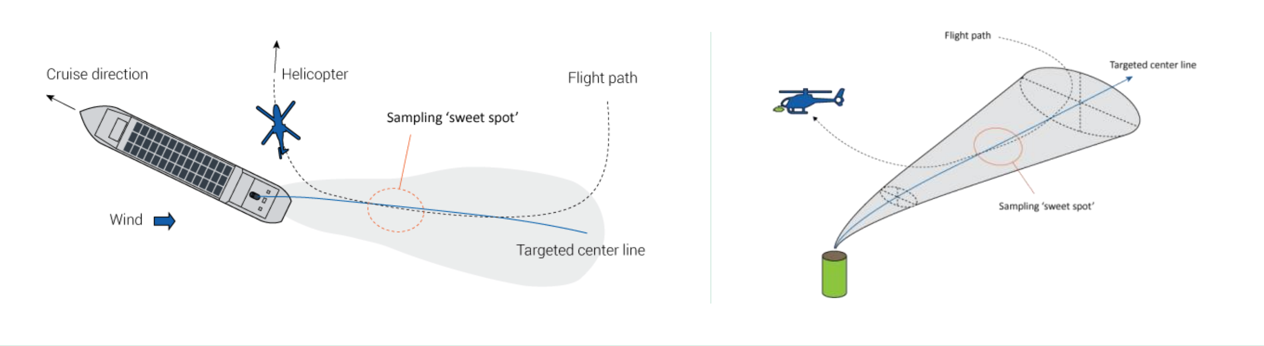

FIGURE 5. Locating the sweet spot in the vessel exhaust plume.

Simulating plume position
To locate the likely position of the plume within the area of operation, the team uses a software plume simulation model, developed by Explicit, based on the vessel course AIS data and online data on local wind conditions. The model forecasts the rough position of the plume vis-à-vis the ship position and course.

Smart Flight
Once in close proximity of the plume, the team uses Smart Flight, a unique pilot assist method patented by Explicit, to locate the sweet spot inside the plume. Smart Flight allows the operations team to navigate intelligently using the live feedback from the sensors to locate the position with the highest gas concentrations inside the plume. In order words, the team 'sniffs' it's way to the optimal position, removing any dependency on exact wind data and reducing the risk of failed or weak measuring attempts dramatically.

The fastest reacting sensor (NO) is used to find the sweet spot, while the peak signal on the slowest sensor (CO_2) is used as an indicator for how long the pilot needs to stay in position. Monitoring the live CO_2 feed to ensure a sufficient and stable signal is particularly important when navigating the plume because of the CO_2 impact on the calculated FSC.

The two sensor parameters used in Smart Flight to navigate the plume, NO and CO_2, are also the two parameters used to subsequently assess the quality of the individual measurement. For more on the quality scoring protocol, see section 2.4.2.

From the time of approaching the plume, each measurement takes approx. 15-20 seconds. Another minimum 1-2 minutes is subsequently needed in free air to evacuate the sensor air chamber in preparation for the next measurement.

For further on best practice flight patterns for navigating vessel exhaust plumes reference is made to the best practice report issued by CompMon[4]. The report details various considerations surrounding airborne monitoring of maritime sulphur emissions, including the use of rotary aircraft as experienced by Explicit.

3.5 Data processing and quality control

All data collected during missions is processed through the Sensor Operator Ground Control Station, where data from sensors, GPS and AIS tracks are merged using UTC time stamps to link a specific measurement to a specific ship in time and space. Data is subsequently relayed to the Explicit E-lab (cloud) for the final FSC analysis before all data is combined to form a final emissions report on a ship observation.

Before issuing a final emissions report on a vessel, the results are subject to a manual quality control by the Explicit team, including verifying sensor performance and FSC outputs, investigating low quality scores and rejecting measurements that do not meet the minimum quality score criteria as previously outlined in 2.4.2.

In essence, the data infrastructure – from sensor devices to finish reports – converts the full EMSS to a 'flying lab service' covering all steps from identifying the target and point of sampling to the presentation and storage of a quality-controlled emissions result.

The principal data infrastructure of the EMSS is depicted in Figure 6:

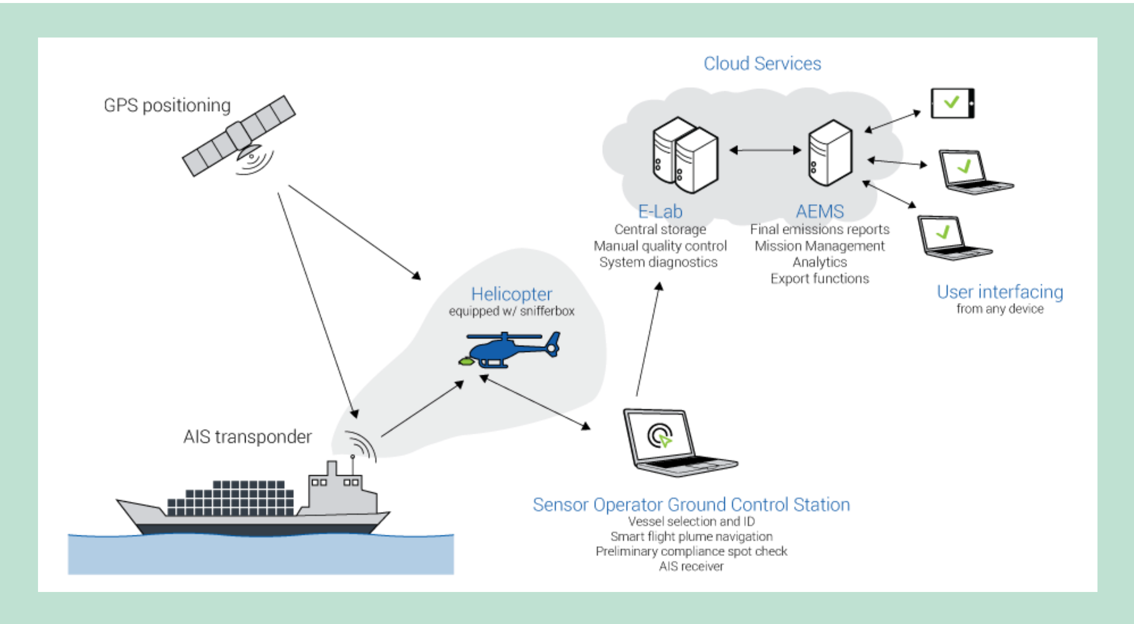

FIGURE 6. Principal data infrastructure of the Explicit Mini Sniffer System.

Both the E-lab and AEMS is hosted in a cloud environment using Microsoft Azure Cloud Services, one of the World's leading clouding service providers. Azure is a fully scalable cloud platform including advanced state-of-the art data protection and backup systems. The high level of service combines easy access, speed, storage capacity and data integrity at any time.

[4] Best Practices Airborne Marpol Annex VI Monitoring, CompMon.

For this reason, the solution is a preferred choice for many both private and government clients.

The cloud not only handles all data processing of the raw data from each mission, it also hosts the final datasets on each ship observation in a virtual MS SQL database. The physical data is stored in a Microsoft data centre within the EU in accordance with safe-harbour regulations.

3.6 Reporting

Once data processing is completed, final emissions reports on all observed vessels are made available to DEPA via the Explicit Airborne Emissions Monitoring System (AEMS), a web-based reporting module that allows users access to the reported data from any device.

The AEMS includes different views and search options to examine the final data as illustrated in Figure 7. The reporting system also has options to export the data in XLSX, CSV, and XML formats.

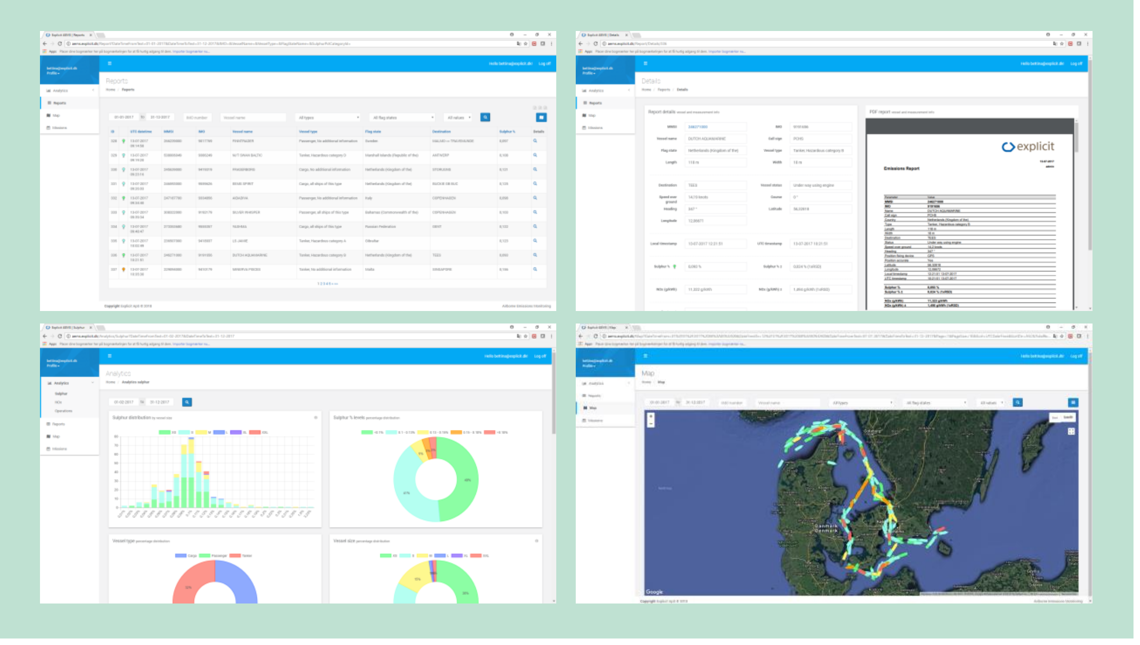

FIGURE 7. Examples of the AEMS interface.

Each dataset on an observed vessel also includes a 4-page PDF report documenting how the FSC value was derived, see image G.

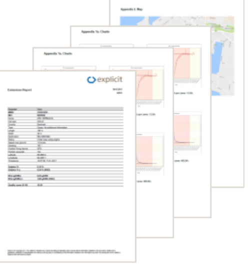

Image G
Each ship observation is documented in detail in a 4-page PDF report.

Data from a flight mission is generally processed immediately after landing and alerts on suspected violations issued to DEPA via email for further action. Such actions may include, but are not limited to:

- Reporting suspected violations to the Danish national Port State Control (PSC) in cases where a ship is on route to a Danish port.
- Reporting suspected violations to THETIS, the EU-wide PSC database into which various maritime violations and inspections are reported, for possible action by another EU Member State.
- Contacting the relevant flag state and/or shipowner directly depending on the circumstances and severity of the violation.

4. 2017 Campaign Results

The 2017 Campaign was conducted during the months of July through December 2017 over the course of 12 flight days. All flights were initiated from either Roskilde or Aalborg Airport. The results are presented below.

4.1 Dataset composition

The full dataset for the 2017 Campaign consists of 404 independent ship observations. Each observation represents of an averaged consolidated result of two independent measurements taken in parallel as described in section 2.2.4. Although some ships were measured multiple times during the campaign (up to 3 times) due to their frequent return to Danish waters, no vessel was measured more than once on a single day.

Ships were observed throughout Danish waters with an emphasis on the international shipping lanes and areas with the highest maritime traffic density. Except for 2 anchored vessels, all ships were observed while underway. The map in Figure 8 depicts the location of all measurements including vessel headings and corresponding FSC levels.

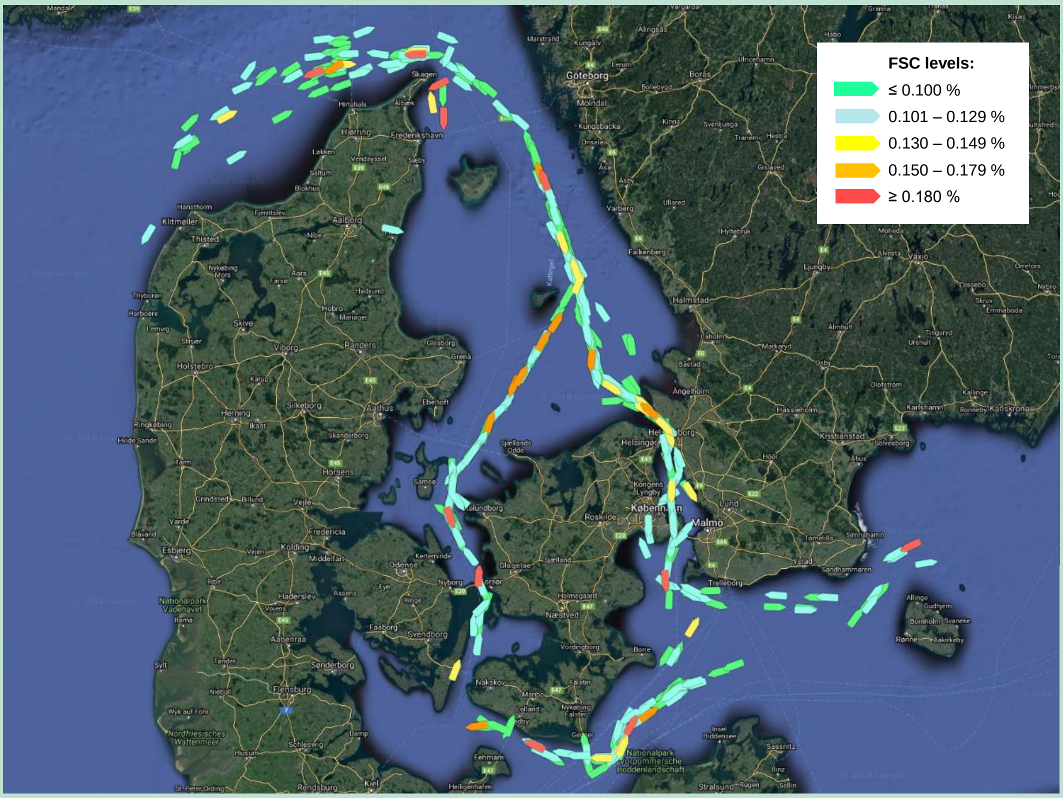

FIGURE 8. Geographical map of all measurements.

All ships were identified based on their AIS signals collected directly from the vessels by the operational team during flight. No third-party sources have been used to establish ship ID.
A breakdown of the dataset according to primary vessel type, based on the AIS data, is presented in Table 3.

TABLE 3. Distribution of measurements by vessel type

Type	Cargo	Tanker	Passenger	Not available	Total
Measurements	251	128	23	2	404
% of total	62.1 %	31.7 %	5.7 %	0.5 %	100 %

4.1.1 Period distribution and operational capacity

Due to an unusually rainy summer season in July and August, with unfavourable flight conditions, some of the initially planned flights had to be postponed to September. The distribution of measurements over the full campaign period as well as by hour on the day, is presented in Figure 9 and 10 respectively.

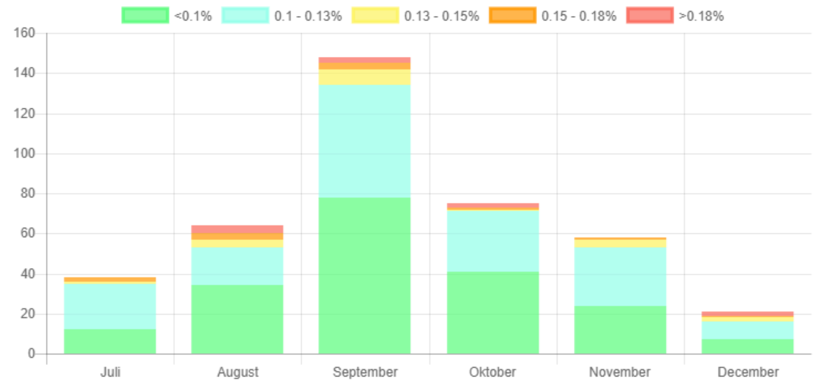

FIGURE 9. Distribution of measurements by campaign month. Note, the colours indicate FSC levels. For further see 4.2.

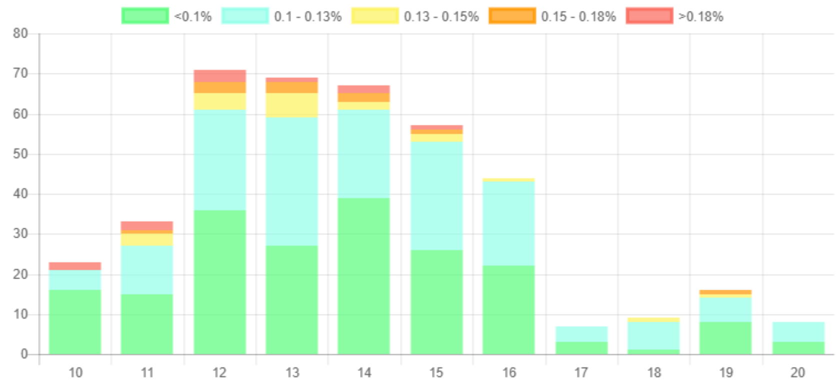

FIGURE 10. Distribution of measurements by hour interval. Note, the colours indicate FSC levels. For further see 4.2.

Over the course of the Campaign, the average amount of vessels the team was able to measure ranged from 6 – 10 vessels per flight hour. This is more than what has previously been in past airborne campaigns in Danish waters with fixed-wing sniffer aircraft[5], and more than what the team has experienced with drone operations.

In general, the team has found the manned helicopter to be an extremely efficient aircraft platform when considering both reach, output and cost.

In a best-case scenario with optimal conditions and high traffic density, the manned helicopter is estimated to have a maximum operational capacity (i.e. hourly output) of up to 14 vessels per hour without compromising quality.

4.1.2 Measurement quality

Overall, the campaign was able to demonstrate a consistently satisfactory quality level significantly above what other similar campaigns/technologies have been able to achieve.

Of the 404 ship observations, 390 measurements (96.5 %) were classified as high quality (≥ 6.00 in quality score) according to the quality scoring protocol.

A breakdown of the quality scores is presented in Table 4.

TABLE 4. Distribution by quality scores

Quality score	Low	Medium	High	Total
Measurements	4	10	390	404
% of total	1.0 %	2.5 %	96.5 %	100 %

[5] See Mellqvist et.al (2017), Surveillance of Sulfur Emissions from Ships in Danish Waters.

4.2 Observed FSC levels

Looking at the distribution of the measurements on different FSC levels, the data corresponds to the pattern observed in other surveillance findings with an approximate normal distribution peaking in and around the 0.10 % regulatory threshold applicable within the SECA. The data even identifies a slight subpeak at the 0.05% FSC level which could be explained by the fact that standard marine diesel oil from several Danish suppliers to smaller ships contains 0.05 % sulphur due to a Danish sulphur tax.

As with other remote monitoring datasets[6], the 2017 Campaign also demonstrates a 'tail' of higher FSC values (≥ 0.15 %) which doesn't appear to fit any particular bunker fuels available, indicating that these values either stem from late changeover to SECA-compliant fuel for ships coming from outside the SECA, or too early changeover to high sulphur fuel oil for ships leaving SECA. Ships may also have received fuel with a sulphur content slightly above 0.10 % from the supplier. While we draw no conclusion as to the behaviour behind these elevated values, we note that this pattern has now been documented by several studies.

The measurement distribution by FSC level is presented in Figure 11.

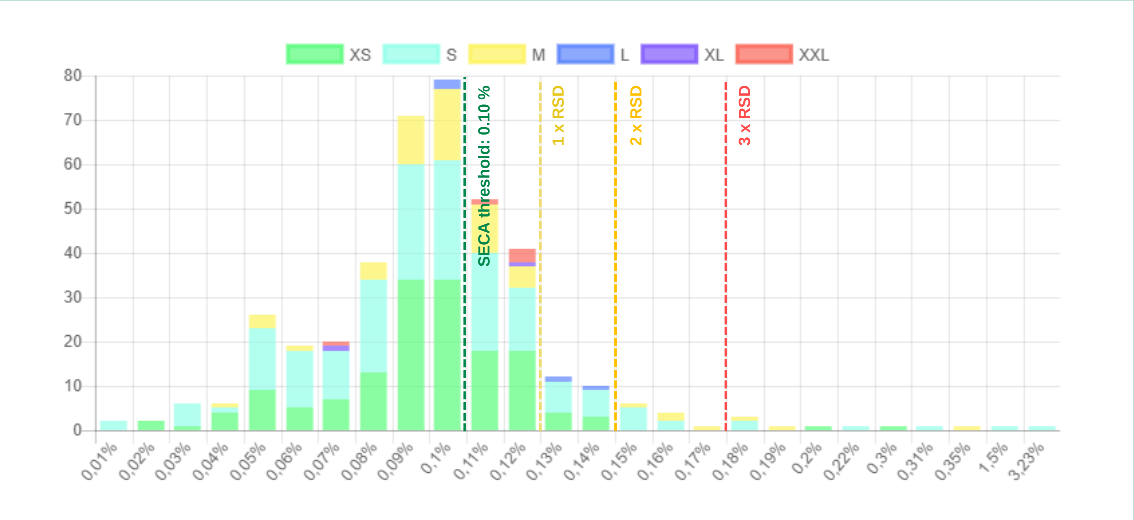

FIGURE 11. Distribution of measurements by measured FSC. Note: The colours indicate difference in vessel sizes according to their length[7]. The dotted lines indicate the various compliance cut-off levels for 1xRSD, 2xRSD and 3xRSD respectively.

4.2.1 Distribution of FSC values by cut-off level

As shown in Figure 11, the threshold at which a measurement can be deemed to breach the regulator compliance threshold of 0.10 % FSC, depends on the RSD uncertainty applied to the measurement. The higher the RSD applied, the stronger the probability that the measurement is in fact above the SECA threshold.

Applying different RSD thresholds, the following amount of ships were found to be above the SECA limit of 0.10% indicating non-compliant fuel being burned:

[6] Reference is made to the data reported in relation to the CompMon project (www.compmon.eu) and by Explicit during the Rotterdam Campaign 2016.

[7] XS = <130m, S = 130-220m, M = 220-290m, L = 290-300m, XL = 300-366m, XXL = >366m.

- Values above ≥ 0.13 % = 1xRSD (68% coefficient) = 44 ships or 10.8 % of total.
- Values above ≥ 0.15 % = 2xRSD (95 % coefficient) = 22 ships or 5.4 % of total.
- Values above ≥ 0.18 % = 3xRSD (99.7% coefficient) = 11 ships or 2.7 % of total.

At the 95% coefficient level – the level normally used when interpreting analysis results according to ISO 4259 – the number of vessels measured with elevated FSCs corresponds to approx. 1:18 ships. This finding is in line with previous results reported from other surveillance campaigns.

The distribution data is summarized in Table 5 according to RSD level. Reference is also made to the system cut-offs defined previously in section 2.4.1:

TABLE 5. FSC distribution by level of uncertainty

FSC	RSD	Colour	Measurements	% of total
≤ 0.100 %	N/A		196	48.5 %
0.101 – 0.129 %	N/A		164	40.6 %
0.130 – 0.149 %	1 x RSD		22	5.4 %
0.150 – 0.179 %	2 x RSD		11	2.7 %
≥ 0.180 %	3 x RSD		11	2.7 %
Total			**404**	**100 %**

4.2.2 Distribution of FSC values by vessel type

When comparing the FSC distribution by vessel type, focusing only cargo and tanker vessels which make up 94 % of the total dataset, no material discrepancies appear. (Passenger ships and others are excluded, because of the low number of measurements).

At the 95% coefficient level (2xRSD), cargo and tankers display similar levels of non-compliance with 5.2 and 5.5 % of vessels respectively registering elevated FSC values ≥ 0.15 %.

The FSC distribution by vessel type is summarized in Table 6.

TABLE 6. FSC distribution by vessel type and level of uncertainty

FSC	RSD	Colour	Cargo		Tanker	
			Measurem.	% of total	Measurem.	% of total
≤ 0.100 %	N/A		128	51,0%	55	43,0%
0.101 – 0.129 %	N/A		94	37,5%	61	47,7%
0.130 – 0.149 %	1 x RSD		16	6,4%	5	3,9%
0.150 – 0.179 %	2 x RSD		8	3,2%	2	1,6%
≥ 0.180 %	3 x RSD		5	2,0%	5	3,9%
Total			**251**	**100%**	**128**	**100%**

4.2.3 Distribution of FSC values by geographical location

As illustrated by the map in Figure 8, there is no clear geographical pattern in the compliance behaviour. Various degrees of non-compliance are found throughout Danish waters. Similarly, there are no clear directional patterns. Non-compliance is found just as frequently with vessels heading outbound towards the North Sea as inbound from the North Sea or with vessels operating within the surveyed area.

One thing is however worth noting: With the exception of 3 vessels – all measured on the same day in Easterly wind with significantly elevated FSC values of 0.145 %, 0.306 %, and 0.356 % respectively (see image H) – no values were registered ≥ 0.13 % in the Great Belt, indicating a possible deterrent effect of the fixed measuring station on the bridge. The compliant pattern does however not extend beyond the Great Belt.

Image H
Elevated FSC levels in the Great Belt observed during Easterly winds.

4.3 Other observations

In addition to the above, the following observations are noted:

In general, flight operations were carried out without incident. Approx. 10 % of ships used the option to communicate with the pilot team via channel 16 to confirm intent, and in all cases the response from captains was professional and generally very positive. In one incident, the team was able to assist a ship in testing various functions in relation to its radio communications.

No negative FSC outputs were observed. Negative sulphur values have otherwise been known to be a problem in other similar measuring campaigns, likely caused by e.g. noise and/or incorrect cross interference adjustments. The absence of negative values in the 2017 Campaign supports the conclusion that both the operational and technology solution applied is a very robust approach for monitoring vessel sulphur emissions from the air.

Similarly, the overall distribution profile shows a median FSC value of 0.101 % with a peak value at 0.096 % FSC, indicating full alignment with the dominating bunkering pattern of 0.10 % FSC within the SECA. In order words, the data shows no immediate bias.

As per DEPA, in 2017 Danish PSC collected 174 fuel samples with an average value of 0.08 % FSC. The datasets are, however, not entirely comparable as only approx. 10 % of the vessels measured by air were destined for Danish port and the vessel composition differs (small/large, type, etc.).

No material technical difficulties were experienced during missions. Any interruptions in the flight plan was entirely due to weather conditions and not equipment failure. The flexibility of the setup, with redundancy available on both aircraft, sensor instrumentation and computer processing, meant that any issues could be easily and immediately mitigated with no impact on the operation or the overall quality of the output.

Finally, we would like to note that the 2017 Campaign also estimated the NO_X emissions (in g/kWh) based on NO and NO_2 measurements in the plume. While the methodology and results concerning NO_X are not a subject of this report, the dataset has been provided to DEPA for possible further analysis.

5. Discussion

As reported, the 2017 Campaign marked the first instance were micro sensor technology in the form of a Mini Sniffer System has been used officially by any authority to monitor vessel sulphur compliance with MARPOL Annex VI. As such, it is appropriate to evaluate the performance of the technology, its limitations and potentials as a tool for airborne sulphur emissions surveillance on a broader scale.

By and large we find that both the technology and overall approach to airborne measurement demonstrated in the 2017 Campaign shows an attractive way forward for airborne emissions surveillance of ships. The robust performance observed adds another important tool to the arsenal available to authorities when they design their sulphur enforcement strategies.

The results show that, not only can low-cost micro sensor technology be made to perform in an otherwise very difficult measuring environment, the added features of *Smart Flight* and *Multiple Parallel Sampling* unique to this solution, greatly increase the quality of the output vis-à-vis other airborne measurement technologies.

With 96.5 % of all measurements classified as high-quality, the sensors, system and operational approach used in the 2017 Campaign appears to outperform any other technology approach tested so far[8]. It should however be pointed out, that there is no uniform quality assurance standard in place to truly judge and compare technologies against. But even despite this, the high ratio of good-quality measurements stands out.

Both the principles of Smart Flight and Multiple Parallel Sampling are Explicit inventions. Their development was original motivated by a desire to prove the following core hypotheses challenging previous approaches:

(a) That *plume positioning* has material impact on *any* airborne sniffer technology's ability to consistently produce quality emissions results. The monitoring challenge is not just about sensor selection; it's equally about how to navigate the plume.
(b) That through better plume positioning, it is possible to use (even) micro sensors, despite their inherent need for higher gas concentrations and longer emissions exposure.
(c) That plume positioning can be controlled and optimized through a combination of rotary aircraft and intelligent navigation, were live sensor feedback is used to guide the aircraft to achieve optimal distance and time in the plume.
(d) That the path to achieving low(er) measurement uncertainties doesn't necessarily go through upgrading a single gas analyser to its highest standard. Instead, it can also be achieved by multiplying data points as a way of compensating for minor inaccuracies in (much) less expensive sensor equipment.

So far, the 2017 Campaign and other previous results produced by Explicit, have shown all of the above to be true.
As for Multiple Parallel Sampling, this approach also has the potential to improve the legal merit of airborne measurements, as violations are documented in multiples and cross-checked through A-X sampling.

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[8] See, among others, the various reports released by compmon.eu.

All of the above being said, it is also apparent from this and other (test) campaigns that micro sensors also raise challenges that must be appropriately addressed to ensure measurement accuracy. In particular, pre-deployment quality protocols (test and calibration of assembled units) as well as well-defined replacement routines are critical. While we have found commercially available micro sensors to generally have an above-expected performance, variances can occur, emphasising the need for thorough testing before every EMSU is used in the field. For this reason, Explicit continues to put considerable effort into monitoring sensor performance, collaborating with FORCE Technology on calibration and validation to preserve and advance quality. For the same reason, we also encourage and welcome any effort to further advance our understanding of the various sulphur enforcement technologies available, their strengths and weaknesses, and how to set appropriate standards for their reliable deployment.

Airborne Monitoring of Sulphur Emissions from Ships in Danish Waters 2017
Annual report presented by Explicit ApS
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