CompMon

Compliance monitoring pilot for Marpol Annex

Fixed remote surveillance of fuel sulfur content in ships from fixed sites in the Göteborg ship channel and Öresund bridge

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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, an automatic sniffer sensor system has been applied in the Göteborg ship channel at the Älvsborg island during 3 years (2014-2016) and at the Öresund Bridge during two months at the end of 2016. The typical distances from the ships here varied between 500 -1000 m. The sniffer system is based on several extractive instruments measuring concentrations of SO_2 and CO_2 and others species, such as NO_x, in the ship emission plumes that drift over the measurement station. In addition to fixed stations, the system can also be used from mobile platforms such as harbor patrol vessels and aircraft. From the data above, together with information about the ships from AIS (Automatic Identification System) and wind data, the FSC is automatically calculated and the ship is identified. This is done using software developed as part of this project (Single Emitter identification Tool).

The measurement precision (1σ) of the sniffer system is approx. 0.04 % m/m for ships using a FSC of 0.1 % m/m. The sniffer system also has a negative bias in the measured FSC, varying between 0.04 % to 0.08 % m/m and this is accounted for when calculating the threshold for non-compliance. Based on the above, it is possible to identify ships with FSC above 0.18 % m/m with 95% confidence limit, if the bias is corrected for statistically. For the measurements at the Älvsborg island site in 2014 and 2015, the corresponding limit is higher, 0.29 % m/m, due to a measurement artifact that was eliminated in 2016. On board measurements in 2015 and 2016 by the Swedish port state control authority shows that most non-compliant ships had FSCs between 0.1 % to 0.2 % m/m when controlled at berth and this is generally below the 95% confidence limit threshold of the sniffer. Therefore many non-compliant ships will not be detected when using the sniffer close to harbors and a more precise sensor is therefore preferred.

The measurements at the Älvsborg island were carried out during a time period when the allowed FSC limit changed significantly. The data for 2014, corresponding to more than 4000 measurements of 500 individual ships, shows that 99 % of the ships were using compliant fuel below the FSC limit of 1 % m/m. In 2015 the FSC limit changed to 0.1 % m/m. The measurements in 2015 and 2016, corresponding to the same amount of ships as in 2014, showed that 91.5 % and 98 %, respectively, were using compliant fuel with respect to FSC. The lower compliance rate in 2015 compared to 2016 is potentially influenced by measurement artifacts that were later eliminated in 2016. At the Öresund Bridge. 58 ships were measured as part of the CompMon project. The measurements continued another month with support from the interreg project Envisum, with another 62 ships measured. The compliance level at the Öresund Bridge corresponds to 98 %. This is actually comparable to the corresponding measurements elsewhere and at the Älvsborg island site during the same time period.

Index

Acronyms

AIS	Automatic Identification System
IGPS	Identification of Gross Polluting Ships
CRDS	Cavity ring down spectrometer
DEPA	Danish Environmental Protection Agency (Miljöstyrelsen)
FSC	Fuel Sulfur Content in mass percentage (m/m)
IMO	International Maritime Organization
MEPC	Marine Environment Protection Committee
MARPOL	Marine Pollution
NDIR	Non dispersive infrared
PSC	Port State Control (authority)
SECA	Sulfur Emission Control Area

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 US 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 for instance 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, 2017c) by the Danish environmental protection agency and fixed station measurements in Germany are associated to the CompMon project.

In this report we describe work as part of the CompMon project in which we have carried out remote ship emission measurements at two fixed sites, i.e. the ship channel to the port of Göteborg and the Öresund Bridge. As part of the CompMon project we have also further developed a software tool (Single Emitter identification Tool) that is used to automatically obtain the ship emissions when in flight and send these to a database together with email alerts. This is described in this report and in a parallel one in which we carried out airborne compliance measurements at the SECA border in the English Channel (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 the CompMon project we did a EASA (European Air Safety Agency) approved installation of the system in a Navajo Piper aircraft and in 2016 this system was used in a measurement campaign at the SECA border. The system 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 is associated to the CompMon project and it also included automatic measurements at the Great Belt Bridge. 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 aircraft.

The advantage with fixed site measurements is the capability, under the right meteorological conditions, to automatically measure the emissions from by-passing ships and to send real time alerts if ships are above the compliance limit. A site at a good position can in this way monitor up to 4000 ships a year and the measurements therefore are relatively cost effective. The disadvantage with fixed surveillance is the fact that the ship operators will know where the monitoring is occurring and they may therefore adapt their behavior at the measurement sites.

2 Hardware

The sniffer system used at the fixed sites is 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. The system used by us (Mellqvist, 2014) was originally developed for airborne measurement, requiring fast measurements and small weight and shape. For instance, to be able to obtain a fast response time the SO_2 instrument was operated without the so called "kicker" which is a diffusion tube which removes organic substances from the sampling stream before the measurement chamber. This was the case for all airborne measurements (Mellqvist, 2017a) and for the earlier fixed station measurements in this project, but in the later part of the project the kicker was put back.

In Table 1 the precision (basically same as half of the detection limit) of the instruments and their response times are also shown. The t_{90} parameter corresponds to the time that the instruments need to change from 10 % to 90 % of the signal when making a step change.

The instruments below have been combined with a wind meter, AIS (Automatic Identification System) receiver, GPS (Global Positioning System), pumps, and a common gas inlet with automatic valves that makes it possible to calibrate the instruments automatically.

All systems are controlled by common software that identifies ship, calculates the FSC and sends the data to a database.

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 (CRDS) with custom hardware and sampling (sniffer)	Picarro G-2301m	<1 s	0.1 ppm
CO_2	Mixing ratio (sniffer)	Non dispersive infrared (NDIR) 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*/40 s	5 ppb*/2 ppb
NO_x	Mixing ratio (sniffer)	Chemiluminiscence (modified)	Thermo 42i-TL	1 s	1 ppb

* No kicker

3 Method

3.1 Overall

A sniffer system for automatic compliance monitoring of ships has been built into a water tight box, Figure 1, as part of the IGPS project (Mellqvist, 2014). The sniffer system is equipped with sensors for SO_2 (UV fluorescence) and CO_2 (CRDS) as well as an AIS receiver, GPS sensor, wind sensor, internet modem, control electronics and a computer for logging the data, section 2. The total flow is about 12 l/min.

The measurements are typically carried out at the ground, or using a low mast, and even though the ship chimneys are positioned high on the ships, the exhaust generally gets mixed to the ground by the turbulence of the ship itself. The exhaust from the ships can be observed from a distance of 100 m to several kilometers, but when the distance is too large it is difficult to interpret from which ship the exhaust originates. In harbor ship channels with intense traffic and industrial sources a distance of a few hundred meters is probably the optimal one, Figure 2.

The ship emission data can be sent to Port State Control (PSC) authorities for further action, such as on-board inspection of the ships. In this project the data was sent automatically to a web database as described in section 3.2 and in addition mail alerts were sent out. During a part of the CompMon project, in end of August and beginning of September 2016, a common test was carried out in which alerts were sent out to all participants through a shared mail address. Several ships that were non-compliant were also reported to the EU database Thetis-EU through the Swedish port state control authority (Swedish transport agency) who participated in the CompMon project. This database is used by the European authorities to flag non-compliant ships.

The advantage of fixed measurements is the fact that they can run automatically and a large number of ships can be controlled. The disadvantage is that the shipping industry may learn the location of the sniffer and adapt to it.

Figure 1. The yellow box developed for automatic emission measurements.

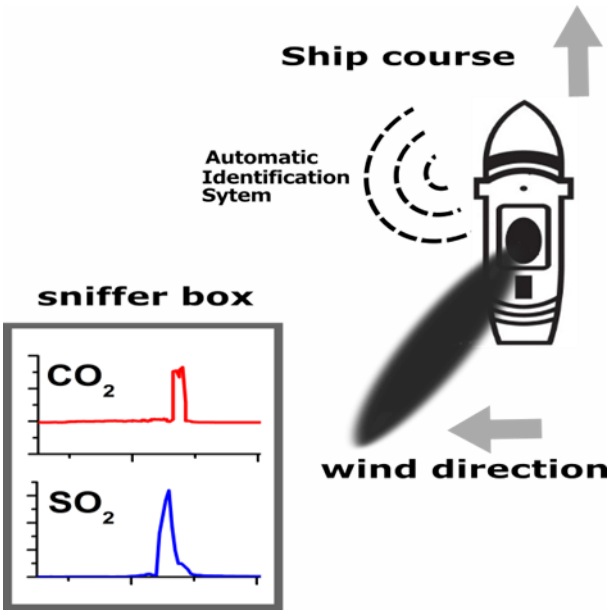


Figure 2. Schematic of the sniffer system and ship identification. An emitter ship is identified by combining wind measurements and the transponder signals through the Automatic Identification System AIS.

Sniffer measurements

The FSC is directly obtained by sampling of the gas concentrations in the ship plumes with the sniffer. It is based on several commercially available gas analyzer instruments. The FSC is obtained from the ratio between SO_2 and CO_2 inside of the plume. Eq. 1 shows a more general equation of this calculation, which is consistent with the on board method described in the MEPC guidelines 184(59).

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

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 %, which 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.

3.2 Single emitter identification tool and web data reporting

A custom made analysis software package (Single emitter identification tool) has been developed that plots ships on a map, Figure 4, and which automatically identifies the presence of a ship exhaust gas plume and the ship it originates from, using information of the ship's position and the wind. The program calculates the FSC for the ships from the ratios between the SO_2 and CO_2 according to Eq. 1 and 2. Also the NO_x emission factor in g/kWh can be obtained using a slight modified variant of Eq. 1 and an assumed specific fuel consumption of the measured ships.

The software is automatic and it detects the presence of the ship plume when the current value exceeds the long term background value, obtained from a 10 minute running median value, by a certain threshold derived from the variability of the signal. It then assumes that both sides of the plume correspond to the background and it fits a line through these values which is subsequently used as the current background value. The quality of the measurement is categorized in three levels (HIGH, MEDIUM, and POOR) based on the parameters in Table 2. The quality flag is a combination of measured parameters such as CO_2 peak signal and empirical observations of conditions when the measurements or identification of the ships are more certain, for instance how many ships that are present in the upwind sector. One important consideration here is the comparison of CO_2 in the ship plume against the variation of the ambient background CO_2, which comprises both variations of the background (upwind fixed source like a city) and the noise of the instrument. The quality level may also be degraded if different hardware warning flags are raised while the instruments are operating. These flags are mostly associated to issues related to abnormmal temperature, low voltages, flow, interruptions, etc.

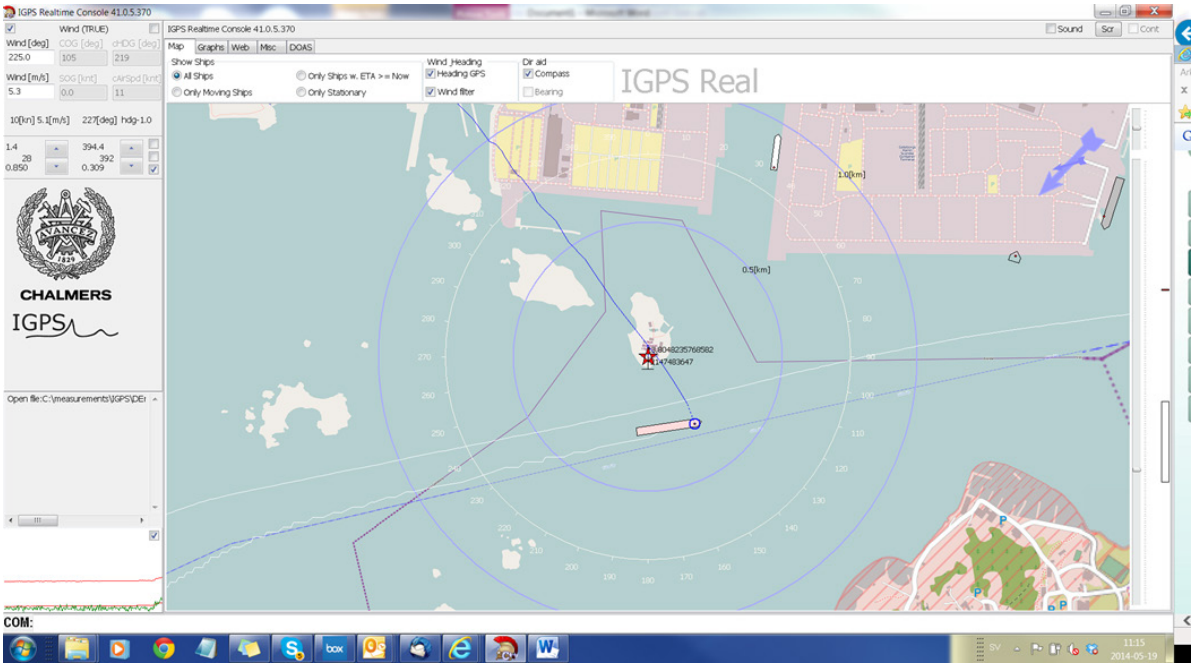


Figure 3. A view from the real time program IGPS-real when running sniffer measurements from the yellow box in Figure 1 in the inlet channel of Göteborg. The passage of the ship Stena Scandinavica and it's modeled smoke plume (blue).

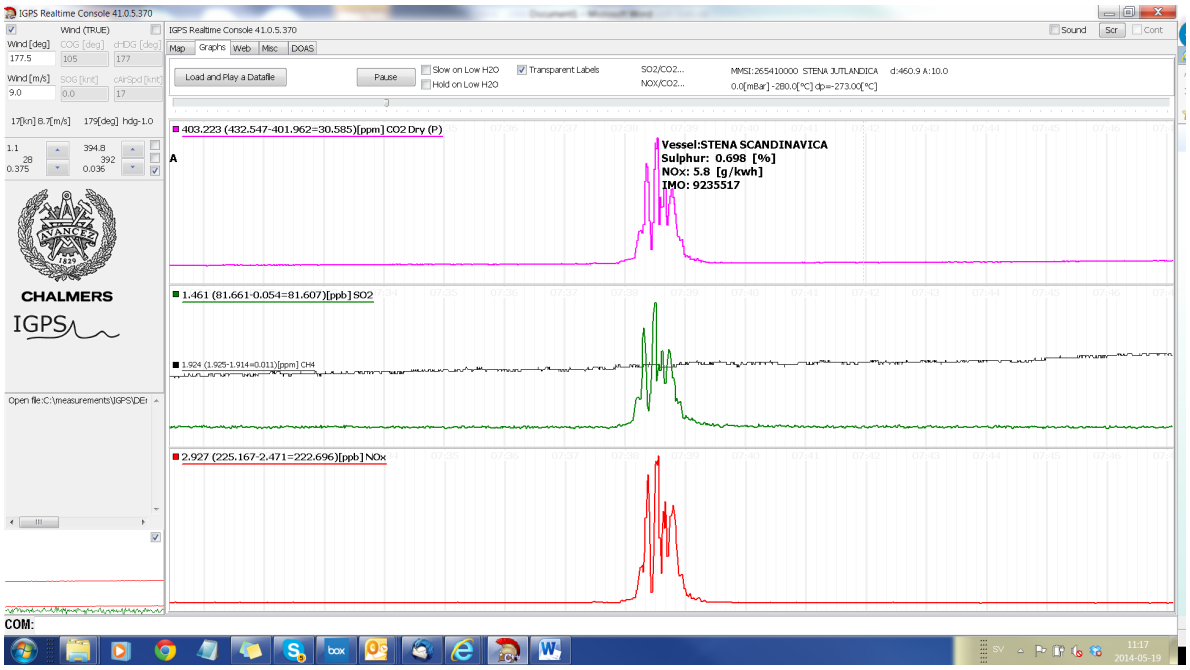


Figure 4. A view from the real time program IGPS-real when running sniffer measurements from the yellow box in Figure 1 in the inlet channel of Göteborg. Here is shown the measured data of CO2 (pink), SO2 (green) and NOx (red)during the passage. From the ratio of SO_2 and NO_x, respectively, towards CO_2, the sulfur fuel content (0.7%) and the NOx emission (5 g/kWh) is obtained.

Table 2. The quality criteria applied for the fixed measurements at the Great Belt bridge during 2015 to 2017. Some of the criteria suggested for future use are also given,

Criteria	Comment	High	Medium	Poor
Normal operation	Warning flags for the hardware not set, such as high/low temperature, low voltages etc	Required	Required	Depends
ΔCO_2 in plume	Peak height	>3 ppm	>2 ppm	0.5 ppm
$\Delta CO2_{plume}$		>50 ppms	>25 ppms	3> ppms
Δt_{CO2} in plume	Time duration in plume	<100 s	<150 s	<240 s
Wind direction	Wind relative to ship movement	±30°	±60°	±60°
Wind speed		>3 m/s	>2 m/s	> 1 m/s
No of ships with overlapping plumes		1	1	1
FSC	Filtering out low values	>-0.2	>-0.2	>-0.2
ΔSO_2 in plume	Peak height	NI	NA	NA
ΔSO_2/ (1.5%*ΔNO)	Interference effect, If interference dominates uncertainty increases	NA	NA	NA

Below is given a short overview of the measurements and data analysis software that is part of the Single emitter identification tool package. The software is described also in a separate report with more focus on the airborne application (Mellqvist 2017a).

The optical and sniffer data are handled by a combination of three custom made software applications running unattended and continuously: *TCPlog*, *IGPSpresent* and the *IGPS mailer*.

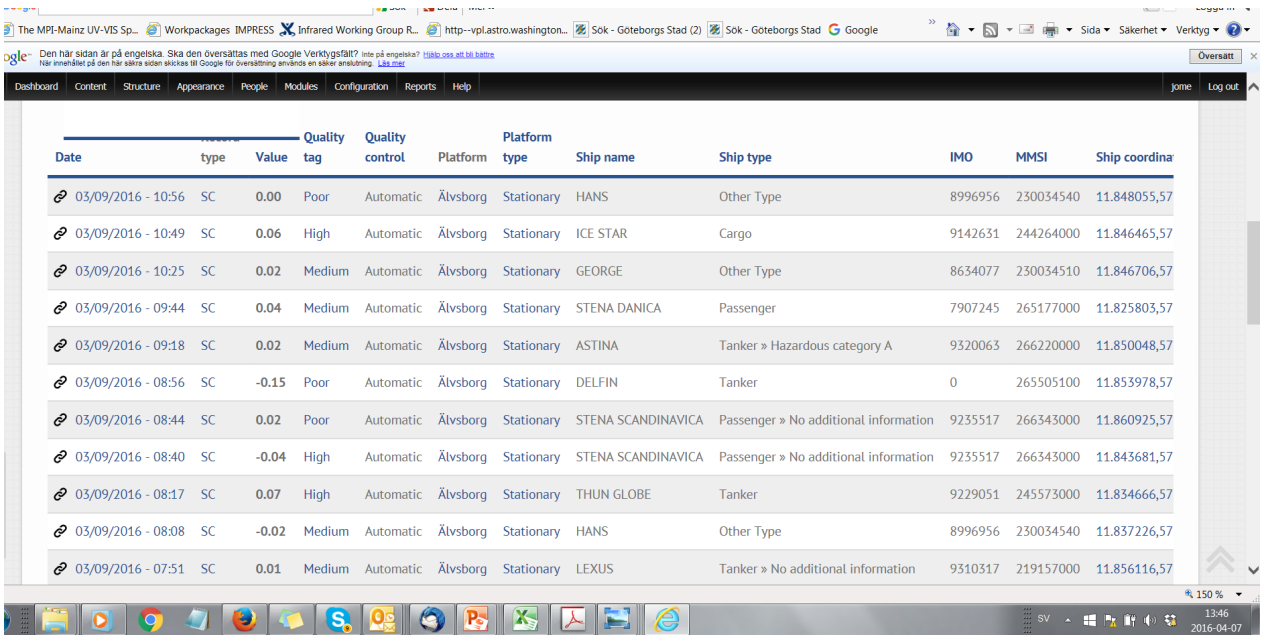
The software *TCPlog* has the most critical task which is continuously logging all the available instruments with a sampling period of approximately one second. This includes data from the sniffer and optical sensors, wind meters, AIS receiver and in case of the airborne platform also information from the aircraft.

The *IGPSreal* program analyses the data in near-real time, namely calculating the FSC through ratio measurements between the concentrations of SO_2 and CO_2. Moreover, the IGPSpresent identifies the presence of ship plumes and its corresponding source of origin. For the fixed station the program initiates a calibration every 5th day.

Finally, the *IGPSmailer* program automatically sends evaluated and compiled measurements to the database at Chalmers University of technology, see an example in Table 3 from the Älvsborg island site in the ship channel of Göteborg obtained in the Compmon project. The database includes the FSC values as well as date, time, position and ship specific data.

The Single emitter identification tool also generates alerts as emails or SMSs when a high emitter ship has been detected or when there is a possible system malfunction. These alert messages combined with regular remote logging, has been of key importance to ensure reliable measurements.

Table 3. Example of data base setup from the Älvsborg island site.



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

3.3 Uncertainties and Cross interference

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 et al, 2014). This may lead to an overestimation of the FSC by up to 0.1 % m/m 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 in the given measurement situation. Measurements at the Great Belt Bridge (Mellqvist, 2017b) show that the median value of the NO to NO_x ratio was 71 % at approximately 1 km downwind distance from the ship. We have used this information and corrected the data according to Equation 2.

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

Another measurement artifact in the SO_2 instrument is caused by the absence of the so called "kicker", which was the case for the sniffer instrument at the Älvsborg island site during 2014

and 2015. The kicker removes the influence of organic substances such as aromatic volatile organic carbons. Generally the aromatic 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 causes a response in the SO_2 fluorescence instrument. In real measurements when not using a kicker, especially at the inlet channel of Göteborg, we sometimes observed significant tails in the SO_2 time series of the ship plumes which we believe are caused by the organic condensable material mentioned above. This effect is further discussed in the results section. The problem is usually mitigated by excluding the tail of the plume in the calculation of the FSC. The kicker effect is assumed to be strong at the Älvsborg site since it is positioned where the ships are changing speed and this causes transient emissions with generally are 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.

In Table 4 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 4. 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 CO2 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 but 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 gas manufacturing companies
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	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	Causes 2% additional random uncertainty

3.4 Calibration

The quality assurance of the sniffer instruments is obtained by repeated calibrations. The instruments are remotely calibrated using electrically controlled gas valves that injects calibration gas just after the measurement inlet and replaces the inflow of air.

For the calibration, premixed gas standards are used which are diluted in nitrogen, or air in case of SO_2, with values ranging 200 - 450 ± (5 %) ppb, 210 - 300 ± (5 %) ppb and 380 - 420 ± (1 %) ppm for SO_2, NO_x and CO_2 respectively.

At the Öresund bridge and at the Älvsborg island site during 2014 and 2015 the CO_2 measurement was carried out using a CRDS, Table 1, which is based on spectral tuning of a near infrared laser across a narrow infrared absorption line and measuring the light absorption. This makes the instrument very stable and linear and only one calibration gas is then needed. For the Älvsborg island site the CO_2 measurement for 2016 were based on a non-dispersive infrared instrument (Licor 7000). This instrument measures the difference in absorption between two measurement chambers using a relatively broad wavelength band and in one of the chambers a pure nitrogen gas is flown. This instrument is nonlinear and requires calibration by two CO_2 span gases, typically 380 ppm and 420 ppm. In addition it requires a constant flow of nitrogen in the reference chamber.

In most cases the instrument were not recalibrated and instead the output from the instruments was post-corrected using the calibration factors. However, when the instrument response deviated too much from the nominal value a hardware recalibration of the instrument was carried out.

Figure 5. Premixed calibration gases of CO_2, SO_2 and NO_x are connected to the sniffer system via electrically controlled gas valves.

4 Measurements

4.1 Measurements at Älvsborg island, port of Göteborg

An automatic sniffer instrument has been in semi-continuous operation at the inlet channel of Göteborg, Sweden, as part of the CompMon project at the Älvsborg island (57°41'08.64'', 11°50'17.08''). Measurements have been on-going during the full extent of the CompMon project (2014 to 2016) with up to 4000 ship measurements each year of approximately 500 individual vessels. The location of the site and position of by-passing ships is shown in Figure 3, with an example of the corresponding raw measurement data shown in Figure 4.

Figure 6. The measurement site at the Älvsborg island. The bottom panel shows the warehouse where the sniffer instrument is placed on the north side of the ship channel to port of Göteborg. The top right panel shows the yellow sniffer box which includes the sensors for SO_2 and CO_2 as well as AIS receiver, GPS sensor, internet modem, control electronics and logging-computer. In the top left panel the gas inlet and wind meter on the roof are shown at about 25 m above the sea level.

During 2014 and 2015 the yellow sniffer box, described in section 3.1 was used, Figure 6, connected to a gas inlet on the roof of the warehouse with a 10 m long and 10 mm thick heated Teflon tubing. The gas inlet was an overturned funnel and the height of the gas intake approx. 25 m. The wind was measured from the same mast using a sonic anemometer, Figure 6. In 2016, the yellow box was replaced with a 19'' rack in which a NDIR-instrument (Licor

7000) was used instead of the CRDS sensor for the CO_2 measurement. The sampling line was also shortened to 4 m. The system has it's independent internet link through a 4G modem.

The measurements worked well for wind directions with a southerly component, e.g. south westerly to north westerly. The border for reduced speed is located just outside the Älvsborg island and the ships are therefore either accelerating or deaccelerating when being measured. This has impact on the NO_x and particulate emissions and indirectly on the SO_2 measurements when using an instrument without kicker as discussed in section 3.3.

4.2 Öresund bridge, entrance to Baltic sea

As part of the CompMon project a short measurement pilot at the Öresund Bridge was carried out during December 2016. The measurements were continued also during January 2017 through the interreg project Envisum project. All in all, 120 ships were measured with good or medium quality and 58 of these were measured during December 2016 as part of CompMon. The Öresund Bridge connects the city Malmö in Sweden with Copenhagen in Denmark, Figure 8. The bridge goes into a channel towards Denmark and the ships can either sail under the bridge or above the tunnel.

The sniffer system, built into the yellow box (Figure 1) and described in section 3.1 was used. Here the SO_2 instrument was running with a kicker but without NO_x measurements. The NO interference potentially increases the FSC by 0.1 % m/m and we have therefore compensated all data using ship emissions calculations by a model developed by FMI named STEAM (Jalkanen, 2009). The system was placed outdoors on a platform at 50 m height above sea level at the eastern Pylon, Figure 7 and Figure 9. It was difficult to measure the wind at this site due to severe turbulence, so instead wind measurements on the upper part of the bridge by the Bridge operator (Öresundsbron) were used. These were retrieved in real-time through internet.

Figure 7. The Öresund bridge seen from the east, viewing westwards towards Denmark. Measurements were conducted at the eastern Pylon on a platform at approx. 50 m above sea level.

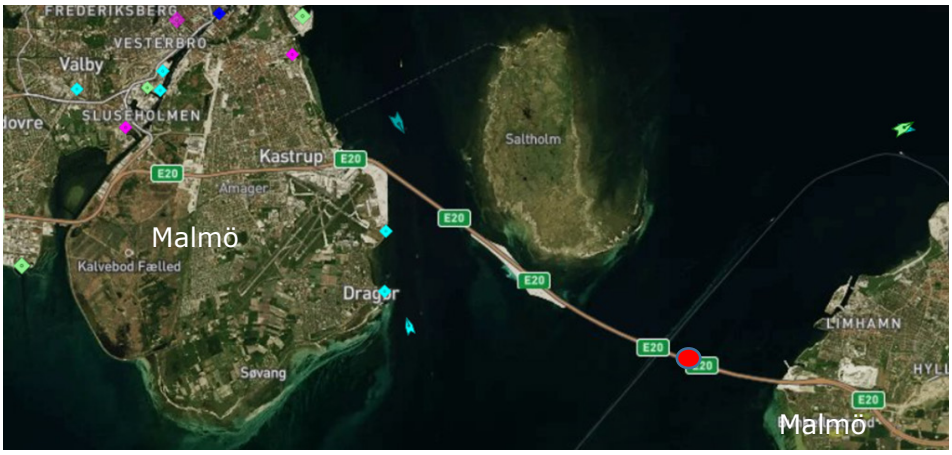


Figure 8. The Öresund bridge connects the city Malmö in Sweden with Copenhagen in Denmark. The approximate location of the measurement site is shown in red.

Figure 9. Fixed sniffer system installed at the Öresund Bridge between Sweden and Denmark. The gas is extracted from the funnel shaped gas inlet which is connected to the railing.

5 Precision, accuracy and compliance threshold

In a parallel project funded by the Danish EPA (Mellqvist, 2017b) fixed measurements have been carried out during 2015 and 2016 at the Great Belt Bridge, using the same instyruments as described in Table 1. The *precision* of the measurements was obtained from multiple observations (> 9) of 30 individual ships measured during 2015 and 2016 were used. From the square root of the sum of the variances of individual ships we obtained an overall precision (1σ) of 0.04 % in FSC units. In this project the precision derived from the measurements at Great Belt Bridge has been used for the measurements also at the Öresund Bridge, since the data is limited to only 120 ships. For the assessment of the precision at the Älvsborg island site we have instead fitted a noise frequency distribution to the measured data, as explained in section 6.

In the Danish EPA project (Mellqvist, 2017b) 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 fixed measurements should be the same as the on board samples a negative bias of 0.055 % m/m was obtained for the fixed system. For the Öresund site in 2016 the corresponding negative bias in FSC is 0.047 % m/m. For the Älvsborg site the negative biases are 0.015 % m/m and 0.08 % m/m, respectively, for year 2015 and 2016. The reason for the negative bias is not understood and potentially it could be caused by tubing losses.

Due to the bias, ships that run with a compliant FSC value of 0.1 %, will hence be measured as having a lower FSC on average. For the Öresund Bridge this value corresponds to 0.053 % m/m while for the Älvsborg site the corresponding FSC values are 0.085% m/m and 0.02 % m/m, respectively, for 2015 and 2016. However, since the measurement have random noise associated with them corresponding to a precision with standard deviation 0.04 %, the data will be spread out according to a Gaussian distribution. For instance in the case of the Öresund Bridge most of the data (95 %) will be within 2 standard deviations from the biased 0.053 % value; this gives an upper value of 0.133 % 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 real threshold for the data, since in this case one should use the non-biased threshold. Forinstance, in the case of the fixed measurements at the Öresund Bridge data the real non-biased threshold, at 95 % confidence limit is 0.18 %. This means that it is not possible to detect non-compliant ships using a FSC in the range 0.1 - 0.18 % 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 we did such a comparison (Alfoldy et al. 2013) for high FSC ships comparing our airborne sniffer measurements with on board sampling on a RoPax ferry. The comparison showed an overall estimated uncertainty for SO_2 of 23 % with a precision of 0.19 % at the 1% 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 FSC 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. As part of the same project (Mellqvist 2017b) a puff test was carried out in which a calibration gas with a high concentration mixture of SO_2 (203.9 ppm) and CO_2 (4.293 %) was injected in front of the measurement instrument. The SO_2 to CO_2 ratio here corresponded to a 1.1 % FSC ship according to Eq. 1. The FSC obtained from the sniffer measurements corresponded to 1.01± 0.13 % m/m; hence there was a negative bias of -0.1 % (corresponding to the accuracy) and a spread of the data corresponding to a precision of 0.13%.

In Table 5 the overall estimated uncertainty for the measurements is summarized.

Table 5. Estimated overall uncertainty for the sniffer measurements in this study. All values correspond to the absolute FSC unit.

	Fuel: 0.1% m/m	**Fuel: 1 % m/m FSC**
Random uncertainty abs FSC unit	±0.04% m/m	±0.19 % (1) m/m
Systematic bias	-0.04%-0.055% m/m	-0.1 % (3) m/m
Threshold(2) for compli-ance limit (95 % confidence limit)	0.18% m/m	

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

6 Results and discussion

6.1 Älvsborg island site.

In Figure 10, the statistical distribution (probability density function) of the measured FSC data for 3 years is shown for 2014, 2015 and 2016 for the Älvsborg island site in the ship channel of Göteborg. The data corresponds to more than 4000 measured ship plumes per year and about 500 individual ships.

The green curve corresponds to the random noise distribution (precision) of the measurements fitted to part or all of the data, as explained for the different years below. From this we have calculated the compliance level thresholds according to section 5. In 2014 the FSC limit was 1 % m/m, however, since the measurements have a 20 % uncertainty the threshold for noncompliance is set at 1.2 % m/m. In 2015 the FSC limit was 0.1 %. It can be seen that the frequency distribution exhibits a skew shape, and our interpretation is that this is caused by interferences with organic vapors, since the instrument was run without a kicker. Here the median value of the FSC data is 0.07 %. The data was fitted to a lognormal distribution, using only FSC data below 0.14 % m/m. From the fitted curve the 95 % confidence limit can be estimated, and following section 5, a FSC threshold of 0.28 % m/m is obtained.

In 2016 the SO_2 sniffer instrument at the Älvsborg island site was equipped with a kicker and the frequency distribution hence gets much more symmetric. Here the noise distribution corresponds to a Gaussian distribution with a width corresponding to a measurement precision of 0.03 % m/m and a negative bias of 0.08 % m/m.

From the difference in measurement results between 2015 and 2016 we conclude that the effect of the kicker at the Älvsborg island site increases the median FSC value by 0.07 % m/m and the precision from 0.03% to 0.1 % m/m. Here it is assumed that the used FSC for the two years is the same as indicated by port state sampling (pers comm Caroline Petrini).

In Figure 11 the fraction of the measured ship plumes below a certain FSC threshold are shown for the data obtained at the Älvsborg island site at Göteborg ship channel for 2014 (top), 2015 (middle) and 2016 (lower panel). In addition the biased SECA compliance thresholds are shown, following the discussion above. Hence in 2014 it can be concluded that less than 1 % of the ships were using non-compliant FSC above 1 % m/m. In 2015 and 2016 the corresponding values were 8.5 % and 2 %. It hence appears that there were considerably more non-compliance cases in 2015. However, one should be careful not to over interpret this, since there is a risk that a part of the kicker effect may still influence the 2015 results.

It is noteworthy that the data at the Älvsborg island site for 2016 show better compliance rates (98 %), than the port state controls in Sweden for 2016 (pers comm Caroline Petrini) corresponding to 95 % m/m. The reason for this discrepancy is likely the fact that the non-compliance cases generally correspond to ships that have used FSC between 0.1- 0.2 % m/m and these low levels are difficult to detect with the sniffer instrument. One conclusion here is hence that for near port measurements it is worthwhile to get a more precise sensor.

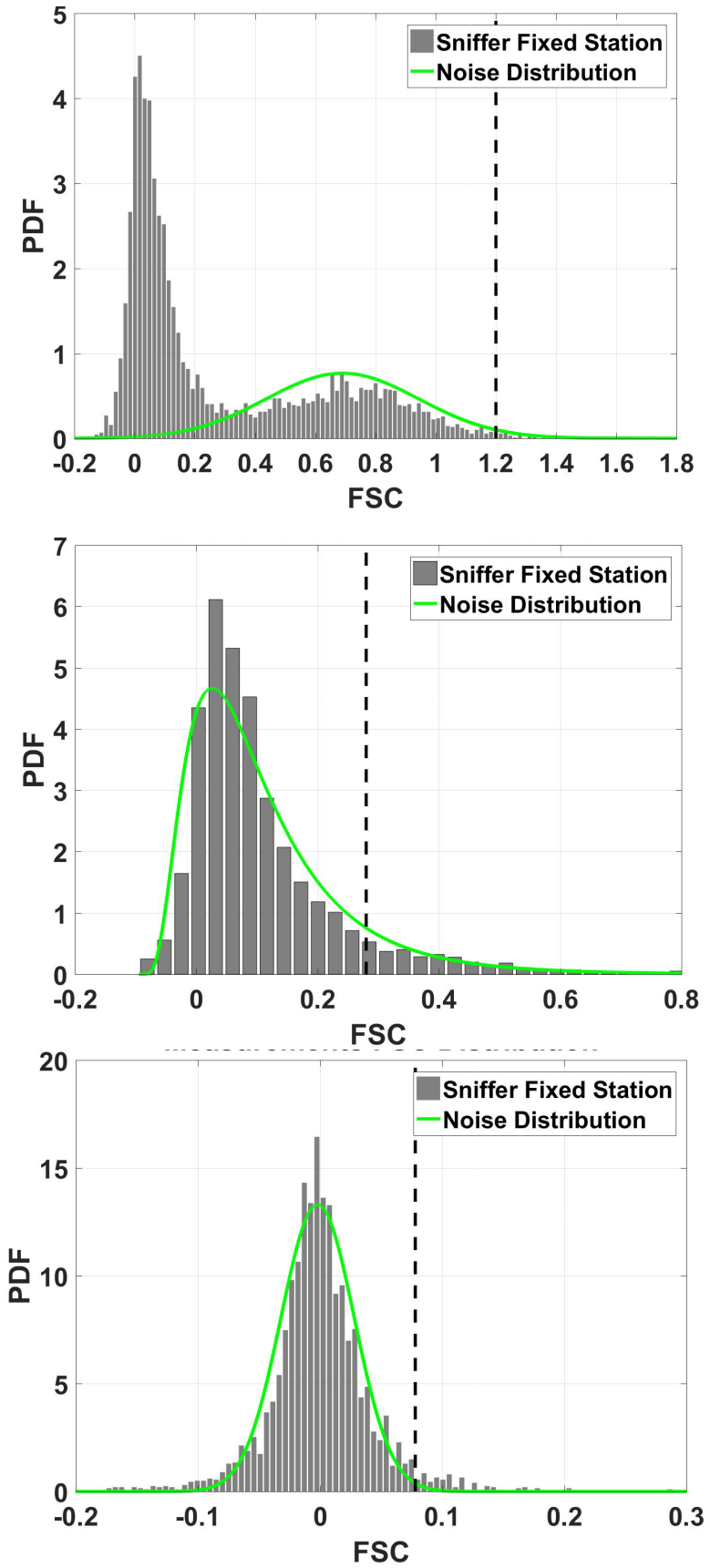


Figure 10. Statistical distribution (probability density function) of the FSC from ship measured with sniffer from the Älvsborg island site in the inlet channel to Göteborg during 2014, 2015 and 2016. The green curve corresponds to the random noise distribution (precision) of the measurements obtained by fitting to part or all of the data. The dotted line is the estimated non-compliance limit for which the instrument errors (precision and bias) have been accounted for.

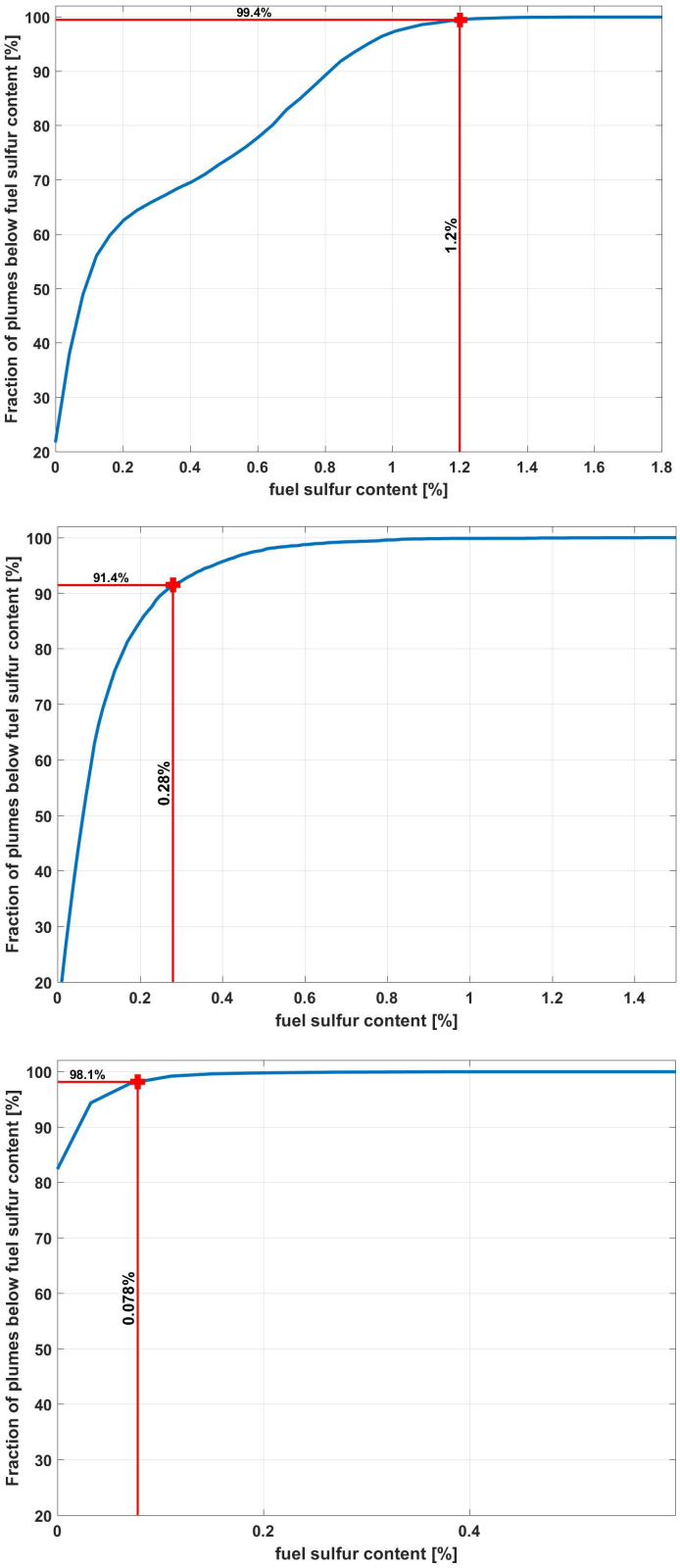


Figure 11. The fraction of plumes below a certain FSC threshold is shown here for the Älvsborg island site at Göteborg ship channel for 2014 (top), 2015 (middle) and 2016 (lower panel). In addition the biased SECA compliance threshold is shown based on the calculation described in section 5 including the measurement bias.

6.2 Öresund Bridge site

In Figure 12 the statistical distribution (probability density function) of the FSC for the measurements at the Öresund Bridge site are shown, corresponding to 120 measured ship plumes. The green curve corresponds to the random noise distribution (precision) of the measurements obtained from a parallel study at the Great Belt Bridge (Mellqvist 2017b) by the Danish Environmental protection agency, with a 1 σ precision of 0.04 %. It can be seen distribution fits rather well to the measured data, even though the amount of samples is quite small. The median value is here 0.03 % m/m, and the biased appears to have a negative bias of about 0.05 % m/m.

In Figure 13 the fraction of the measured plumes that were below a certain FSC threshold are shown for the Öresund bridge measurements. In addition, the biased SECA compliance threshold is shown, following the discussion in section 5. It can be seen that in the end of 2016 the compliance rate at the Öresund Bridge was 98 %. This is actually comparable to the corresponding measurements at the Great Belt Bridge (Mellqvist 2017b) for the period January to May 2017 and to the corresponding measurements at Älvsborg island site in 2016.

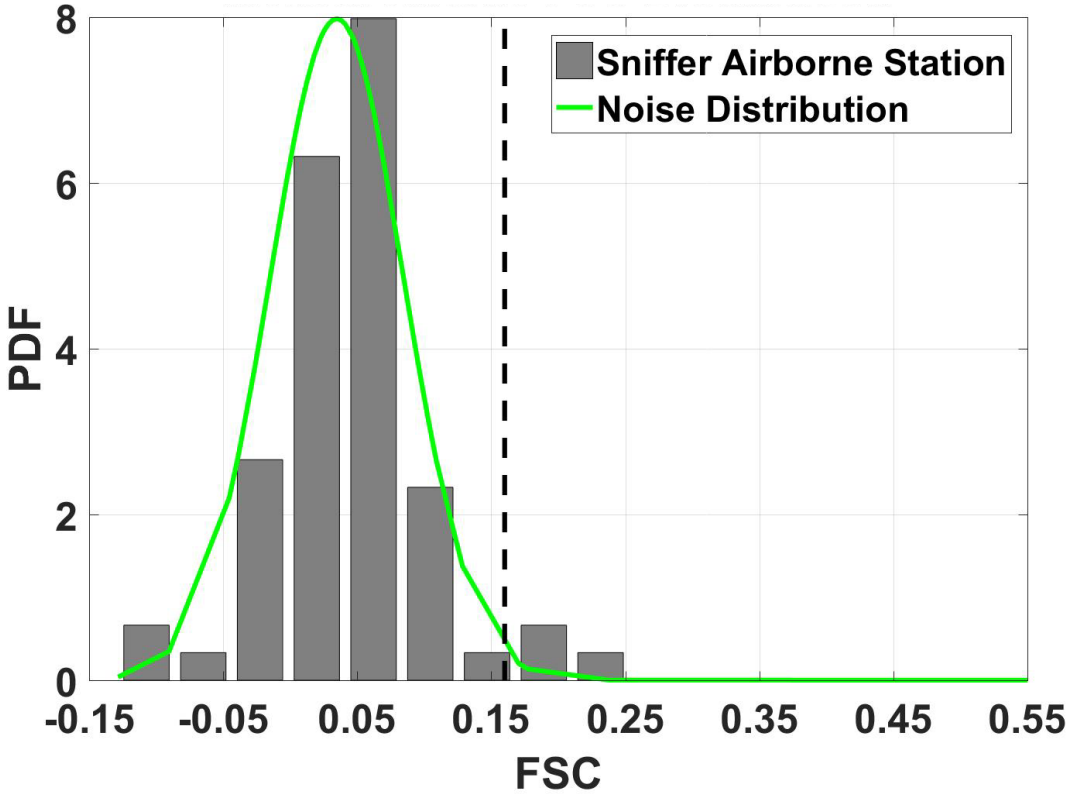


Figure 12. Statistical distribution (probability density function) of the FSC from ship measured with sniffer from the Öresund Bridge during December 2016 and January 2017. The green curve corresponds to the random noise distribution (precision) of the measurements obtained from elsewhere. The dotted line is the estimated non-compliance limit for which the instrument errors (precision and bias) have been accounted for.

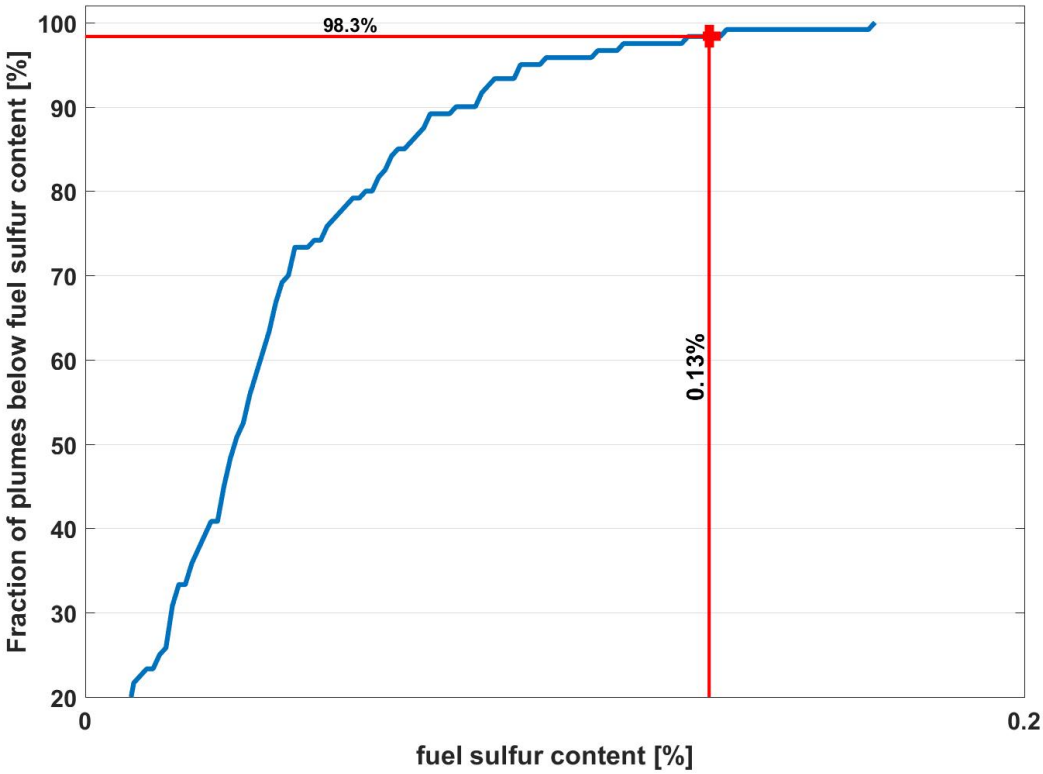


Figure 13. The fraction of plumes below a certain FSC threshold are shown here for sniffer measurements at the Öresund Bridge. In addition the biased SECA compliance threshold is shown.

7 Acknowledgment

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