CompMon

Compliance monitoring pilot for Marpol Annex

Certification of an aircraft and airborne surveillance of fuel sulfur content in ships at the SECA border

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CompMon

Compliance monitoring pilot for Marpol Annex VI

Date
08.12.2017

Title of publication
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Commissioned by, date
December 8, 2017

Keywords
Sulfur surveillance, ship, compliance, SECA, Airborne, EU sulfur directive

Contact person	Language of the report
Johan Mellqvist	English

Abstract

In 2015 new rules from the IMO and legislation from EU (Sulfur directive) and the US requires ships to run with maximum fuel sulfur content (FSC) of 0.1 % m/m in northern European and North American waters. In order to promote a level playing field within the shipping sector, there is a need for measurement systems that can make effective compliance control and this is the main objective of the CompMon project, funded through the European CEF program (Connecting Europe Facility). As part of this project, a sensor system has been certified for ship surveillance measurements in a Piper Navajo aircraft and it has been demonstrated for airborne measurements of FSC in individual ships on the English Channel.

The measurement system consists of an optical module which measures total emissions of SO_2 and NO_2 in g/s and a sniffer system by which FSC is retrieved from extractive measurements of SO_2 and CO_2. It can be used from fixed sites, patrol vessels and from aircraft. The advantage with airborne surveillance is the capability to check ships that are operating in the main shipping lanes, up to 200 nautical miles from shore. The precision of the estimated FSC from the sniffer system is 0.05 % m/m and hence at the 95 % confidence limit, ships above a FSC of 0.2 % m/m can be checked. The sniffer system also has a negative bias in the FSC of approximately 0.04 % m/m which is accounted for in the FSC calculations.

The optical system has larger measurement uncertainties than the sniffer but it is intended mostly for guidance of other controls.

As part of the CompMon project, a measurements campaign with the Navajo Piper aircraft was carried out at the SECA (Sulfur Emission Control Area) border in the English Channel at longitude 5 W. Six flight missions with duration of 4 to 5 hours were carried out from September 2 to 10, 2016, flying from Brest airport. In this manner it was possible to cover the longitude range 2° - 6° W. During the campaign, 114 ships were measured with the sniffer system, corresponding to 71 ships inside the SECA and 42 ships outside. The level of compliance inside the SECA was here 87 % and this is considerably lower than measurements carried out elsewhere within CompMon in other parts of the SECA (95-99 %). Two thirds of the non-complying vessels were leaving the SECA. With the optical system 110 individual ships were measured, 42 outside and 68 inside the SECA. The measurements show a similar pattern as the sniffer data but with a few false values. Nevertheless it is shown that both low and high FSC ships will be classified correctly with about 80-90 % probability with the optical system and this system is hence very promising as a tool to guide further compliance controls.

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Acronyms

AIS	Automatic Identification System
IGPS	Identification of Gross Polluting Ships
DEPA	Danish Environmental Protection Agency
DOAS	Differential Optical Absorption Spectroscopy
FSC	Fuel Sulfur Content in mass percentage (m/m)
IMO	International Maritime Organization
MEPC	Marine Environment Protection Committee
MARPOL	Marine Pollution
PSC	Port State Control (authority)
SECA	Sulfur Emission Control Area
STC	Supplemental Type Certificate
UV	Ultraviolet

1 Introduction

In 2015 new rules from the IMO and legislation from EU (Sulfur directive) and the US requires ships to run with maximum fuel sulfur content (FSC) of 0.1 % m/m on northern European and North American waters. The extra cost of this fuel is 50 % or more, corresponding to about 10,000 Euros extra per day of ship operation. At present compliance monitoring of ships is carried out by port state control authorities that take fuel samples of ships at berth. Since this procedure is time consuming only few ships (4 %/year in Europe) are being controlled, and none while underway on open waters. The high extra cost for low sulfur fuel and the relatively small risk of getting caught, creates a risk that unserious ship operators will run cheaper high sulfur fuel. In order to promote a level playing field within the shipping sector there is hence a need for measurement systems that can make effective compliance control, without stepping on board the ships. This is acknowledged by the EU commission who has funded the CompMon project (https://compmon.eu/) through the CEF program (Connection Europe Facility) to pilot various applications of sulfur compliance monitoring. This includes fixed site measurements in Sweden, Finland, the Netherlands and airborne ones in Belgium and the English Channel. In addition airborne and fixed site sulfur compliance measurements in Denmark (Mellqvist, 2017b) and fixed station measurements in Germany are associated to the project.

In this report we describe work carried out within the CompMon project to certify a sensor system for ship surveillance measurements in an aircraft and demonstration of the system for airborne measurements in the English Channel at the SECA border. As part of the CompMon we have also further developed a software tool that is used to automatically obtain the ship emissions when in flight and send these to a database together with email alerts. We also carried out fixed ship surveillance measurements at the port entrance of Göteborg (Älvsborgfästning) and at the Öresund Bridge, one of the main passage ways to enter or leave the Baltic Sea (Mellqvist 2017a).

The actual measurement system used in this project has been developed in the Swedish project *Identification of Gross-Polluting Ships* (IGPS) (Mellqvist, 2014). In the same project and as part of CompMon we did installation of the system in a Navajo Piper aircraft with approval by EASA (European Air Safety Agency). In 2016 this system was used in a measurement campaign at the SECA border, as described in section 6. It was also used to monitor ships on Danish waters in 2015 and 2016 in a parallel project funded by the Danish Environmental protection agency (Mellqvist 2017b). This project also included fixed automatic measurements at the Great Belt Bridge and it is associated to the CompMon project. Similar ship surveillance activities, with earlier measurement systems, have been carried out by the authors elsewhere and this includes measurements in the Baltic sea (Beecken et al., 2014a; Berg et al., 2012), Göteborg (Mellqvist et al., 2010; 2014), Rotterdam (Alfoldy et al., 2011 and 2013; Balzani-Loov et al., 2014) and Saint Petersburg (Beecken et al., 2014b).

The measurement system we describe here can be used from fixed sites, patrol vessels and from aircraft. The advantage with airborne surveillance is the capability to check ships that are operating in the main shipping lanes, up to 200 nautical miles from shore. Due to the short time to react, when discovering the surveillance aircraft, it is not possible for the ships to switch their fuel as in the case for the fixed sites. The disadvantage with flight surveillance is the high cost (1000-3000 Euro/h) but since the measurements are carried out in locations with a higher probability of finding ships that use non-compliant fuel, these measurements may still be cost effective compared to fixed site measurements. In addition if the measurements are conducted on already existing surveillance aircraft, such as operated by coast guard, the cost will become even lower.

2 Hardware

2.1 Instruments

The sniffer and optical systems, respectively, are based on the instruments described in Table 1. The sniffer instruments are commercially available as state of the art instruments and they are being used worldwide as reference methods for air quality measurements. To fulfill flight requirements these instruments have been modified for fast response, smaller weight, smaller shape (form factor) and field robustness. The gas inlets of each single instrument are also connected to a common pressure regulated gas inlet. To be able to obtain a fast response time the SO_2 instrument in the flight system is operated without the so called "kicker" which is a diffusion tube which removes organic substances from the sampling stream before the measurement chamber. Other adaptions correspond to replacement of toxic material, such as PVC (Poly Vinyl Chloride), in the instruments and extra shielding of electromagnetic radiation (Mellqvist, 2014). Note in in Table 1 that two different CO_2 instruments are being used. Here the cavity ring down spectrometer is much more stable than the non-dispersive infrared instruments and the former does hardly need any calibrations. The optical method is based on two spectrometer (f.c. 303 mm/ f.c. 160 mm) equipped with UV-sensitive cameras based on CCD (Charge Coupled Device) sensors. A pair of telescopes with 150 mm focal length are connected to the spectrometers through liquid guide fibers (Berg, 2010). In Table 1 the precision (basically same as detection limit) of the instruments and their response times are also shown. The t_{90} parameter corresponds to the time that is needed for the instruments to change from 10 % to 90 % of the signal when making a step change. It has been demonstrated that the instruments in Table 1, built into suitable boxes, can be used under harsh ambient conditions. For instance we have operated the instruments from 2 helicopters, two harbor vessels, and two aircraft.

Table 1. The instruments employed for ship surveillance. Response time (t90) and measurement resolution uncertainty (σ) is given.

Species	Quantity	Method	Model	t_{90}	1σ
CO_2	Mixing ratio (sniffer)	Cavity ring down spectrometer with custom hardware and sampling (sniffer)	Picarro G-2301m	<1 s	0.1 ppm
CO_2	Mixing ratio (sniffer)	Non dispersive infra-red instrument, single cell with multiple filters.	LI-COR 7200	0.1 s	0.3 ppm
SO_2	Mixing ratio (sniffer)	Fluorescence (modified)	Thermo 43i-TLE	2 s	5 ppb
NO_x	Mixing ratio (sniffer)	Chemiluminescence (modified)	Thermo 42i-TL	1 s	1 ppb
SO_2	Column (optical)	Optical meas (DOAS)	Andor: Shamrock SR–303i , Newton 920BU	1 Hz	20 ppb over 50 m
NO_2	Column (optical)	Optical meas (DOAS)	Andor: Shamrock SR–303i, Newton 920BU	1 Hz	20 ppb over 50 m

2.2 Aircraft installation

The main measurement system used here was developed in the Swedish project IGPS (Mellqvist, 2014). The system was installed in a Navajo Piper aircraft (OY-MST) partly through the activities in the Compmon project, Figure 1. This aircraft is owned by the Danish surveillance company Aircraft Aps that owns two Navajo Piper aircraft for oil pollution surveillance work and that has a special low flying permit. To obtain a permanent installation in the aircraft an approval to modify the aircraft had to be requested from the European Air Safety Agency (EASA) and which was issued in Dec 2014 (Supplemental Type Certificate (STC) 10051623, European Air Safety Agency). The preparatory work required extensive activities by a certified design and production organization, in our case LD aviation in Prague, who was responsible for the overall work including communication with EASA through the Czech air safety agency, CAA. The STC work included design of dedicated IGPS instruments and equipment that were tested regarding electromagnetic interference and magnetic properties (RTC DO 160/issue M/cat M/section 21 and section 15) in an accredited laboratory (Saab in Linköping).

Figure 1. The Navajo Piper OY-MST owned by the collaborating Danish company Aircraft Aps was chosen for the IGPS installation. The airplane is stationed in Roskilde, 30 minutes flight time from the main shipping lanes in the southern Baltic sea. Aircraft Aps has specialized in oil pollution surveillance and has a special low flying permit.

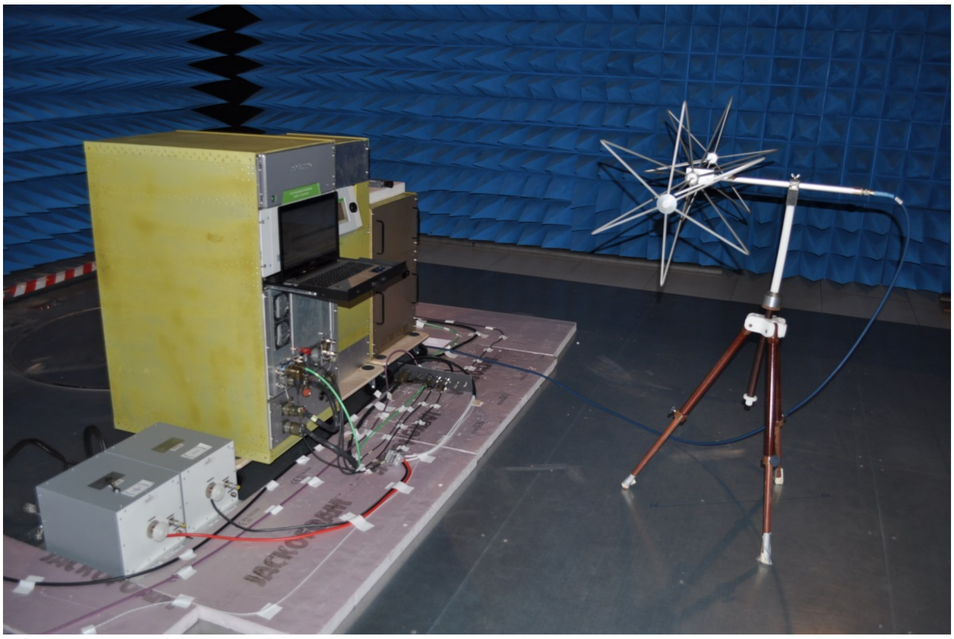


Figure 2. EMI testing of the IGPS equipment at the SAAB reference laboratory in Linköping following the requirement RTC DO 160/issue M/cat M/section 21 and section 15).

As part of the STC work an investigating of the production of toxic gases that would be produced in case of fire was carried out, including removal of most of the components made of PVC which produces hydrogen chloride when burning. Special instrument racks, withstanding high gravitational forces, were designed and produced by LD aviation. A window in the airplane was replaced by a probe plate carrying windows for two telescopes and one video camera and probes to extract particles and gases from the outside air. The airplane has been equipped with a wind sensor and the data was transmitted to the IGPS system using a special protocol (ARINC).

In Figure 1 the installation of the IGPS system in the Navajo Piper airplane is shown including some specifics of the instruments. The system in the aircraft is divided into different instrument racks for optical remote sensing measurements and sniffer measurements of gases and particles). In addition a window was exchanged by a probe plate equipped with both telescopes and probes, Figure 3.

A special instrument (SO_2/CO_2 module) has been designed, Figure 4, that fits into a 19” rack with a weight of 47 kg and a power consumption of 15 A at 28 V-DC. This module includes all necessary hardware to carry out sulfur compliance measurements from the air, i.e. logging computer, AIS (Automatic Identification System) receiver, GPS (Geographical Positioning System) receiver, power converter, calibration gases, SO_2-sensor, CO_2-sensor and pressure regulators. The module is also the central system in the airplane setup in the Navajo Piper aircraft. In Figure 1 and Figure 5 the optical module is also shown containing two UV spectrometers with cooled CCD detectors for simultaneous measurements of SO_2 and NO_2.

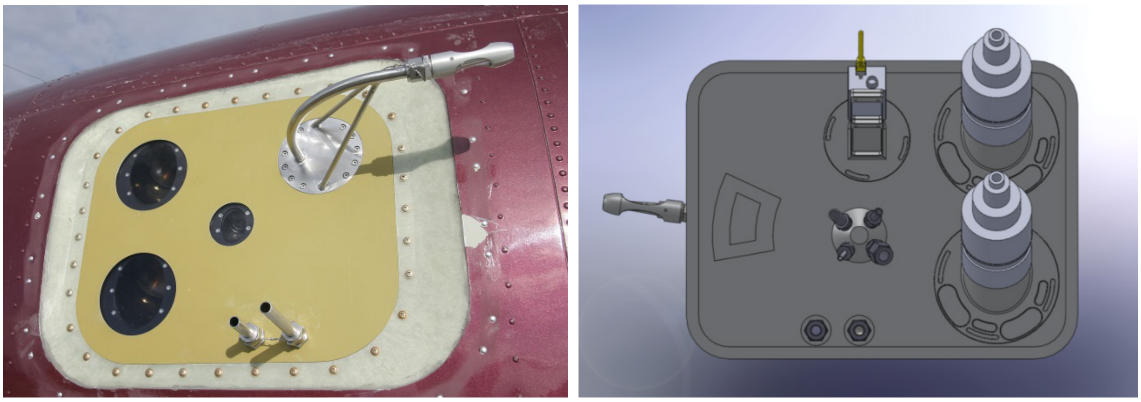


Figure 3. The left picture shows a window probe plate that has replaced one of the airplanes windows and which is equipped with two small windows for optical telescopes (left), one small window for a video camera (middle), one particle probe (upper right), and gas probe, (lower right) and one gas exhaust pipe (lower middle).

Figure 4. A custom designed FSC sniffer module. This box fits into a 19" rack, weighs 47 kg and utilizes 15 A at 28 V-DC. The system includes all instruments needed to monitor the FSC of ships from the air, i.e. a logging computer, AIS receiver, GPS receiver, power converter, calibration gases, SO_2 sensor, CO_2 sensor and pressure regulators. It is also the central system in the measurement system in the Navajo Piper aircraft.

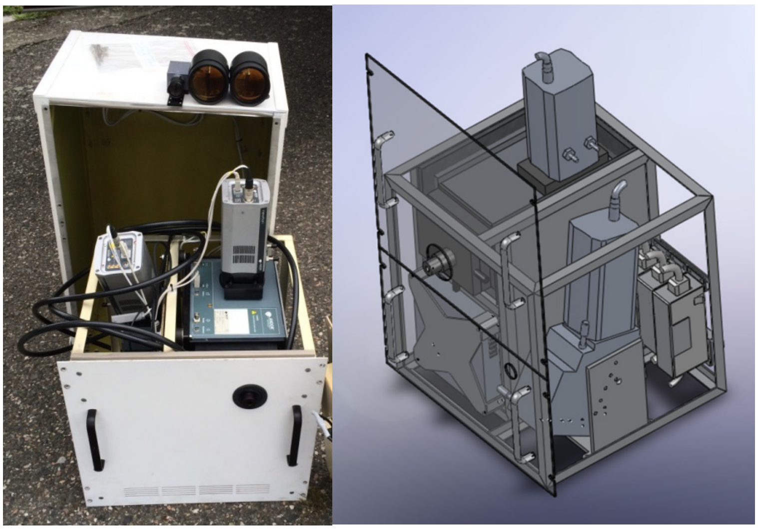


Figure 5. The optical module contains two UV spectrometers from Andor equipped with cooled CCD detectors for simultaneous measurements of SO_2 and NO_2.

3 Method

The flight operation is illustrated in Figure 6 when using the sniffer and optical hardware that were described in the previous section. From the optical module (Berg et al., 2012) the total emissions of SO_2 and NO_2 in g/s are measured at approx. 200-400 m flight altitude. The sniffer system measures the ratio of SO_2 against CO_2, from which the FSC can be derived.

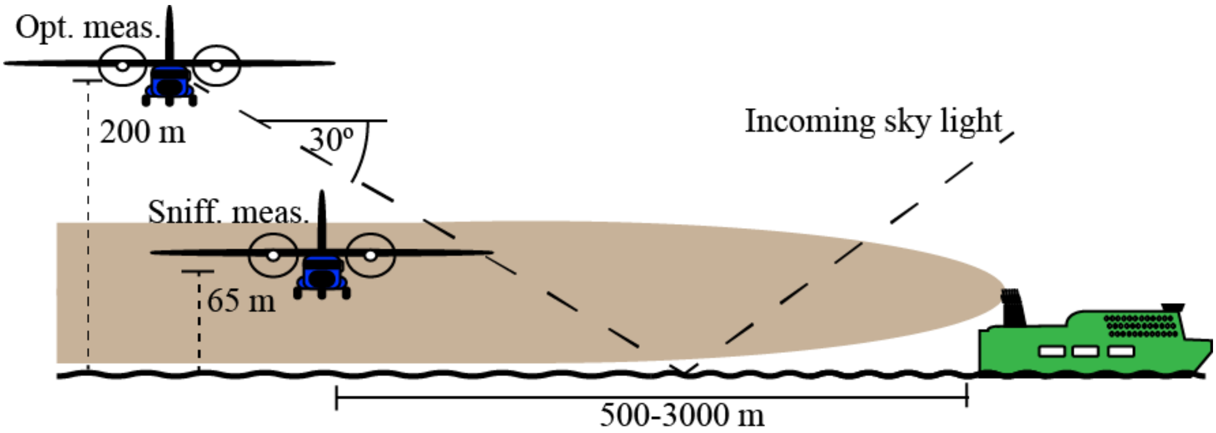


Figure 6. An illustration of the flight modes for the optical and sniffer system for surveillance of FSC (Fuel Sulfur Content). The optical measurements are carried out through the smoke from 200 m flight altitude. If the values indicate high FSC a flight at lower altitude (65 m) is carried out.

3.1 Sniffer measurements

From the sniffer system the FSC is directly obtained by sampling of the gas concentrations in the ship plumes, usually at low flight altitude around 65 m (200 feet). The sniffer is based on several commercially available gas analyzer instruments. The FSC is obtained from the ratio between the pollutants and CO_2 inside of the plume. Eq. 1 shows a more general of this calculation, which is consistent with the on board method described in the MEPC guidelines 184(59).

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

Here CO_2 and SO_2 corresponds to the gas concentrations expressed in ppm (parts per million) and ppb (parts per billion), respectively. The subscript bkg (background) corresponds to the ambient concentration neighboring the plume. The constant 0.232 corresponds to the sulfur-carbon atomic weight ratio multiplied with a factor of 87 %, that relates the carbon to the fuel, and a correction for different units.

The FSC as described on Eq.1 can be considered to be directly proportional to the sulfur to carbon content in the fuel, assuming that all sulfur is converted to SO_2. However, this is only partly true since some studies have shown that around 5 % of the sulfur is present as sulfate in particles (Moldanova et al., 2009; Petzold et al., 2008); hence, the apparent FSC obtained from the SO_2 to CO_2 ratio will be somewhat lower than the true FSC.

The SO_2 analyzer response has cross sensitivity to NO. For example our laboratory tests show that 200 ppb of NO will cause a 3 ppb response in the SO_2 analyzer (Alfoldy, 2014). This may lead to an overestimation of the FSC by up to 0.1 % if not accounted for. To remove the influence of NO on the SO_2 measurements, the NO_x species have been measured in parallel to the SO_2 measurements. However, NO_x consists of the two gas species NO and NO_2 and one therefore need information about the ratio between NO and NO_x at the measurement situation. Measurements at the Great Belt Bridge (Mellqvist, 2017b) show that the median value of the NO to NOx ratio was 71 % approximately 1 km downwind the ship. We have used this information and corrected the data according to Equation 2.

$$FSC = 0.232\frac{\int\left[SO_2 - SO_{2,bkg}\right]_{ppb}dt - 0.0098\int\left[NO_x - NO_{x,bkg}\right]_{ppb}dt}{\int\left[CO_2 - CO_{2,bkg}\right]_{ppm}dt}\text{[\%sulfur]} \tag{2}$$

A second measurement artifact in the flight SO_2 instrument is caused by the absence of the kicker, as mentioned above. The kicker removes the influence of organic substances such as aromatic volatile organic carbons. Generally these species are not present to any larger extent in the flue gas of the ships. However, by performing laboratory test it turned out that the instruments are also sensitive to other organic species, vapors or particles, present in engine lubrication oil and that these species seem to condensate easily in the tubing of the instrument. In a recent engine laboratory study (Eichler et al., 2015 and 2017) they performed advanced measurement of organic particles in the flue gas which showed that the mass spectra of these particles are very similar to the ones from condensed lubrication oil and that they consist of long chained cyclic alkanes (C_{20}-C_{25}) with low volatility. It is likely that these species also cause a response in the SO_2 fluorescence instrument. In real measurements when not using a kicker, significant tails in the SO_2 time series of the ship plumes were sometimes observed which we believe are caused by organic condensable material. This effect was extra pronounced for measurements in the inlet channel of Göteborg, where we also carried out measurements as part of the CompMon project (Mellqvist, 2014; Mellqvist 2017a). We estimate, by analyzing measurement with and without kicker, that this effect causes a 0.1 % m/m positive bias of the FSC on average and a significant increase in the random uncertainty from ±0.04 % m/m to ±0.12 %. The problem is usually mitigated by excluding the tail of the plume in the calculation of the FSC. The kicker effect is probably strong at the Göteborg site since it is positioned where the ships are changing speed and this causes transient emissions with are generally high on particulates. Similar effects have been observed when measuring at a fixed station at the Great Belt bridge (Mellqvist 2017b) but too lesser degree. *For the airplane measurements carried out in this project there is little evidence of a kicker artifact in the statistics even though this instrument has no kicker*. The reason for this is presumably because the ships are operated at steady state conditions and higher load when measured in the open sea and then particle emissions are usually lower than during low load and transient operation. For instance, one of the ships that regularly showed high readings in the sniffer measurements at Göteborg in 2015 due to the kicker effect, have been sampled low with the aircraft on 3 different occasions on the open sea. This was observed for several other ships as well.

In Table 2 several measurement factors causing errors in the data are discussed. Part of the details in the table can be found in others sections of the report.

Table 2. The main error sources involved in the measurements are shown here

Error source	Description	Comment
Correction for background	Done by statistical fitting of the baseline. *(This procedure is sometimes difficult when there is noisy background of CO_2 from the mainland.)*	Part of random noise.
Measurement noise	CO_2: 0.2 ppm SO_2: 2 ppb NO_x 1 ppb	Part of random noise. It is included in the quality flag assessment
Calibration gas uncertainty	CO_2: 0.5 % SO_2: 3 % NO_x : 3 %	Part of systematic uncertainty. Calibration certificate from AGA Gas and Air Liquide
Calibration interpolation error	Variation of instrument response between calibrations.	Part of random noise.
Cross interference i)	The SO_2 measurement is compensated for cross-interference with NO (0.98%). This is based on NO_x measurements assuming that 71% of NO_x is NO.	Part of measurement bias
Cross interference ii)	The fast responding SO_2 measurements (without kicker) exhibits skewed false SO_2 peaks presumably caused by lubrication oil particles	The effect is mitigated by using the first part of the plume.
Sampling error i)	Uncertainty when measuring short duration plumes (aircraft)	Test with a premixed gas shows a 13% precision and 10% general accuracy
Sampling losses	SO_2 adsorption /absorption conversion on surfaces gas inlets, tubings and instrument.	Most measurements have a negative bias and this could be one of the causes.
Fuel carbon content uncertainty	Usually 87% is assumed	Estimated uncertainty is 2%

3.2 Optical measurements

The airborne sniffer measurement have been complemented by optical remote sensing using several spectrometers that operate in the ultraviolet and visible wavelength region, respectively, for simultaneous gas column density measurements of SO_2 and NO_2 (Berg et al., 2012). This system is able to discriminate between ships running 1% m/m FSC and 0.1% m/m, and in this project it was used as a first alert system for high sulfur ships that were then further analyzed with a sniffer system. The results from the optical system can also be used directly to guide further control by port state control authorities.

The system measures solar light that has been reflected on the ocean through two telescopes pointing down 30^{o} below the horizon. The gas column densities are retrieved from the spectral measurements by applying Differential Optical Absorption Spectroscopy (DOAS) which is a technique widely used for atmospheric measurements from satellites and ground based instruments. From the optical measurements, combined with wind and vessel information, it is possible to estimate the absolute emission rate in gram per second of the retrieved gas species with an uncertainty of about 50 % (Berg et al., 2012). Combined with a model that predicts the instantaneous fuel consumption of a ship (STEAM), an estimate of the FSC can be made (Berg, 2012) following the principles in Eq. 1. The advantage with this method lies in the fact that it is possible to obtain the absolute emission rate. However, it is rather uncertain due to the difficulty of modelling the optical path of the light and uncertainties associated with modelling the fuel consumption. The method also requires crossing the full plume, more or less orthogonally. In this project we have therefore applied a new more flexible variant, using the ratio of SO_2 and NO_2 in the ship plume as an indicator for the FSC. This method does not require knowledge about optical path, wind speed, ship speed nor fuel consumption and it is therefore simpler from an operational point-of-view. In Figure 7 an example of optical measurements of SO_2 and NO_2 is shown. The peaks correspond to measurements of two ships using either low or high FSC, as can be deduced from the SO_2 to NO_2 ratio.

In more detail, ships typically emit 40-90 g NO_x per kg of fuel (Beecken et al., 2014) and the emission depends on several factors such as age, type, size and load and possible emission abatement system. Most of the NO_x (90-15 %) is emitted as NO but in the air it is rapidly converted to NO_2 by reaction with ozone. Measurements at the Great Belt bridge site (Mellqvist 2017b) show that 15-50 % of the NO_x has been converted to NO_2, and that the amount depends on the distance to the ship. A high sulfur ship (1 % m/m FSC) emits 20 g SO_2/kg and a low one (0.1 % FSC) 2 g/kg. This means that a 1 % m/m FSC ship will typically have a SO_2/NO_2 mass ratio of 1 or higher while the ratio corresponding to a 0.1% FSC ship can be 10 times lower. Naturally, this approach has uncertainties mostly associated with the large variation in the NO_x emissions and in the NO/NO_2 ratio in the flue gas, as indicated above. In this project we have used this approach and ships with a SO_2 to NO_2 ratio above 1 were assigned a FSC value of 1 % m/m in the emission database while ships with a ratio below 1 was assigned an FSC value 0.1 % m/m. The results from the optical method are compared to the sniffer one in section, including an uncertainty discussion.

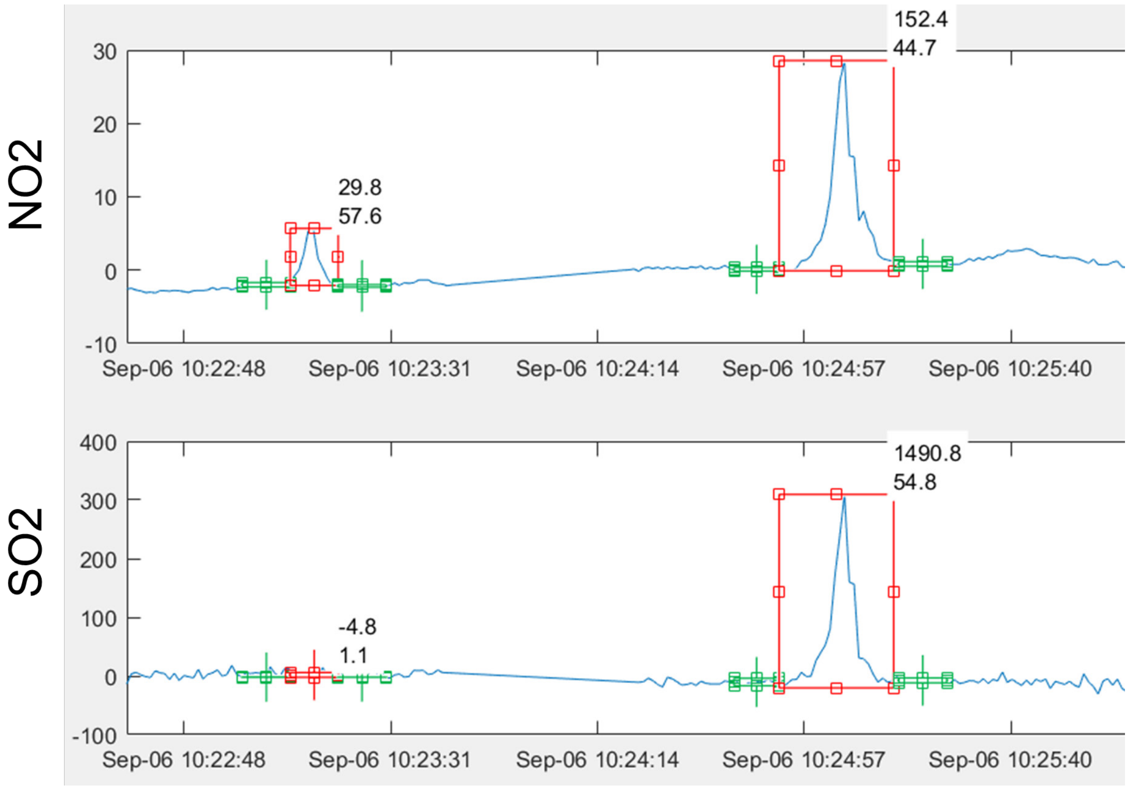


Figure 7. Optical measurements of NO_2 and SO_2 of two ships, one running on 0.1 % m/m FSC and the other on 1 % m/m FSC is shown. The data were obtained at the SECA border as part of the CompMon project.

3.3 Calibration

The sniffer and optical instruments are calibrated before each flight mission on the ground, after preheating of at least an hour. In Figure 8 is shown a calibration in which premixed calibration gas is flushed in front of the gas inlet using Teflon tubing. In the picture can also be seen a validation exercise for the optical measurement in which gas cells filled with SO_2 and NO_2, respectively, are held in front the optical telescopes.

The wavelength setting and the instrumental line shape of the optical instruments are calibrated every day using a mercury lamp. The sniffer instruments are calibrated against premixed gas standards with a typical accuracy of a few percent. The typical gas concentration values for SO_2, CO_2 and NO_x are 401 ± (3 %) ppb, 370 ± (0.5 %) ppm and 191 ± (3 %) ppb. The gas standard of NO_x is diluted in nitrogen while the other gases are diluted in synthetic air. From the calibration the correction factors are obtained which are used to correct the flight measurement. In addition to the standards above, we used a multi-gas calibrator and zero air generator (Thermo 146i and Thermo 1160) together with more stable mixtures of high concentration calibration gases from AGA Special gas AB corresponding to 101 ± (0.5 %) ppm for both NO and SO_2 gases. These calibrations are done a few times a year to check the stability of the calibration gases, and to bridge the gap when switching gases.

Figure 8. Quality control of the sniffer and optical sensors on the Navajo Piper aircraft from Aircraft Aps. The yellow plate includes two windows for optical sensors, a window for a video camera, two inlets for gases and particles, respectively, and one exhaust pipe. The optical system is checked by holding gas cells filled with known concentrations of SO_2 and NO_2 in front of the telescopes. The sniffer system is calibrated by flushing premixed calibration gas in front of the gas inlet using Teflon tubing.

4 Measurement methodology

The airborne surveillance scheme that has been carried out in this project was already illustrated in Figure 6 and consists of two parts:

First, optical measurements of reflected solar light from the water surface are carried out from an altitude of about 250 m and from these the path integrated concentration of SO_2 and NO_2 along the light path can be retrieved (Berg et al., 2012). From these measurements the FSC of the ship scan be estimated in either of two ways, as explained in section 3.2: a) through the calculation of gas emissions in g/s from the ships or b) by utilizing the ratios of SO_2 and NO_2. The other part in the surveillance corresponds to sniffer measurements, in which the exhaust plumes from the ship is extracted trough a gas inlet (sonde) on the airplane and then further analyzed by on-board instruments with respect to SO_2, CO_2 and NO_x. These measurements are carried out at lower altitude (65 - 100 m) than the optical one in order to get in contact with the ship plume. They are carried out at a distance of 500 to 2000 m downwind the ship. In order to improve the reliability of the measurements, 3 measurement repetitions are generally performed for all ships that are measured above the compliance level threshold in the first attempt. With the optical measurements it is possible, under day light conditions, to check the FSC of 10 to 20 ships, depending on how long distance it is between the ships, while for the sniffer system 4 to 8 ships can be checked.

As part of the measurement system, a computer software denoted IGPS-real has been developed for real time flight planning and data retrieval. The movement of ships and aircraft are tracked using AIS and GPS-data that are acquired in real-time. From this information and wind data obtained from an aircraft sensor it is possible to calculate how the emission plumes from the ships travel, and which ship's exhaust plume is measured at a given moment. In close to real time (10-20 s delay) the software automatically calculates the FSC and the NO_x emission factor, when intercepting the ship plume with the aircraft. The main tactical screen is shown in Figure 9 and Figure 10, including some explanations of the provided information. The view can be locked to follow the aircraft, to follow a ship or to a geographical position. The program also controls the optical sensors and calculates emissions according to the description above. The real time program is an essential part of the flight operation since it is used to guide the aircraft and for real-time analysis of the FSC.

When at the ground the data is transferred to a web database. For gross polluting ships alerts can be sent out already from the air, provided that the aircraft is connected to internet. In Figure 11 an extract from a web database used by Chalmers is shown in which the data are stored in closed to real time. The data are stored together with information from AIS which provides the name and speed of the target ship together with quality information that are assessed from the data. In the data evaluation the quality of the measurements is expressed through a quality flag that can alternate between the following levels: HIGH, MEDIUM, and POOR. This assessment is based on the parameters in Table 3 and it is based on a combination of measured parameters such as CO_2 peak signal and empirical observations of conditions when the measurements are more certain. The quality level may also shrink if different hardware warning flags are raised while the instruments are operating. These flags are mostly associated to issues related to high/low temperature, low voltages, flow interruptions, etc.

The data can also be directly transferred to a database for further usage by ship inspection authorities to target which ships to inspect once they are in harbors. A suitable database is THETIS-EU which is developed by the European Maritime Safety Agency (EMSA) to flag ships that are found to use non-compliant fuel with regard to the EU sulfur directive.

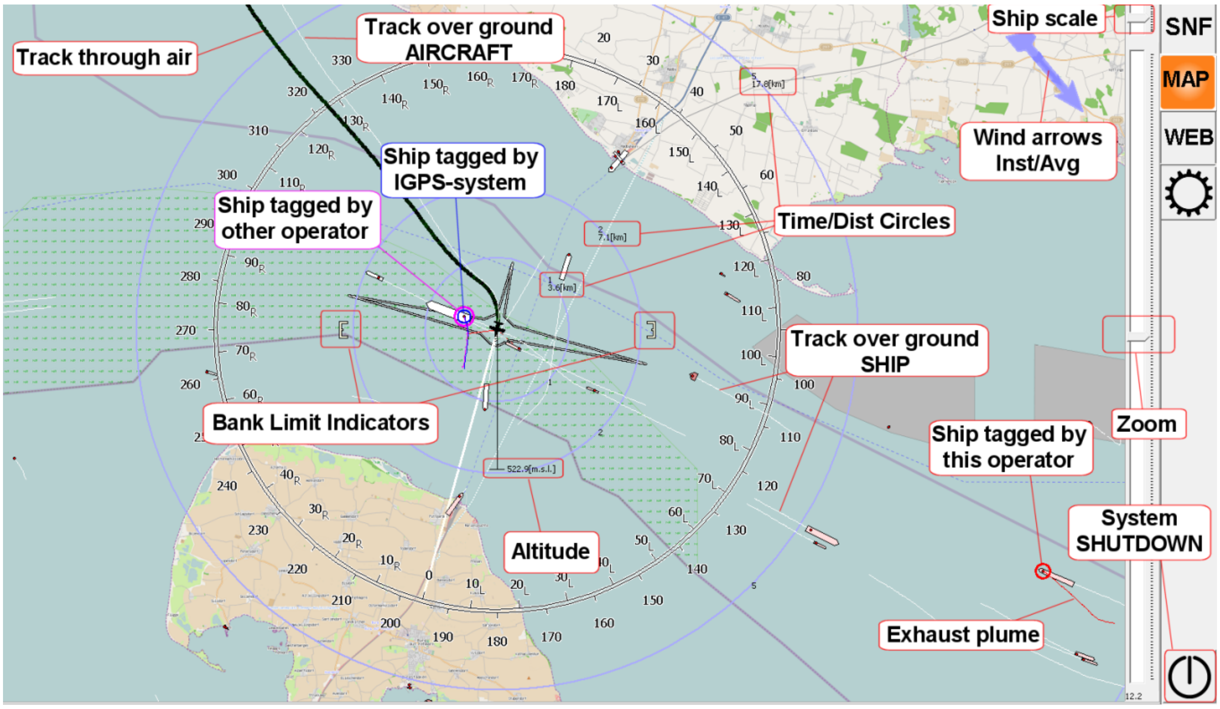


Figure 9. The program IGPSreal when carrying out airborne compliance control. Different type of information that is displayed is explained in the picture.

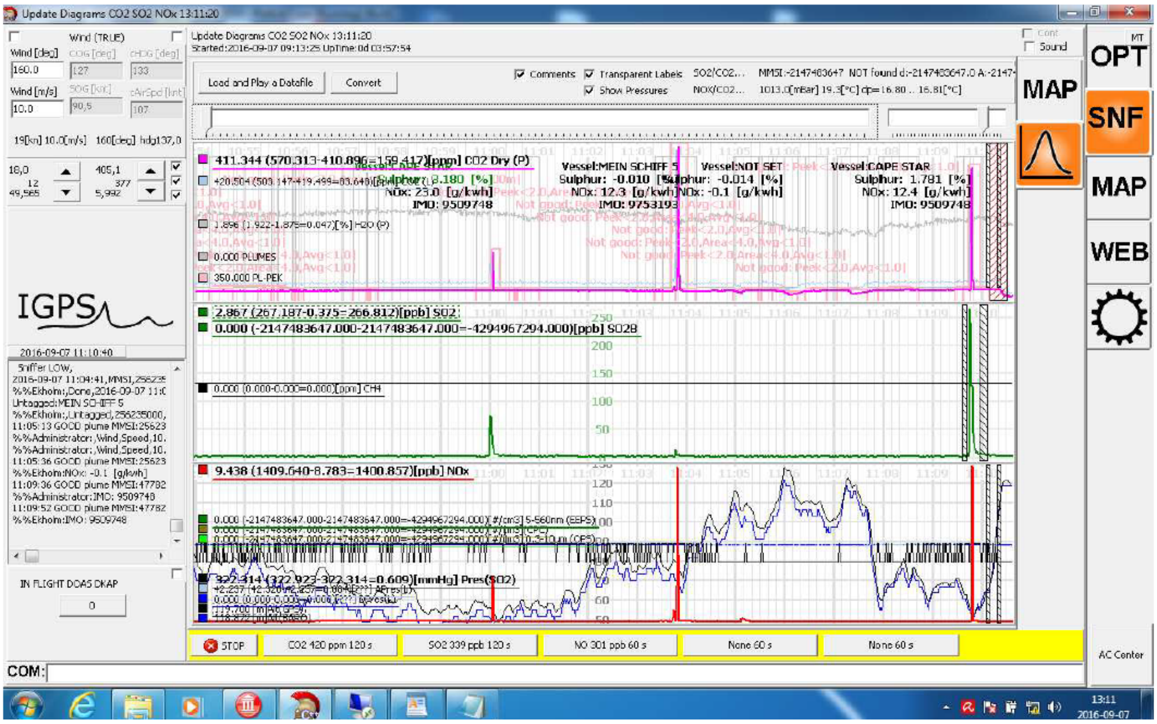
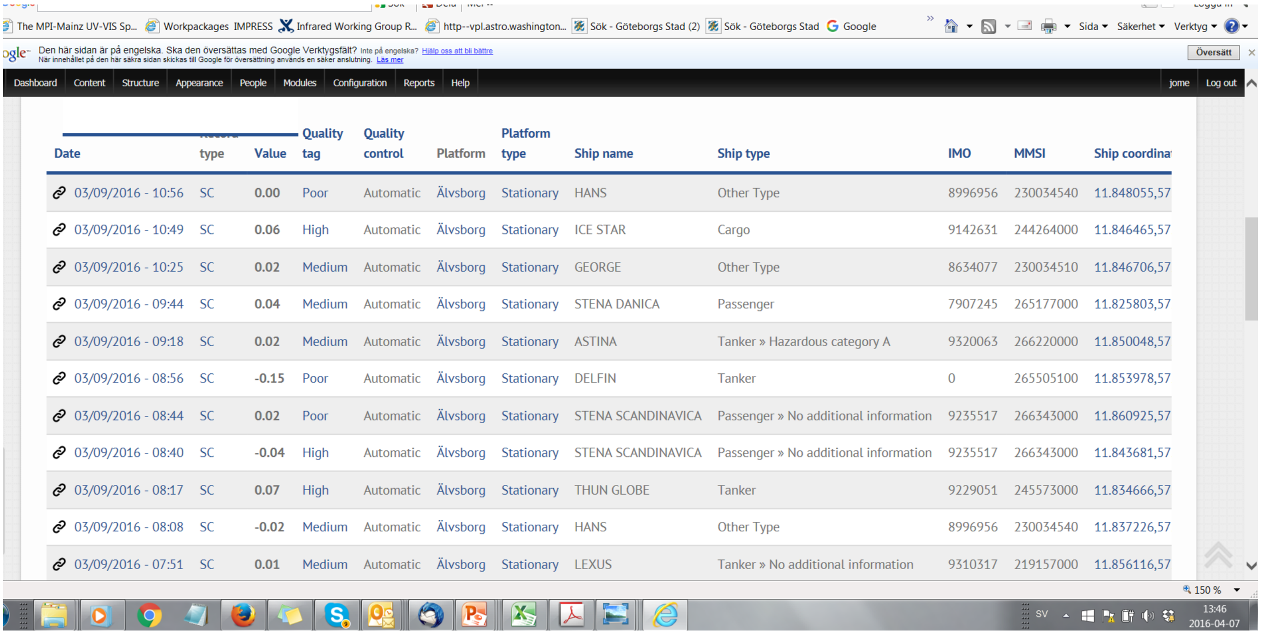


Figure 10. The program IGPSreal when carrying out airborne compliance control. In this scene the real-time concentrations of CO_2 (pink), SO_2 (green) and NO_x (red). In addition the flight altitude is shown in grey.



Date	type	Value	Quality tag	Quality control	Platform	Platform type	Ship name	Ship type	IMO	MMSI	Ship coordina
03/09/2016 - 10:56	SC	0.00	Poor	Automatic	Älvsborg	Stationary	HANS	Other Type	8996956	230034540	11.848055,57
03/09/2016 - 10:49	SC	0.06	High	Automatic	Älvsborg	Stationary	ICE STAR	Cargo	9142631	244264000	11.846465,57
03/09/2016 - 10:25	SC	0.02	Medium	Automatic	Älvsborg	Stationary	GEORGE	Other Type	8634077	230034510	11.846706,57
03/09/2016 - 09:44	SC	0.04	Medium	Automatic	Älvsborg	Stationary	STENA DANICA	Passenger	7907245	265177000	11.825803,57
03/09/2016 - 09:18	SC	0.02	Medium	Automatic	Älvsborg	Stationary	ASTINA	Tanker » Hazardous category A	9320063	266220000	11.850048,57
03/09/2016 - 08:56	SC	-0.15	Poor	Automatic	Älvsborg	Stationary	DELFIN	Tanker	0	265505100	11.853978,57
03/09/2016 - 08:44	SC	0.02	Poor	Automatic	Älvsborg	Stationary	STENA SCANDINAVICA	Passenger » No additional information	9235517	266343000	11.860925,57
03/09/2016 - 08:40	SC	-0.04	High	Automatic	Älvsborg	Stationary	STENA SCANDINAVICA	Passenger » No additional information	9235517	266343000	11.843681,57
03/09/2016 - 08:17	SC	0.07	High	Automatic	Älvsborg	Stationary	THUN GLOBE	Tanker	9229051	245573000	11.834666,57
03/09/2016 - 08:08	SC	-0.02	Medium	Automatic	Älvsborg	Stationary	HANS	Other Type	8996956	230034540	11.837226,57
03/09/2016 - 07:51	SC	0.01	Medium	Automatic	Älvsborg	Stationary	LEXUS	Tanker » No additional information	9310317	219157000	11.856116,57

Figure 11. Example of a web database in which all ship data are stored in close to real time. Data from the Göteborg site Älvsborg are shown for a few ships.

Table 3. Quality criteria applied for the airborne measurements. The data in this project have been evaluated manually with an assessment of measurement quality based on the criteria below.

Criteria	Comment	High	Medium	Low
SNIFFER				
Normal operation	Warning flags for the hardware not set, such as high/low temperature, low voltages etc.	Required	Required	Poor
Preheating	Preheat instrument 2 h before departure	Required	Required	Required
Calibration	1 h before departure. Check that difference in data correction factors are within 20% of nominal value; if so change the calibration parameters of the instruments	Required	Required	Required
ΔCO_2 in plume	Peak height	>4 ppm	2-4 ppm	1-2 ppm
Δt_{CO2} in plume	Time duration in plume.	>3s	>2 s	>1s
$\Delta CO_{2,plume}$/stdev(CO_{2bkg})	Peak signal above background noise (standard deviation)	4	3	2
ΔSO_2 in plume*	Peak height	>4 ppb	2-4 ppb	1-2 ppb
ΔSO_2/ (0.098%*ΔNOx)	*Interference effect, If interference dominates uncertainty increases*	*3*	*2*	*1.5*
$\Delta t_{SO2}/\Delta t_{CO2}$	Skewness of plume, compared to CO2 measurement. In all cases we reduce this effect by using only the time period with CO2 plus 2 s	<2	2-3	3-5
No of ships with overlapping plumes		1	1	1
OPTICAL				
$\Delta NO_{2,optical}$		>10 mg/m2	>8 mg/m2	>7 mg/m2
SNR SO2	(ΔSO_2/stdev(SO_2_baseline))	3	2	2
Compliance threshold	SO_2/NO_2	>3	>2	>1

* Applies for ships above compliance threshold

5 Precision, accuracy and compliance threshold

In a parallel project funded by the Danish EPA (Mellqvist, 2017b) the Navajo Piper aircraft used also in his project flew 240 h around the waters of Denmark. The *precision* of the airborne measurements were estimated from the variability of the data close to the median value A Gaussian distribution function was fitted to the data centered on the median value, i.e. using FSC data only in the range -0.1 % to 0.15 % m/m. In this manner a value of the precision was obtained corresponding to 0.05 % m/m (1σ). This value corresponds to the scatter in the measurements of low FSC ships and it would be an accurate estimate of the precision if all ships were using the same FSC. In the same project the *accuracy* of the sniffer measurements was assessed by comparison to almost 800 on board samples by port state control authorities in Sweden and Denmark. By assuming that the median FSC from the airborne measurements should be the same as the on board samples a negative bias of 0.043 % m/m was obtained for the airborne system. The reason for the negative bias is not understood and potentially it could be caused by tubing losses. Ships running with an FSC value of 0.1 %, will hence be measured as having a FSC of 0.057 % m/m on average. However, since the measurement have random noise associated with them corresponding to a precision with standard deviation 0.05 % m/m, the data will be spread out according to a Gaussian distribution. Most of the data (95 %) will be within 2 standard deviations from the 0.057 % m/m value; this gives an upper value of 0.15 % m/m and this is the *biased corrected compliance threshold* used in our evaluation. Individual ships with FSC measured above this limit are considered to use non-compliant fuel with 95 % confidence limit.

Note that the compliance threshold is modified to account for the bias in our data, so it can be used to calculate compliance levels. It is however not the threshold for the real data, since in this case one should use the un-biased threshold. Forinstance, in the case of the airborne data the real unbiased threshold at 95 % confidence limit is 0.2 % m/m. This means that it is not possible to detect non-compliant ships using a FSC in the range 0.1 to 0.2 % m/m.

Due to the complexity of the measurements it is difficult to assess their accuracy from theoretical estimations and the best approach is to compare to other measurements. In 2008 such a comparison (Alfoldy et al. 2013) was done for high FSC ships comparing our airborne sniffer measurements with on board sampling on a RoPax ferry. The comparison showed an overall estimated relative uncertainty for SO_2 of 23 % with a precision of 0.19 % m/m at the 1% m/m FSC level for the airborne sniffer measurements.

Another comparison of the sniffer measurements was done between fixed measurements at the Great Belt Bridge (Mellqvist, 2017b) and on board sampling on a scrubber ship. The data for 11 coincident measurements showed a difference between the sniffer and the onboard data of -0.02±0.023 m/m % and this is actually smaller than the estimated errors for this system.

One potential measurement artifact in the airborne measurements, compared to fixed ones, is the fact that the contact with the ship gas plume is very short when flying, i.e. usually a few seconds. To evaluate this we have made “puff test” in which a calibration gas with a high concentration mixture of SO_2 (203.9 ppm) and CO_2 (4.293 %) is injected in front of the measurement probe of the aircraft. The SO_2 to CO_2 ratio in this gas corresponds to a 1.1 % m/m FSC ship according to Eq. 1. In Figure 12, an example of one such puff measurement is shown with the measured concentrations of SO_2 and CO2 shown versus time. The corresponding results for several experiments in which the measured ratios of SO_2 and CO_2 have been converted to FSC according to Eq. 1, are shown in Figure 13. The FSC obtained from the plume measurements corresponds to 1.01± 0.13 % m/m; hence there is a negative bias of -0.1 % m/m (corresponding to the accuracy) and a spread of the data corresponding to a precision of 0.13 % m/m. In Table 4 the overall estimated uncertainty for the measurements is summarized.

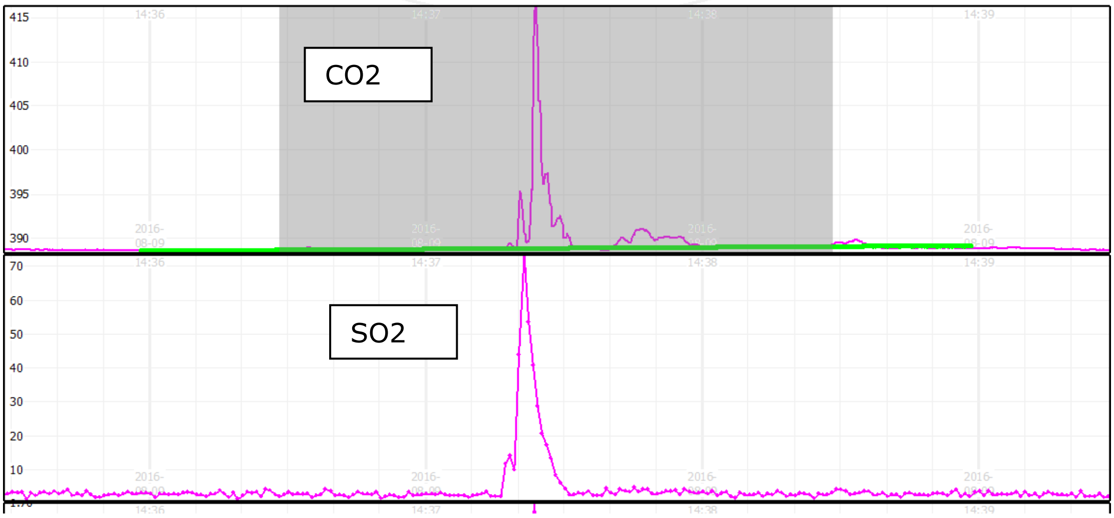


Figure 12. A quality assurance test in which a short pulse (10s) of premixed SO_2 and CO_2 gas was blown across the airplane inlet and analyzed by the sniffer systems in the aircraft. Here is shown the concentration of CO_2 (top) in ppm and SO_2 (middle) in ppb versus time is shown.

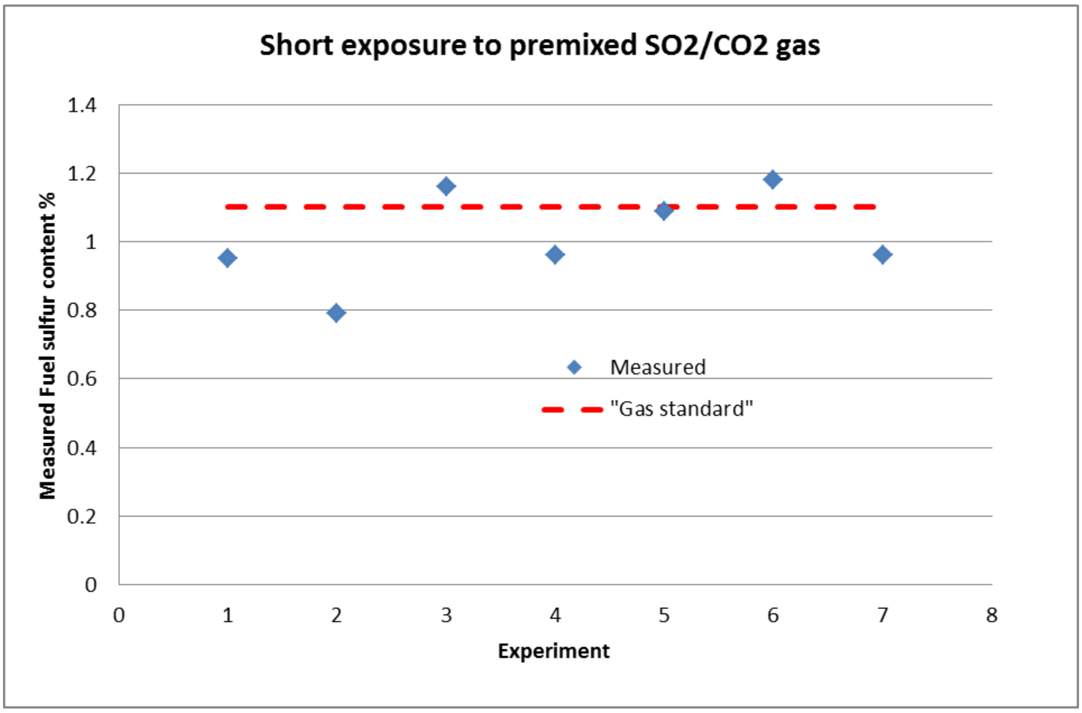


Figure 13. A quality assurance test in which short pulses of premixed SO_2 and CO_2 gas was blown across the airplane inlet and analyzed by the sniffer systems in the aircraft. The general relative accuracy of the sniffer measurements was 10 % (0.1 % m/m) with a relative precision of 13 % (0.13% m/m).

Table 4. Estimated overall uncertainty for the sniffer measurements in this study. All values correspond to the absolute FSC unit.

	0.1% FSC	**1 % FSC**
Random uncertainty abs FSC unit	±0.049% m/m	±0.19 % (1)
Systematic bias	-0.043%	-0.1 % (3)
Threshold(2) for compliance limit (95 % confidence limit)	0.2% FSC	

(1) Beecken 2014a and other studies, see section 2,
(2) Unbiased threshold.
(3) Balzani 2014

6 Airborne campaign at SECA border

As part of the CompMon project a measurements campaign with the Navajo Piper aircraft was carried out at the SECA border in the English Channel at longitude 5 W.

A seven hour transfer ferry flight was first done from Roskilde airport which is the base of the aircraft. Measurements were then carried out from September 2 to September 10, 2016, flying from Brest airport. In this manner it was possible to cover the longitude range 2^{o} - 6^{o} W, as shown in the graphs in the results section.

The Navajo Piper is a two engine aircraft with maximum speed of 160 kts, and typical speed during the measurements of 100 - 120 kts. The endurance during the flights was about 6 hours with two pilots and two operators. This research and surveillance aircraft can reach all places in Europe and can perform similar measurements as in this campaign. The aircraft has a low flying permit (200 feet). The sniffer measurements worked best in moderate wind speeds 0 to 10 m/s and good visibility (VFR). During the project 114 individual ships were measured with good quality during 27 flight hours and 6 flight missions. For each mission, one hour was typically lost during the approach to the ship channel and when returning to the Brest airfield. Hence, whilst in the active ship area an effective measuring rate of 5.5 ships per hour was achieved. For each ship we performed several transects through the plume. The airplane cost for these flights were 2000 Euro per h during the flight missions. Hence the effective surveillance cost here is 470 Euro per ship, excluding the ferry flight and operator cost and instrument rental.

Figure 14. The Navajo Piper aircraft parked at the Brest airport.

7 Results and discussion

7.1 Sniffer measurements

The sniffer measurement results for the six flight missions are shown in Figure 15. Here the measured FSCs for 114 individual ships are shown, color-coded in red, yellow and green, respectively, depending on the measured FSC values. The arrows point towards the travel direction (course over ground) of each individual ship. The ships span the longitude range between 2^o to 6^o W. The SECA border at 5 W is indicated with a black dotted line. The green markers east of the 5^o W line, inside the SECA, corresponds to ships that are compliant with the EU sulfur directive while the yellow ones are just above the 95 % confidence limit threshold. The red markers correspond to gross polluters. In total 71 ships were measured inside the SECA and 42 ships outside.

In Figure 16 the statistical distribution (probability density function) of the FSC of 71 individual ships measured inside the SECA in the English Channel is shown. The green curve corresponds to the random noise distribution (precision) of the measurements obtained from flight measurements in Denmark (Mellqvist, 2017b). The dotted line is the estimated non-compliance FSC limit of 0.15 % m/m for which the instrument errors (precision and bias) have been accounted for. The median FSC value for the distribution is 0.05 % m/m with an average of 0.17 % m/m. Nine out of the 71 ships (13 %) were above the compliance threshold of 0.15 % and two thirds of these ships were leaving the SECA. The non-compliant ships that were sailing in to the SECA were all measured close to the SECA border.

The fraction of ships that were running on low sulfur oil outside the SECA corresponds to 40 % but most of these were observed close to the SECA border.

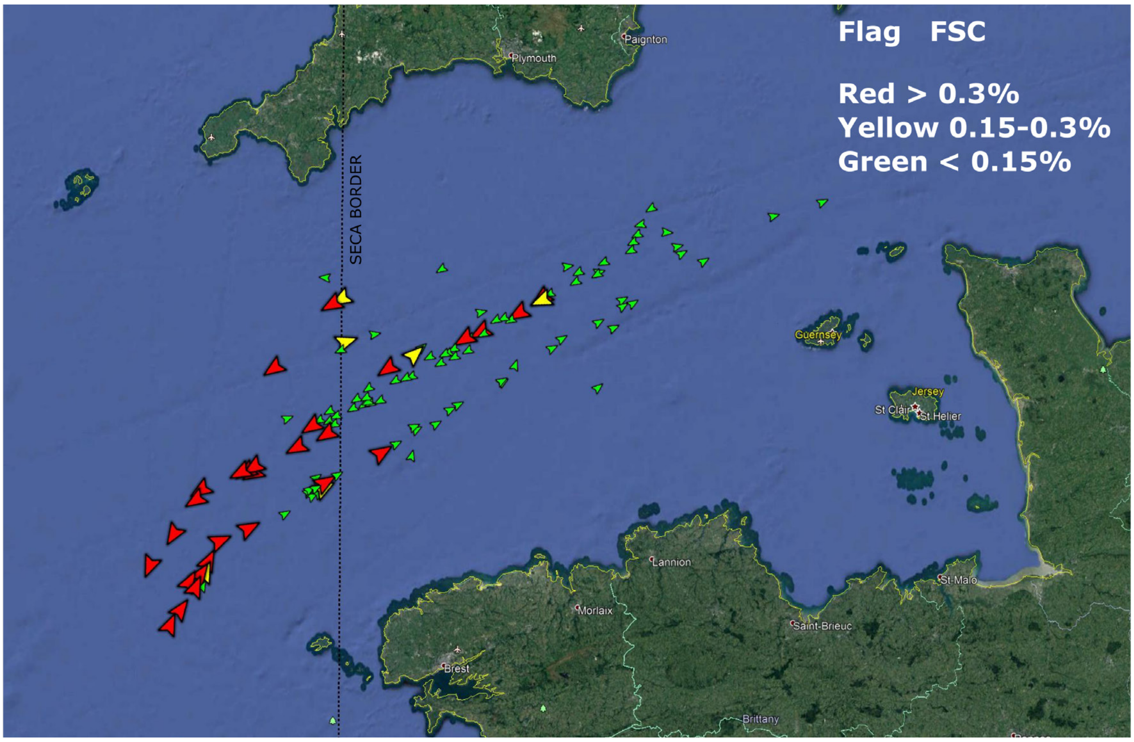


Figure 15. Sniffer measurements of 114 individual ships measured on both side of the SECA border at 5 W. The arrows point towards the travel direction an correspond to an individual ship. The ships span the longitude range between 2^o to 6^o W. The SECA border at 5 W is indicated with a black dotted line. The green markers correspond to ships that are compliant with the EU sulfur directive. In total 71 ships were measured inside the SECA and 42 ships outside.

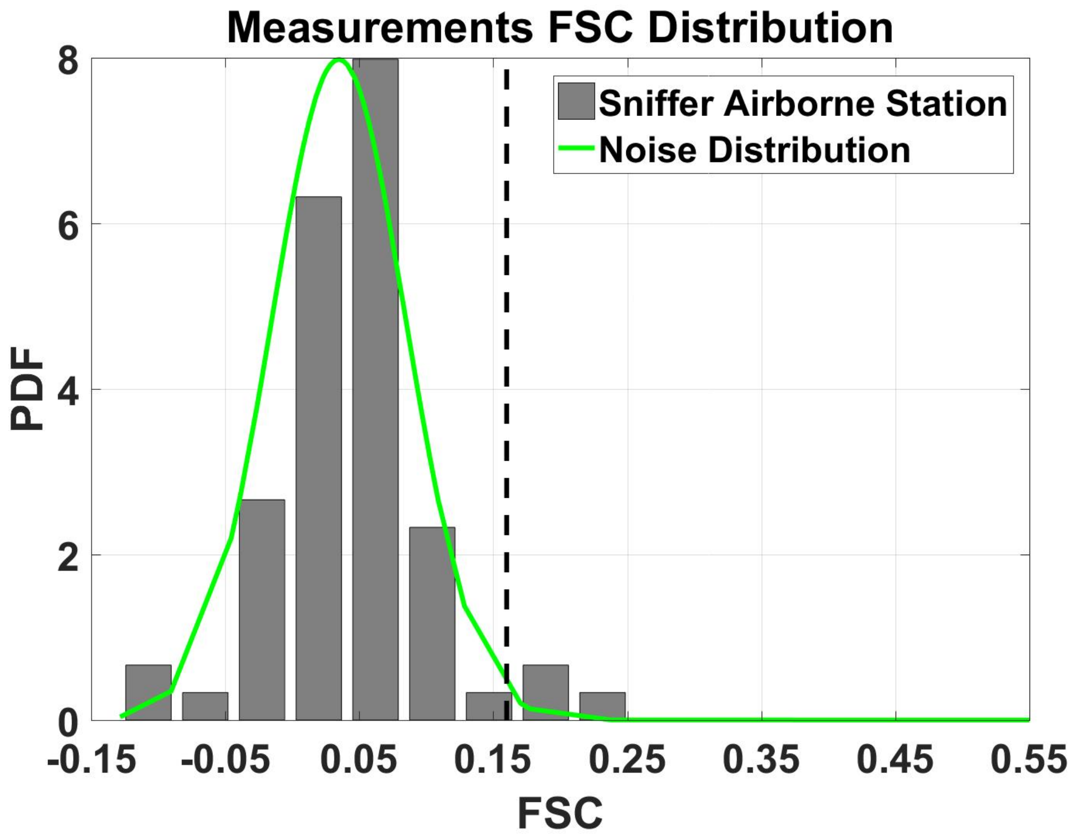


Figure 16. Statistical distribution (probability density function) of the FSC of 71 individual ships measured with sniffer from aircraft in the English channel at 5° W during September 2016. The green curve corresponds to the random noise distribution (precision) of the measurements obtained from elsewhere. The dotted line is the estimated non-compliance limit for which the instrument errors (precision and bias) have been accounted for.

7.2 Optical measurements

Optical measurements of SO_2 and NO_2 in ship plumes was carried out from the Navajo Piper aircraft by analyzing spectra of ocean reflected light that has passed through the ship plumes. Ships with a SO_2-to-NO_2 ratio m/m higher than the value 1 was here categorized as non-compliant with respect to the EU sulfur directive. A measurements example was already shown in Figure 7 when measuring on two vessels outside the SECA border, with low and high FSC, respectively.

The optical data for the Brest campaign is shown in Figure 17, corresponding to 110 individual ships, and in most cases the same ships were also measured by the sniffer system as shown in Figure 15. Here 42 ships were measured outside the SECA and 68 inside. When comparing the two figures it appears that the optical system works reasonably well in differentiating between high and low FSC ships. The optical measurements indicate that 16 % of the ship uses non-compliant fuel inside the SECA, to be compared to the more accurate sniffer value of 13 %. The fraction of ships that were running on low sulfur oil outside the SECA corresponds to 36 % from the optical system, to be compared to 40 % for the sniffer system. Hence, all in all, the optical measurements provide a similar picture of the compliance levels as the sniffer system although somewhat lower compliance.

A more detailed analysis is shown in Figure 18. Here the SO_2-to-NO_2 ratio from the optical method is plotted against the FSC from the sniffer method, for the same individual ship when available. The data in the figure show that 83 % of 53 ships with a FSC below 0.2 % have an SO_2 to NO_2 ratio below the value of 1, following the method section 3.2. Here we use 0.2 % m/m as a FSC limit to account for uncertainties. The corresponding statistics for 32 high FSC ships (>1 % m/m FSC) shows that 94 % of the ships have a SO_2 to NO_2 ratio higher than 1. Hence, both low and high FSC ships will be classified correctly with about 80 - 90 % probability when using an upper limit of 1 for the SO_2 to NO_2 ratio. Since the main idea is to guide further compliance controls we believe that this probability is sufficient.

As already described we have categorized ships with a SO_2 to NO_2 ratio above 1 as using 1 % m/m FSC while ships with a ratio below 1 was assigned an FSC value 0.1 % m/m. In 2020 the FSC limit of all ships outside the SECA region will correspond to 0.5 %. The optical method should be able to distinguish between ships running on FSC 0.5 % m/m against 2.5 % m/m, which is approximately the fleet average, with the same efficiency as distinguishing between 0.2 % m/m and 1 % m/m FSC ships as presented here. However, further investigation is needed to assess the efficiency for the optical method to identify ships running on 1 % m/m FSC against 0.5 % m/m.

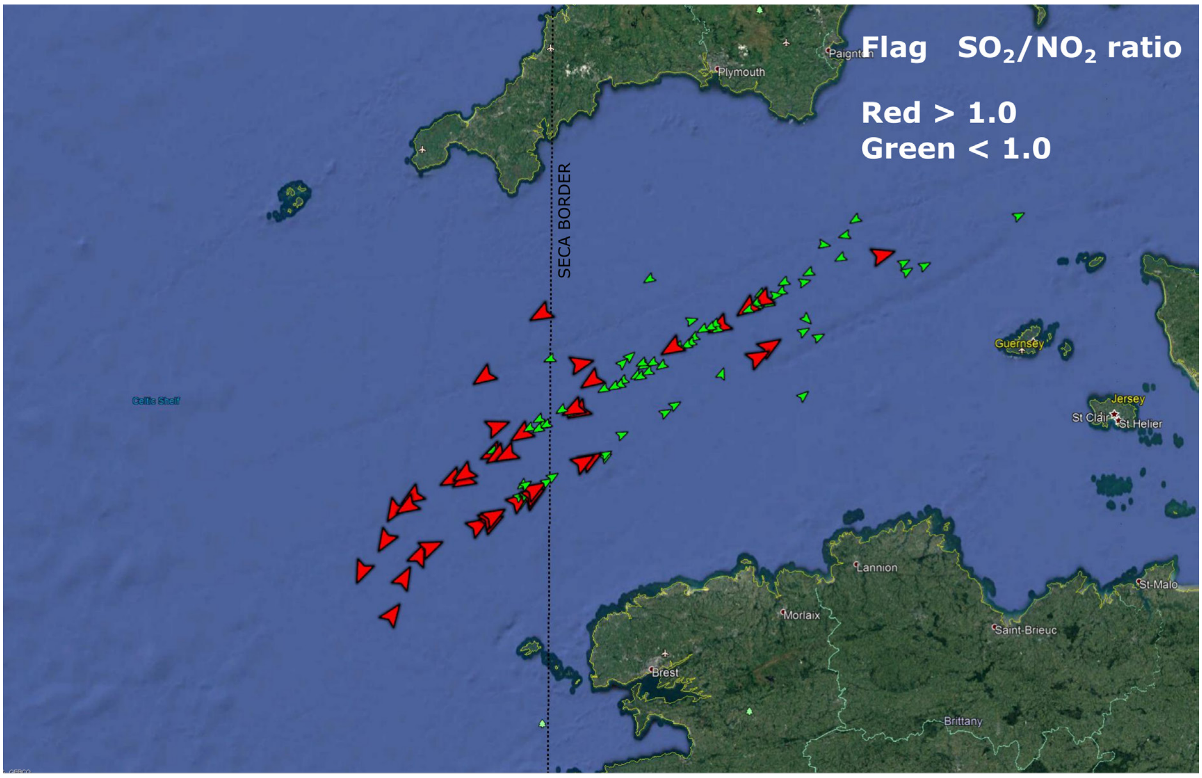


Figure 17. The optical measurements for 110 individual ships. The vessels with a SO_2-to-NO_2 ratio above 1 have been categorized as running on non-compliant FSC and vice versa.

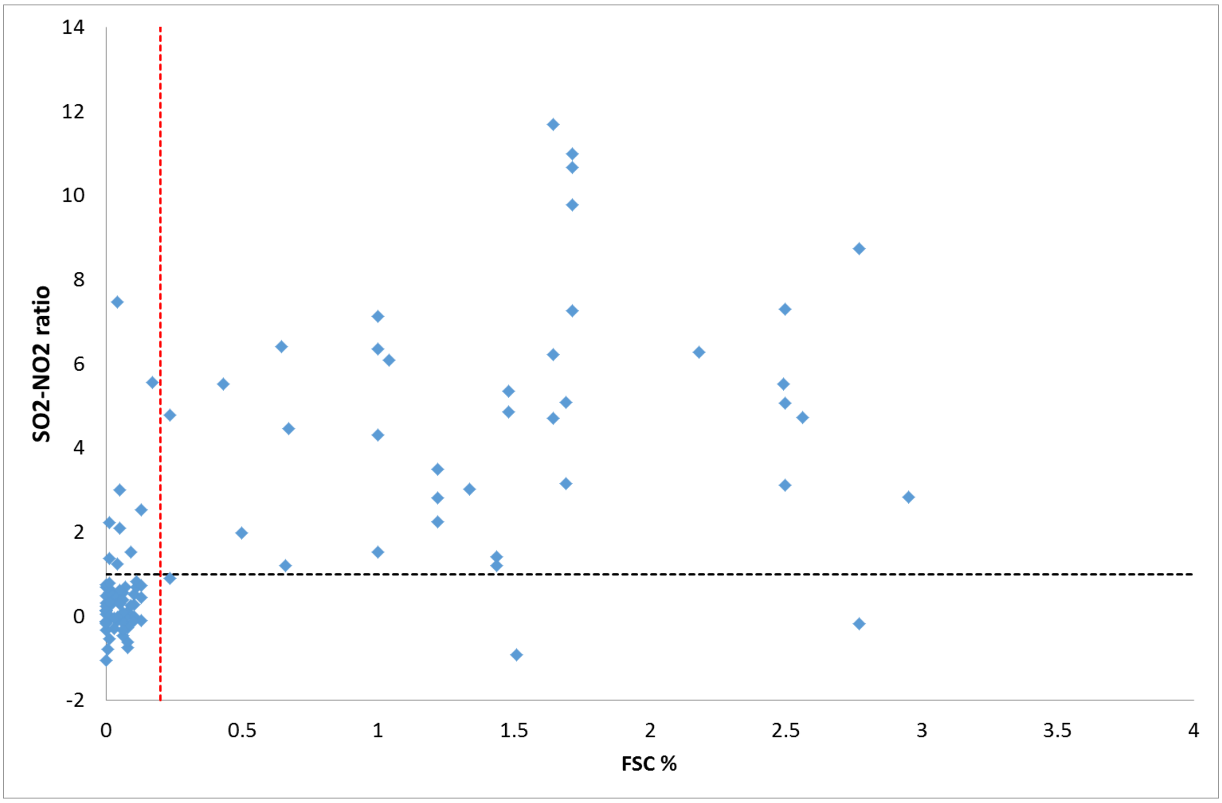


Figure 18. The measured ratio of SO_2 and NO_2 from the optical sensor and the FSC obtained from sniffer measurements.

8 Acknowledgment

We acknowledge the EU project CompMon (Grant agreement No INEA/CEF///TRAN/M2014/1025268 Project No CEF-2014-EU-TM-0546-S) for funding the measurement activities in the project and for developing the software tool for automatic ship detection. We also acknowledge the Swedish funding agency Vinnova (IGPS project) for development of the measurements systems and software. We thank Tue Friis Hansen at Aircraft Aps for providing the aircraft measurements and general support. Caroline Petrini (Swedish transport agency) is acknowledged for providing ports state control data as part of the CompMon project collaboration.

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