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IDENTIFICATION OF GROSS POLLUTING SHIPS TO PROMOTE A LEVEL PLAYING FIELD WITHIN THE SHIPPING SECTOR

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Executive Summary

In 2015 new rules from the IMO (Marpol annex VI) and legislation from EU (directive 2012/33/EU) and the US requires ships to run with a maximum fuel sulfur content (FSC) of 0.1 % on northern European waters and US coastal 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 PSC authorities that take fuel samples of ships at berth. Since this procedure is time consuming only few ships are being controlled, and none while underway on open waters. For instance during 2011, only 32 ships were detained in European harbors due to having deficiencies related to the IMO environmental rules. 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 port state control authorities in Europe and international organizations such as EMSA (European Maritime Safety Agency) and HELCOM (Helsinki Commission).

During the last 8 years two consecutive projects have been carried out, i.e. IGPS (Identification of gross polluting ships) and IGPS-plius (this project), in which a measurement system has been developed and tested for remote compliance monitoring of individual ships with respect to stack emissions of SO_2, NO_x and particulates. The major projects have been funded by Vinnova and the Swedish environmental protection agency with additional support from two EU-projects and Göteborg harbor.

A module based measurement system has been developed and tested from various mobile and stationary platforms such as fixed stations, harbor vessels, fixed wing aircrafts and helicopters. The measurement system consists of two modules:

a) The optical module measures total emissions of SO_2 and NO_2 in g/s from the ships and this is combined with ship emission modeling of the momentaneous fuel usage yielding a rough estimate of the fuel sulfur content. About 10-20 ships per hour can be checked from the air in this manner. The estimated relative uncertainty is 40 %.

b) The sniffer module measures the ratio of various pollutants against carbon dioxide (x/CO2). From the sniffer system the following parameters are obtained: FSC, NO_x emission per fuel unit and particulate emission per fuel unit. The estimated relative uncertainty is about 20 % at 1 % FSC. About 4-8 ships per hour can be checked from the air in this manner.

The sniffer system is based on several state of the art instruments for gas and particle measurements that have been rebuilt for fast response, smaller weight, minimum volume and field robustness. In addition an AIS receiver, GPS sensor, wind sensor, internet modem and control electronics have been added. Custom made software has been developed that plots ships on a map and which automatically identifies ship plumes and calculates emission factors. The measurement system has been tested from different airborne platforms, and furthermore flight certified by the European Air Safety Agency for routine operation in a Navajo Piper aircraft. About 200 ships have been measured in the open sea, see Figure E1 (Beecken 2014a). The IGPS-system has been tested in a field campaign around Rotterdam in 2009 (SIRENAS-R) within an EU DG-Environment feasibility study regarding ship emission compliance monitoring. This included comparative measurements using different

techniques and the sniffer technique was found to be most suitable for the compliance task with a relative uncertainty of 20-30% (Alfoldy, 2013; Balzani-Lööv, 2014). The system has also been used in an EU interregional projects (BSR-Innoship) in Sankt Petersburg during 2011 and 2012 (Beecken, 2014b). The IGPS-system has been in automatic operation in the ship channel of Göteborg during 2012 and 2013 performing several thousand ship inspections.

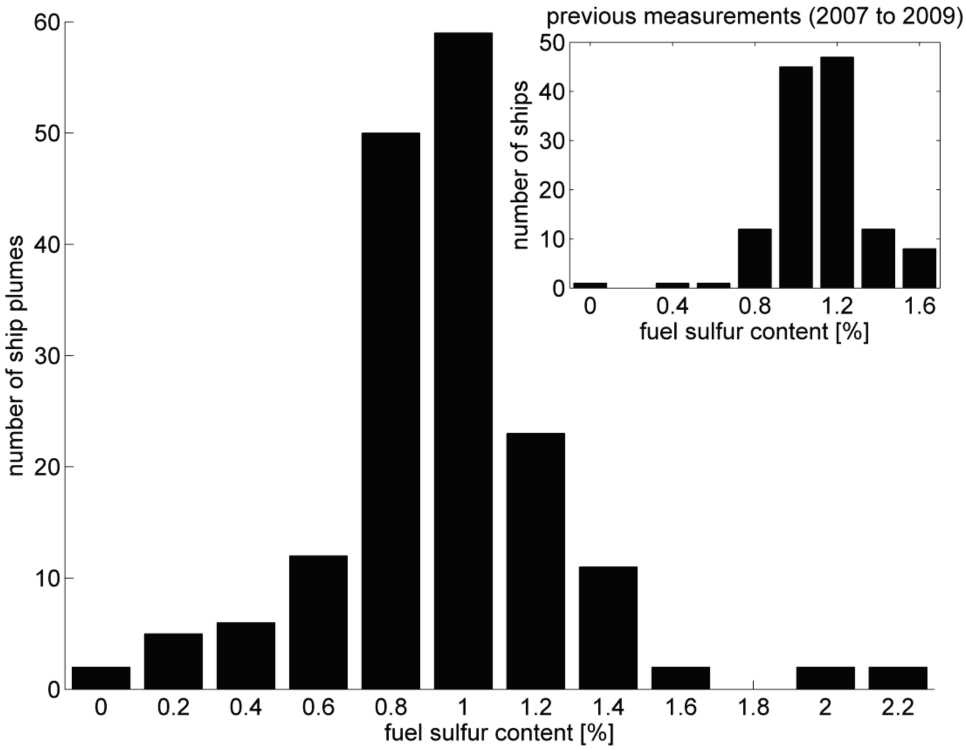

Figure E1. Airborne measurements of the FSC of ships on the Baltic and North sea obtained between 2007-2009 and between 2011-2012, respectively.

The uniqueness of the IGPS system lies in the innovative combination of techniques, a custom made software that provides automatic real time monitoring, a unique optical system for remote operation from airplanes and a unique method to measure particle composition on individual ships. Four tools for compliance monitoring have been developed within the project that is: a sniffer system for fixed measurements, a flight sniffer system, an optical system and general software that can be applied for ship measurements using different hardware. In addition a unique method to capture particles has been employed for particle analysis.

The results of the measurements, both from the airborne and fixed sites, shows that the technique is mature enough to become implemented in a full scale compliance monitoring program. The measurements during 2011 and 2012 on the open sea showed a compliance rate of 95% while almost ships complied in the harbor of Göteborg. The results have been published in several scientific papers as given below, with two more in manuscript.

References

Alfoldy B., ..., Mellqvist J., et al., Measurements of air pollution emission factors for marine transportation, Atmos. Meas. Tech., 6, 1777-1791, 2013

Balzani Lööv J M…. J. Mellqvist, et al., Field test of available methods to measure remotely SOX and NO_x emissions from ships, Atmos. Meas. Tech., 7, 2597-2613, 2014

Beecken, J., Mellqvist, J. et al., Airborne emission measurements of SO_2, NO_x and particles from individual ships using sniffer technique, Atmos. Meas. Tech., 7, 1957–1968, 2014a

Beecken, Mellqvist, J et al., Emission Factors of SO_2, NO_x and Particles from Ships in Neva Bay from Ground-Based and Helicopter-Borne Measurements and AIS-Based Model, Atmos. Chem. Phys. Discuss., 14, 25931-25965, 2014b

Berg, N., Mellqvist, J. et al., Ship emissions of SO2 and NO2: DOAS measurements from airborne platforms, Atmos. Meas. Tech., 5, 1–14, doi:10.5194/amt-5-1-2012, 2012

Abbreviations

DOAS	Differential Optical Absorption Spectroscopy
ECA	Emission Control Area
EEPS	Engine Exhaust Particle Sizer
EMSA	European Maritime Safety Agency)
FSC	Fuel Sulfur Content
HELCOM	Helsinki Commission
IC	Ion Chromatograph
IGPS	Identification of Gross Polluting Ships
IMO	International Maritime Organization
MEPC	Marine Environment Protection Committee
MARPOL	Marine Pollution
(Paris) MoU	(Paris) Memorandum of Understanding
PILS	Particle Into Liquid Sampler
PSC	Port State Control (authority)
SECA	Sulfur Emission Control Area
STC	Supplemental Type Certificate
UNCLOS	United Nations Convention on the Law of the Sea
UV	Ultraviolet

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Appendix

I) IGPS-System-Technical description and installation into a Piper Navajo PA-31
II) The STC approval for installation of the IGPS system in a piper Navajo

1. Introduction

The aim is to develop and test techniques that can be used to enforce the use of low sulfur fuel within the shipping industry by efficient compliance monitoring, according to new environmental regulation within the international maritime organization (IMO) and EU. The objective with the enforcement is to promote a level playing field in the shipping industry making it possible to invest in new technology. We have therefore developed and conducted field tests of new measurement instrumentation that in the future can be used for cost effective surveillance of ship emissions of SO_2 and NO_x.
In an earlier pilot project, IGPS (Identification of Gross Polluting Ships) that was carried out between 2006 and 2008, a prototype measurement system was assembled (Mellqvist 2010, Berg 2011). In 2007 the system was tested from a fixed site by measuring downwind of the ship channel of Göteborg and analyzing the flue gases which blew across the station. From these measurements the Fuel Sulfur Content (FSC) of the ships was directly obtained. Between August 2007 and September 2008 the same system was installed in a CASA-212 airplane KBV-583 of the Swedish coastguard and then flown in various test flights in the Baltic sea (Berg 2011, Berg 2012). The IGPS system was also utilized from a Dolphin helicopter on the North Sea and from a ground station in the ship channel of Rotterdam harbor as part of an EU project aimed at testing techniques for ship surveillance (Balzani 2014, Alfoldy 2013). The conclusion from this project was that the so called sniffer method was most suited for compliance monitoring and by comparing several independent sniffer measurements it was concluded that an accuracy of 20-30 % was possible to achieve in the estimation of FSC.

In the present project (IGPS-plius), carried out between 2009 and 2014, an improved measurement system has been designed and assembled together. The system has been tested on four airborne platforms (MI-8 helicopter in Neva Bay, Dauphine helicopter in North sea, Paternavia in Baltic and North sea and Navajo Piper in Baltic sea) (Beecken 2014a, Beecken 2014b). The system has been installed and certified (Supplemental Type Certificate 10051623, European Air Safety Agency) for permanent use in a Navajo Piper stationed in Denmark. A fixed version of the IGPS system has been used for stationary measurements in the ship channel of Göteborg and Neva bay, Sankt Petersburg (Beecken 2014b).

To investigate measurement uncertainties a detailed analysis of particle emissions and sulfate content in the particles has been carried out, section 5.

In this report an overview is provided of the project activities, description of system used and some results. More detailed technical information can be found in appendix I and in several published papers (Berg 2012, Beecken 2014a, Beecken 2014b). Most emphasis here is on compliance monitoring of sulfur and the reader should check the papers for detailed information about emission factors of particles and NO_x. The papers can be downloaded freely from the internet, Table 1. Two additional papers is presently in manuscript that summarizes the IGPS project and measurements at the inlet channel of Göteborg. i.e.: i) Mellqvist et al., Compliance monitoring of shipping to obtain a level playing field and ii) Salo et al., Particle Analysis of individual ships using plume catching by MEGA chamber.

During early spring 2015 a PhD thesis with the title "Measurements of Gas and Particulate Matter Emissions from Ships" will be defended by Jörg Beecken.

Table 1. Additional material

	Comment
Appendix I	*Title: IGPS-System-Technical description and installation into a Piper Navajo PA-31* A detailed technical description of a installation of a full system in a PIper Navajo aircraft certified by EASA (Euroepan air safety agency) is described.
Appendix II	The STC approval for installation of the IGPS system in a piper Navajo
Paper 1	*Title: Ship emissions of SO2 and NO2: DOAS measurements from airborne platforms* http://www.atmos-meas-tech.net/5/1085/2012/amt-5-1085-2012.pdf Optical measurements of SO_2 and NO_2 from ships were carried out from airplane on the Baltic sea and helicopter in the North sea. Comparions were done to a ship emission model.
Paper 2	*Title: Emission Factors of SO_2, NO_x and Particles from Ships in Neva Bay from Ground-Based and Helicopter-Borne Measurements and AIS-Based Model* http://www.atmos-meas-tech.net/7/1957/2014/amt-7-1957-2014.pdf Measurements of sulfur, NO_x and particle emissions from 200 ships in the Neva bay during 2011 and 2012 has been carried out from a moored ship downwind of the ship channel. In addition measurements were carried out from a MI-8 helicopter. Comparisons of the measurements were done against a ship emission model.
Paper3	*Title: Airborne emission measurements of SO2, NOx and particles from individual ships using sniffer technique* http://www.atmos-chem-phys-discuss.net/14/25931/2014/acpd-14-25931-2014.pdf Airborne measurements of SO_2, NO_x and particle emissions from 160 individual ships on the Baltic and North sea during 2011 and 2012. have been carried from 3 platforms, i.e. 2 airplanes and one helicopter.

2. Environmental impact, regulations and enforcement

2.1 Impact of ship pollution

Sulfur is naturally present in liquid and solid fuels such as oil and coal. Most marine fuels contain sulfur. The combustion of fuels containing sulfur gives rise to emissions of sulfur dioxide (SO_2), and particulate matter (PM): including primary soot particles, and secondary inorganic sulfate particles formed as a result of atmospheric oxidation of sulfur dioxide. Nitrogen oxides (NO_x) are also emitted when fuels are burned, as a result of oxidizing atmospheric N2, and to a lesser extent the nitrogen content of the fuel. SO_2 emissions can damage human health and the built environment, and contribute to acidification, damaging sensitive ecosystems. PM emissions can damage human health. NO_x emissions contribute to acidification, and to the formation of ground level ozone, which can harm human health and vegetation. They also contribute significantly to nitrification on the sea.

Emission modeling (EMEP, 2002) shows that ship traffic contributes significantly to "acid rain" in many parts of Europe. A term denoted critical load of acidity is used to quantify such effects, defined as the maximum deposition of sulfur and nitrogen not causing harmful leaching of acidity. Critical loads vary depending on geological and ecological factors, which mean that ecosystems in northern Europe are generally more acid-sensitive than those in the south. The modeling shows that ship traffic contributes to exceedances of critical loads of acidity by more than 50 % in most of the coastal areas along the English Channel and North Sea, in the Baltic Sea along the coast of Germany and Poland, and also in large parts of southern Sweden and Finland. We also know that throughout the EU, ship emissions contribute between 20 % and 30 % to the air concentrations of secondary inorganic particles (PM) in most coastal areas. Secondary PM, as well as primary PM, SO_2 and NO_x, has impacts on human health throughout the EU. Both short-term and long-term exposure to air pollutants gives rise to health impacts – in terms of effects on mortality and on morbidity (illness, including exacerbation of asthma, incidence of bronchitis and heart failure). Recent modeling (Corbett 2007) indicates that smokestack emissions from international shipping kill up to 64,000 people a year, including 27,000 in Europe, at a cost to society of more than US$330 billion per year.

The average sulfur content of marine heavy fuel oil worldwide is currently 2.7 %, or 27,000 parts per million (ppm), compared to 2,000 ppm maximum for heating oil, and a forthcoming limit of 10 ppm for automotive petrol and diesel. This means that ships are now one of the biggest sources of SO_2 emissions in the European Union. Research (EU Commission, 2002) shows that within 10 years, ship emissions of SO_2 are likely to be equivalent to all land-based emissions, including emissions from all transport modes, combustion plants and heating engines which burn liquid fuels. However new rules have been implemented within the IMO Marpol annex VI which will reduce the FSC dramatically in certain areas from 2015 and onward, see below.

2.2 Regulation

IMO ship pollution rules are contained in the “International Convention on the Prevention of Pollution from Ships”, known as MARPOL 73/78. In 1997, the MARPOL Convention was amended by Annex VI titled “Regulations for the Prevention of Air Pollution from Ships” which came into force in 2005. MARPOL Annex VI sets limits on NO_x and SO_x emissions from ship exhausts, and prohibits deliberate emissions of ozone depleting substances. The Annex VI was further revised in 2008 (MEPC 176/58, 2008), becoming into force in 2010.
Annex VI includes a global cap of SO_2 and contains provisions allowing for special SOx Emission Control Areas (SECA) and NOx Emission Control Areas (NECA) to be established. Alternatively, ships must fit an exhaust gas cleaning system or use other technological methods to limit their emissions. In the global cap and the SECA limits of FSC are plotted. Noteworthy, is the fact that from 2015 the FSC (FSC) used by vessels operating in SECAs must not exceed 0.1% and by 2020 ships worldwide are restricted to 0.5% FSC. The global SO_x cap may be postponed until 2025 dependent from the result of an IMO fuel availability review in 2018. However the EU sulfur directive requires all ships within EU waters to use 0.5% from 2030, independent of the availability review.

The Baltic Sea Area, the North Sea and English Channel and the coastal waters around USA and Canada are designated as SECAs. In addition, the latter area is also designated as a NECA. Following IMO annex VI the EU commission has adopted a legal framework of its own starting with the EC Sulfur directive (1999/32/EU) and further amended by Directive 2012/33/EU in order to align the EC regulations on sulfur content of marine fuels with the IMO revised MARPOL Annex VI regulations. The Directive is applicable in all EU member states, who are also obliged to implement the regulations on their respective territorial waters.
The key elements of the EU regulation is:
1. The EC regulations are aligned with the revised MARPOL Annex VI, both inside and outside EU SOX Emission Control Areas (SECAs) including Baltic Sea, North Sea and English Channel.
2. All ships at berth in EU waters have to use low sulfur fuel (0.1 %) since 2010.
3. The 0.50% limit outside EU SECAs will apply in EC waters from 1 January, 2020, regardless of the outcome of the IMO fuel availability review, which is due by 2018;
4. Emission abatement methods (e.g. exhaust gas cleaning systems, mixtures of marine fuel and boil-off gas, and biofuels) are permitted for ships of all flags in EC waters as long as they continuously achieve reductions of SO_x emissions which are at least equivalent to using compliant marine fuels.

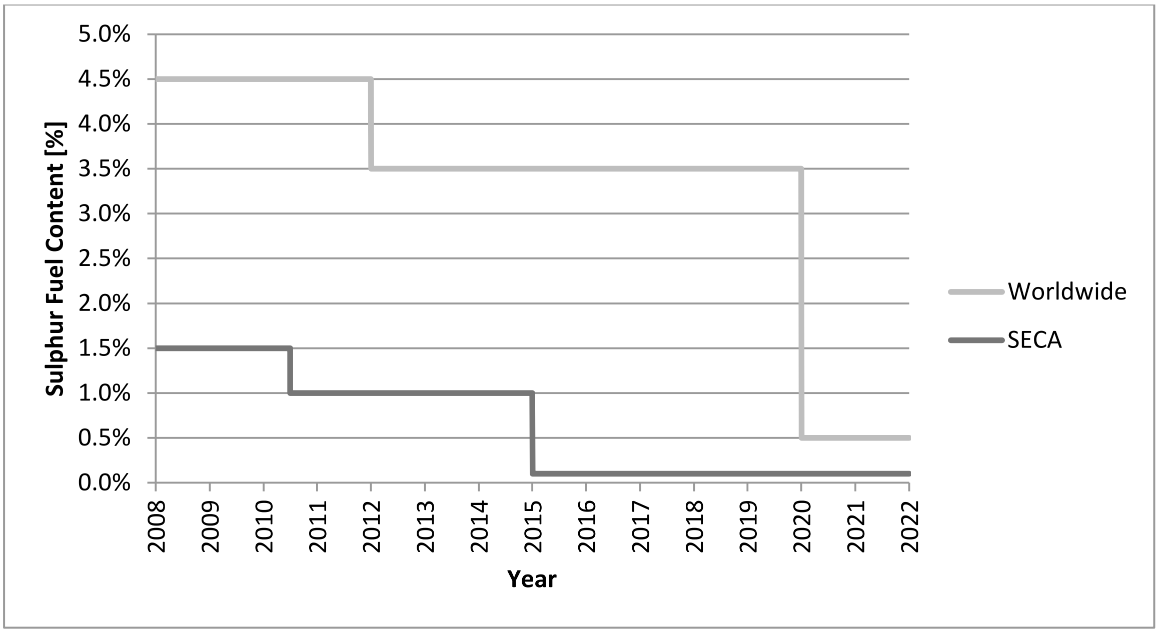

Figure 1. Regulation of FSC [%] in the world and SECA areas. The Worlwide cap in 2020 may be postponed until 2025, depending on fuel availability.

The IMO regulation regarding ship emissions is more complicated for NO_x than for sulphur, since NO_x is produced in the combustion process rather than coming from the fuel. IMO has therefore chosen a limit that corresponds to the total NO_x emission in gram per axial power produced from the engine in kWh. This limit is hence dependent on the fuel efficiency of the engine in use. Large ships, such as container vessels and tankers, usually run with slow stroke engines with a rated rotational engine speed of around 100 rev/min. These ships are fuel efficient (down to 165 g/kWh) but due to the long residence time of the exhaust in the cylinders they produce high amounts of NO_x. Ferries and intermediate sized ships usually use medium stroke engines with a rated rotational speed of around 500 rev/min and these engines are less fuel efficient (175-250 g/kWh), but on the other hand they produce less NOx compared to the slow stroke engines.

Due to the complexity described above an emission curve as a function of rated engine rotational speed has been put forward by IMO , i.e. NO_x Technical Code [MEPC 177/58, 2008]. The NO_x emission limit corresponds to weighted emission factors for typical loads versus rated rotational speeds. The regulation requires all ships built after year 2000 to fulfill the IMO Tier 1 emission values, and for ships built from year 2011 to fulfill Tier 2. Ships built between 1990 and 2000 will also be forced to retrofit NOx abatement equipment, if a cost effective upgrade is available.

According to the revised annex, the rather stringent limits of Tier III will be applied to all ships constructed after 1st of January 2016 and operating inside NECAs. However at the last IMO-MEPC meeting in London in May 2013 an amendment was discussed that may postpone the Tier 3 starting year to 2021.

The IMO code within MARPOL annex VI protocol requires that all ships flying flags of the states that have ratified the protocol (i.e. about 90% of the gross tonnage of the world's merchant fleet) respects the emission limits of Annex VI on international water and in SECA areas. For ships flying flags of states that have not ratified the protocol this is only required when operating in other countries exclusive economic zones.

According to the EU sulfur directive (2012/33/EU) effective sampling and dissuasive penalties throughout the community are necessary to ensure credible implementation of this Directive. Member States should take enforcement action with respect to vessels flying their flag and to vessels of all flags while in their ports. It is also appropriate for Member States to cooperate closely to take additional enforcement action with respect to other vessels in accordance with international maritime law. The latter is usually done through various agreements (Memorandum of Understandings, MoU), as discussed below.

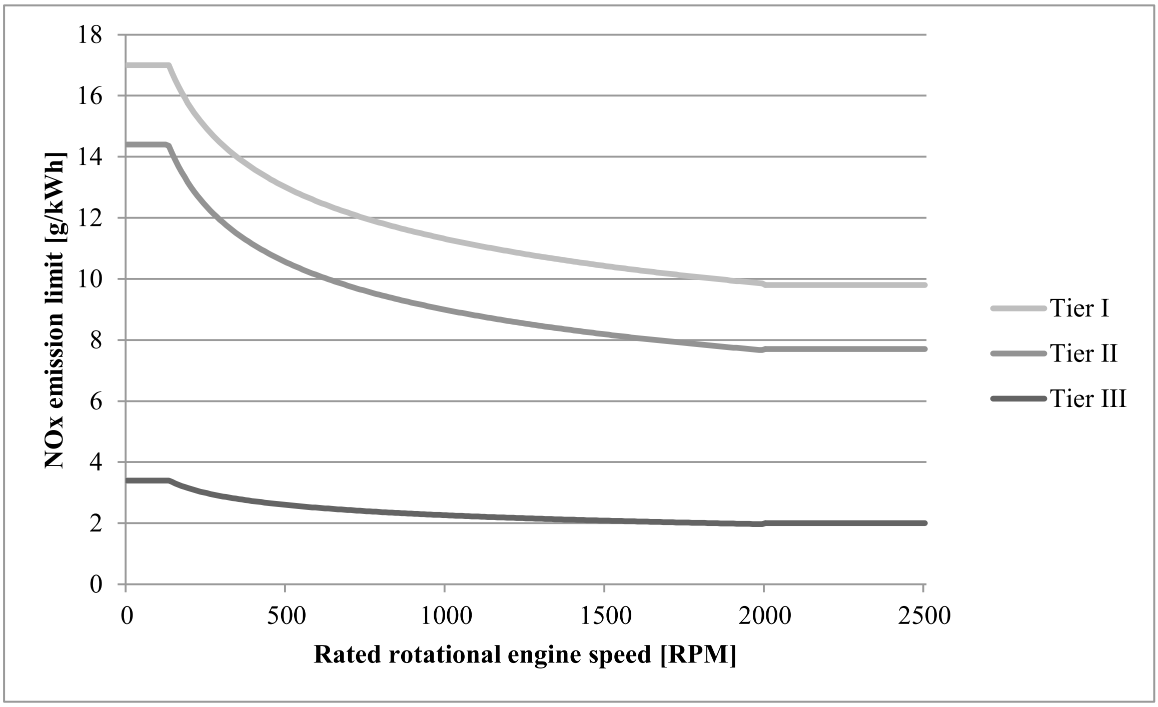

Figure 2. **NO_x emission limits versus rated engine rotational speed (rev/min) for ships built after 2000, Tier 1. Tier 2 corresponds to the limit for 2011 and Tier 3 for future foreseen limits for NO_x Emission Control Areas**.

2.3 Enforcement

Port State Control (PSC) authorities have the right to inspect ships on internal waters (harbors, inland waters) and can also carry out enforcement actions such as detaining ships in harbors and even imposing civil penalties. The enforcement actions and penalties vary from country to country, although the states have tried to harmonize their control according to the Paris MoU, and other similar agreements.

When ships are outside internal waters but in the exclusive economic zone, on board inspection can only be carried out if there are clear grounds to suspect that the ship is not respecting the regulations, according to the United Nations Convention on the Law of the Sea (UNCLOS 1982) and the MARPOL code. On international waters inspection control is not possible but instead a complaint to the flag state should be filed, if there are grounds for violation of the IMO code.

2.4 Additional actions for enforcement

The SO_2 emission from a ship is directly proportional to the FSC in use. However, since there is a large price difference between fuel with low (0.1 %) and high (1 %) FSC, there is considerable economic advantage in ignoring the regulation. To prevent this and to promote fair competition within the shipping industry enforcement actions are needed.

Port state control authorities presently conduct on board inspections in harbors checking fuel logs, bunker delivery notes and occasionally collecting fuel samples. If the FSC of the samples in the fuel line or day tank is above the IMO limit, enforcement action can be taken since this corresponds to what the ship has recently been running on. It is however much more difficult to prove that ships have been running on high FSC during part of their voyage to the destination port since then a detailed audit of the fuel log and fuel balances is required. Note that ships often carry different fuel qualities which are mixed in the day tanks, so it is not enough just to identify that high FSC is carried in one of the fuel tanks. All in all, on board inspections are inefficient and only few ships have been detained for this reason, for instance during 2011, 32 ships were detained in European harbors due to having deficiencies related to annex VI, following statistics from the Paris MoU.
In addition, when ships are operating outside internal waters, such as transportation routes, on board compliance checks are generally not carried out, since clear evidence for violation of the IMO code is then needed, as discussed above.
In order to reduce, control and to get an overview of the distribution of the emissions from the shipping sector there is a need for the development of measurement systems for effective compliance control done remotely, without stepping on board the ships. This is acknowledged by for instance EMSA and HELCOM.

3. Instruments and platforms

3.1 General instruments

The IGPS system, see Table 2, consists of optical instruments for remote sensing measurements and extractive instruments for sniffer measurements of gases and particles in the exhaust plume of the ships , see appendix I and the associated papers (Berg, 2012, Beecken 2014a, Beecken 2014b). The gas instruments are based on the following physical principles: UV fluorescence for SO_2, chemiluminiscence for NO_x and cavity ring down spectroscopy and non-dispersive infrared absorption, respectively, for CO_2. The particle instruments are based on measuring the number size distribution of the particles between a mean diameter of 5 nm to 10 µm (sub micron to PM10). The particles below 500 nm are measured by electric mobility while the larger ones are measured by laser scattering. The number size is converted to mass by calculating the mean volume of the particles multiplied with the assumed density. In addition the amount of soot in the ship exhaust plumes has been measured in one campaign by using an aethalometer that utilizes the optical properties of the soot for the detection.

The extractive techniques for gases are available as commercial state of the art instruments and they are being used worldwide as reference methods for air quality measurements. In the IGPS system we have modified these instruments to obtain fast response, smaller weight, smaller form factor and field robustness. In the flight version the instruments are equipped with pressure regulators at the inlets to compensate for varying flight altitude.

The optical method is based on the same hardware and data analysis as being used in satellite measurements. The application of carrying out ship emission measurements is unique for this project, however.

The quality assurance of the sniffer measurements is based on calibration against gas standards with a typical accuracy of 1 %. The SO_2 instrument has a small sensitivity to NO (100 ppb NO corresponds to 1.5 ppb SO_2 reading), that makes the measurements of FSC less accurate for ships running marine gas oil, i.e. FSC 0.1 %, see discussion below.

Table 2. The instruments used in the project for compliance measurements. A few additional instrumnets have been used but these are mentioned in the section regarding complementary measurements.

Species	Quantity	Method	Sample rate	Detection limit	Mode A: airborne, M: mobile, F: fixed
CO_2	Mixing ratio (sniffer)	Cavity ring down spectrometer with custom hardware and sampling (sniffer)	2 Hz	0.2 ppm	A, F, M
CO_2	Mixing ratio (sniffer)	Non dispersive infrared instrument .	1 Hz	0.2 ppm	A, F, M
SO_2	Mixing ratio (sniffer)	Fluorescence (modified)	1 Hz	1 ppb	A, F,M
NO_x	Mixing ratio (sniffer)	Chemiluminiscence (modified)	1 Hz	0.5 ppb	A,F,M
SO_2	Column (optical)	Optical meas (DOAS)	1 Hz	20 ppb over 50 m	A, F
NO_2	Column (optical)	Optical meas (DOAS)	1 Hz	20 ppb over 50 m	A,F
PN (PM)	Number size distribution 5-500 nm (sniffer)	Electrostatic mobility	10 Hz	n/a	A
PN (PM)	Number size distribution 300-10000 nm (sniffer)	Laser scattering	1Hz	n/a	A,F
$SO4^{2-}$	µg/m3	Particle into Liquid Sampler (PILS), MEGA chamber and ion chromatography		n/a	F
Soot	Optical properties of soot converted to mass	Aethelometer	1 Hz		F, M

3.2 Fixed sniffer instrument

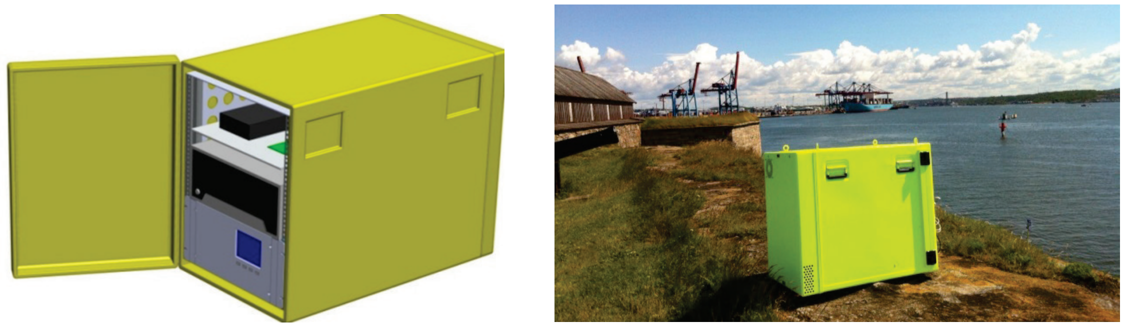

Figure 3. IGPS-system built into a box for automatic measurements at fixed sites or harbors vessels.

A ground based automatic IGPS-system with real time identification of gross polluting ships has been built into a water tight box. The system calculates the sulfur content of individual ship by analysis of their exhaust plumes, according to section 4.

The sniffer system is equipped with sensors for SO_2 and CO_2 as well as an AIS receiver, GPS sensor, wind sensor, internet modem, control electronics and log computer, Table 3. Custom made software, Figure 4, has been developed that plots ships on a map and which automatically identifies ship plumes and calculates the FSC of the ships from the ratio of SO_2 over CO_2. The FSC data can automatically be sent to PSC authorities for further action, such as on board inspection of the ships. In Figure 5 is shown multiple measurements of the same ship during 2 years by the fixed IGPS system in the ship channel of Göteborg. The measured ship corresponds to a small product tanker (GT 478 ton) which runs voluntarily on marine gas oil, i.e. 0.1 % FSC or below. The average FSC corresponds to 0.06 %(+-0.05) and 95 % of the data are lower than 0.17 % (95 % percentile). Here the measured SO_2 data has been corrected for cross interference with NO by simultaneous measurements of this species. If this correction is not done, then the apparent FSC will become somewhat higher for ships running marine gas oil with low sulfur fuel, i.e. a 0.1 % FSC will read as 0.2 % for a large NO_x emitter. This is the case for the system in the yellow box in Figure 3. Nevertheless even without NO correction the accuracy is sufficient to differentiate ships running a FSC of 0.4 % or higher against 0.1 % but to improve this, the system can be complemented with a NO sensor.

In Figure 6 ship emission data obtained in the ship channel of Göteborg in 2007 are shown, using an older version of the IGPS-system (Mellqvist 2010) for ships running FSC of 0.1 %, 0.5 % or 1 %. The figure shows several measurements of ships for which we knew the FSC of. The data demonstrates that the measurement method easily distinguishes between ships running the three different fuel types. In section 6 some results are shown using this system.

Table 3. The hardware included in the fixed IGPS-system which is contained in a thermo controlled, water proof box.

CO2: Cavity ring down	SO2: UV fluorescence
AIS-reciever	Pumps
Calibration gases Power supplies	Measurement computer with realtime software
Wireless internet (3G)	Wind sensor

Figure 4. A screen dump from the software *IGPS-real* which shows the measured data and which calculates the position of the ship plumes. When the station, red star, is hit by a ship plume the program automatically calculates the FSC and then identifies from which ship the gas originates from.

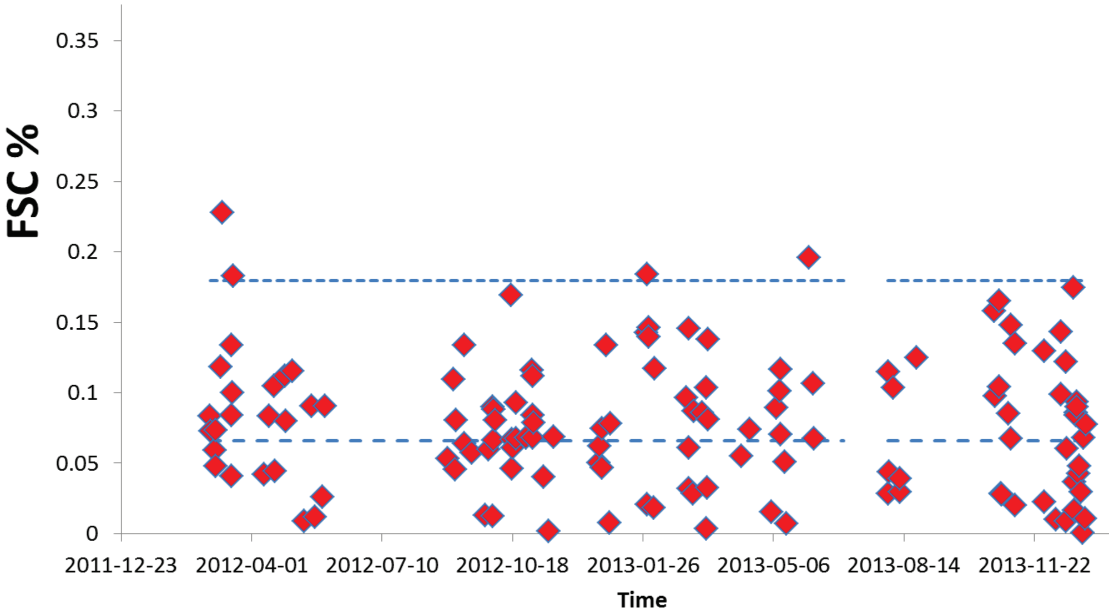

Figure 5. Multiple measurements (150) of the FSC of a small product tanker (GT 478 ton) which voluntarily runs on marine gas oil, .i.e. <0.1% FSC. The data have been measured and retrieved automatically by a fixed IGPS system in the ship channel of Göteborg. The average FSC is 0.06 %(+-0.05) (dashed line) and the upper 95 % percentile of the data corresponds to 0. 17 % FSC(dotted line).

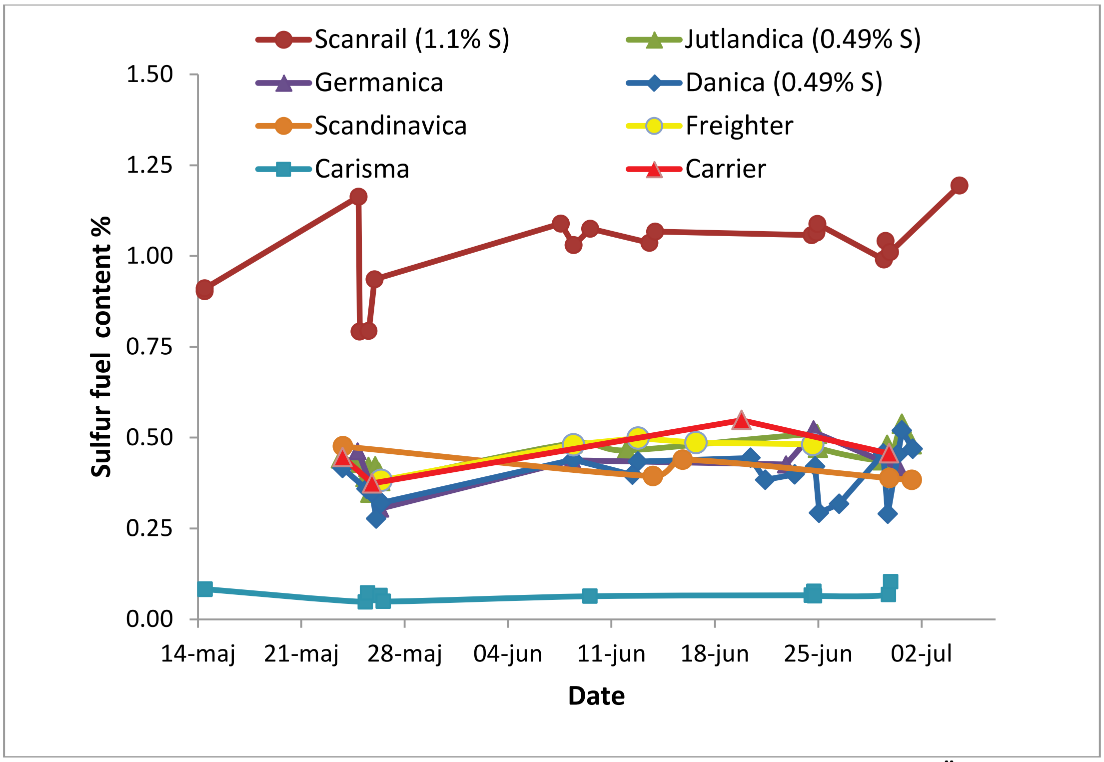

Figure 6. Measurements of FSC in 2007 in various Stena ships in the ship channel of Göteborg, Älvsborgsfästning, using the IGPS extractive system. The reported FSC from Stena is shown in the legend. Stena Carisma is a turbin driven ship running on MGO.

3.3 Flight installation

The IGPS system has been tested on various airborne platforms, both fixed and rotary wing aircraft (MI-8 helicopter, Dauphine helicopter, CASA aircraft, Paternavia P 68 aircraft, Navajo Piper aircraft) (Berg 2012, Beecken 2014a, Beecken 2014b). In these tests the instruments were placed in already available racks and they were taken up as cargo.

In order to carry out dedicated ship surveillance there was a need to interface with the airplanes and to build dedicated racks, obtain power and data from the airplanes and access antennas for the GPS and AIS-system. There was also a need for telescopes and gas and particle probes. A cooperation was established with 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. One of their airplanes, Navajo Piper OY-MST, was chosen for a permanent IGPS installation. See Figure 7.

Figure 7. 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.

To obtain a permanent installation 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 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).

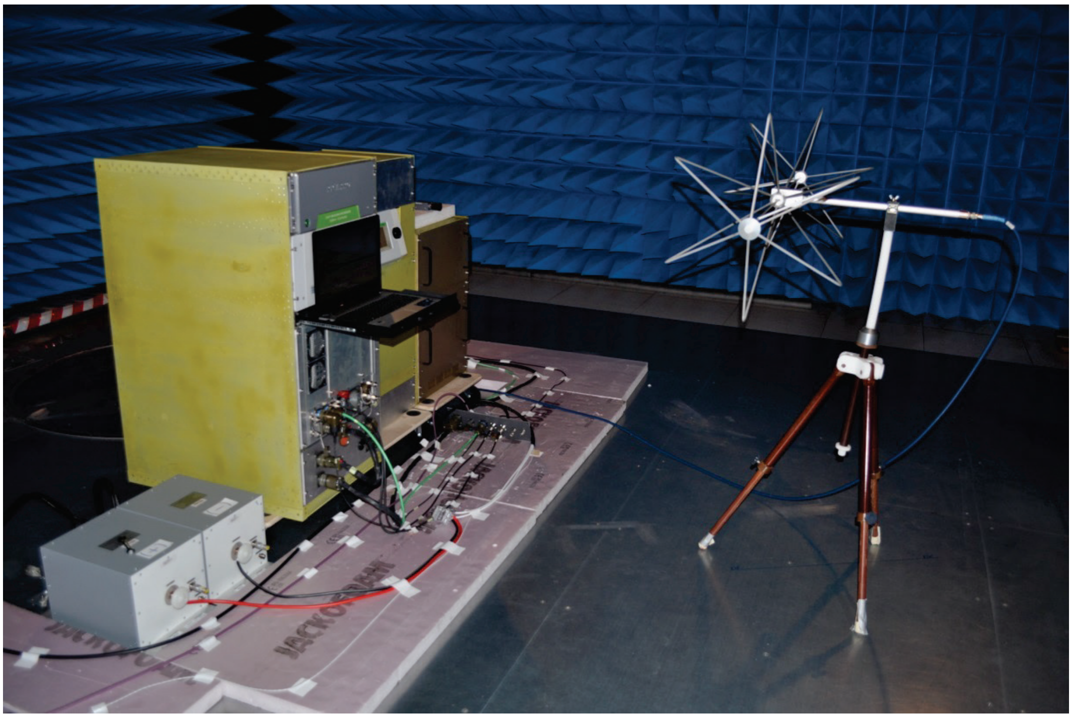

Figure 8. EMI testing of the IGPS equipment at a reference laboratory at SAAB in Linköping (RTC DO 160/issue M/cat M/section 21 and section 15).

An investigating of the production of toxic gases that would be produced in case of fire was carried out, including removing 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 air that is flown through. The airplane has been equipped with a wind sensor and the data was transmitted to the IGPS system using as special protocol (ARINC). More technical information of the airplane installation is found in appendix I and the STC approval in appendix II. It is planned to provide a compliance monitoring service using this aircraft. In addition the experience gained of certifying the system will makes it faster to certify installations in other aircraft.
In the figures below 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 (Figure 9 and Figure 10). In addition a window was exchanged by a probe plate equipped with both telescopes and probes, Figure 11.
A special instrument (SO_2/CO_2 module) has been designed, Figure 12, 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 receiver, GPS 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 13 the optical module is shown containing two UV spectrometers with cooled CCD detectors for simultaneous measurements of SO_2 and NO_2.

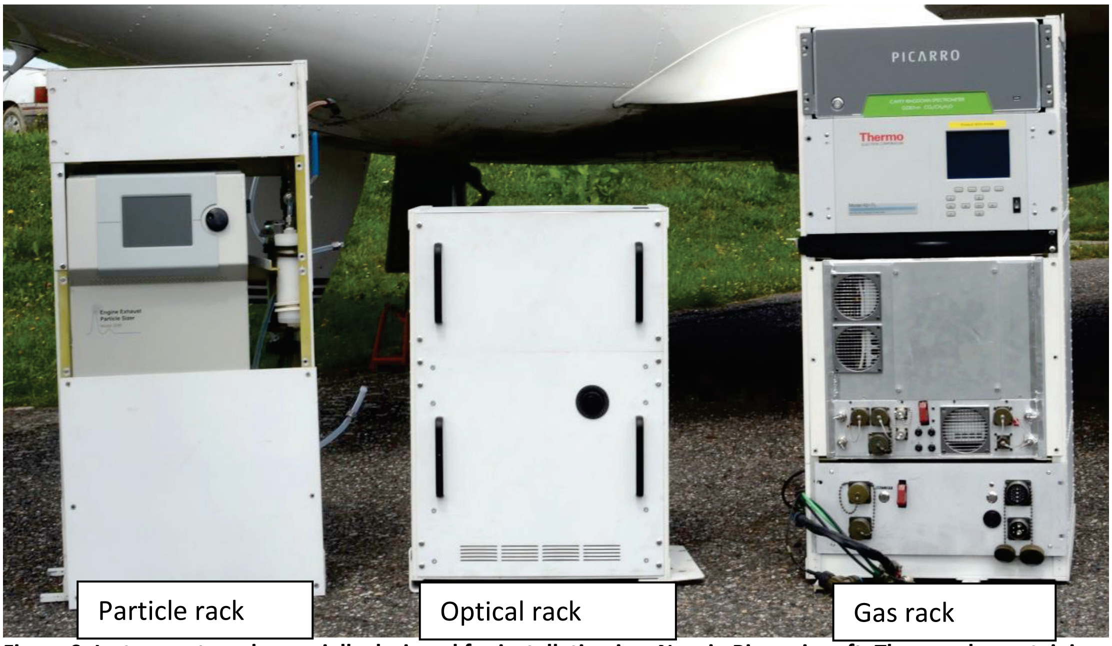

Figure 9. Instruments racks specially designed for installation in a Navajo Piper aircraft. Three racks containing sniffer instruments for particles and gases and optical sensors.

Figure 10. The installation of the instrument racks and window probe plate inside the Navajo Piper aircraft.

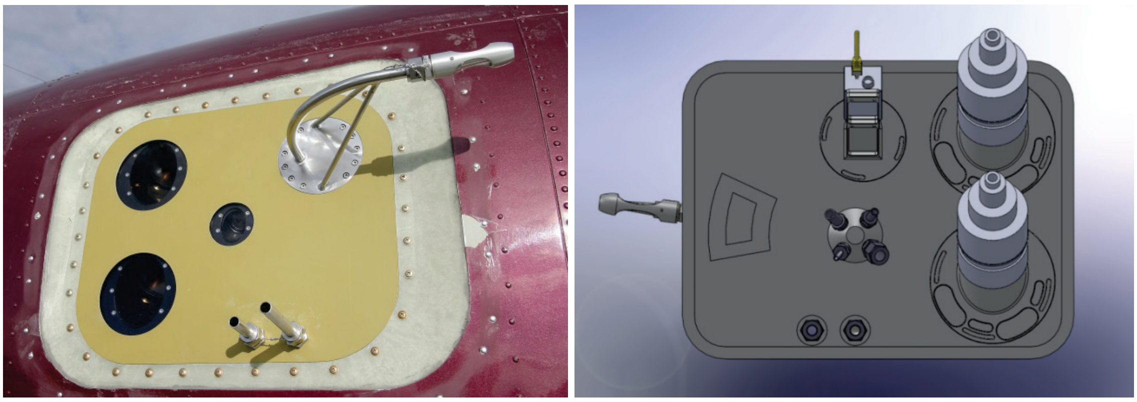

Figure 11. The left picture shows a window probe plate that has replaced one window and which is equipped with two small windows for optical telescopes (left), one small window for a video camera (middle), one particle probe (upper right), and gas probe, (lower right) and one gas exhaust pipe (lower middle).

Figure 12. A specially designed FSC sniffer module. This box which 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 airplane setup in the Navajo Piper aircraft.

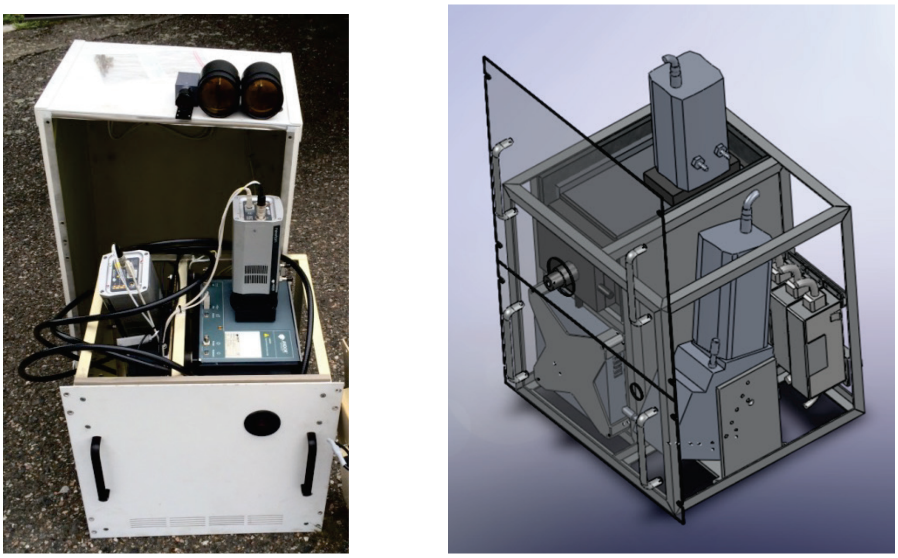

Figure 13. The optical module containing two UV spectrometers from Andor with cooled CCD detectors for simultaneous measurements of SO_2 and NO_2.

4. Methodology and results

4.1 Fixed measurements

Several thousand ship inspections have been performed since 2010 by automatic sniffer measurements of SO_2 and CO_2 in the inlet channel of Göteborg at Älvsborgsfästning, Figure 14, using the system in Figure 3, complemented with NO_x and particle measurements. Similar measurements were also carried out in 2007 using an earlier version of the IGPS system (Mellqvist, 2010). The system is designed to be built into a network positioned at strategic places such as harbor entries, bridges and patrol vessels. It has been used from various fixed sites, i.e. Rotterdam and Sankt Petersburg, and from moving platforms such as a river boat in the Neva bay, a harbor patrol vessel in Rotterdam and from a measurement van in Sankt Petersburg and Rotterdam.

The data measured in Göteborg has been used to control the FSC of ships that participates in a voluntary low sulfur program based on reduced harbor fees, such as the ship in Figure 5. The system can be complemented by an optical module for absolute measurements of SO_2 and NO_2 emissions (g/s) that we have used in Rotterdam and Neva bay (Balzani, 2014).

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 14. The IGPS system calculates the FSC of individual ships from SO_2 and CO_2 measurements in the exhaust plumes. It has been in continuous operation since 2011 at Älvsborgsfästning, in the ship channel of Göteborg, marked with a star. The system includes SO_2, CO_2, sensors, AIS, measurement computer, internet modem and power supplies.

The sniffer measurement at the Älvsborgsfästning site, in the ship channel of Göteborg, is conducted by extracting the by-passing plume of the ships into the instruments through a 10 m tube and then measuring the ratio between SO_2 and CO_2 and NO_x and CO_2, respectively. From the measurements the sulfur fuel ratio and the NO_x emission in g per fuel unit or g/kWh can be derived.

In the sniffer measurements, it is assumed that the SO_2 to CO_2 ratio is directly proportional to the sulfur to carbon content in the fuel, since these two gas species are the main combustion products, see Equation 1. In this equation the CO_2 is given in the unit ppm (parts per million) while SO_2 in the unit ppb (parts per billion) and it assumed that 87 % of the fuel corresponds to carbon and that all sulfur is converted to SO_2 in the combustion. The latter is not entirely true since some of the sulfur is present as sulfate in particles, see section 5. The equation is described in more detail in Beecken et al (2014a).

$$S_{fuel}\% = \frac{\sum SO_2}{\sum CO_2} \cdot 0.232 \qquad \text{Eq.1}$$

From the NO_x to CO_2 ratio, the specific emission of NO_x per mass of fuel is obtained, according to Equation 2. Also here CO_2 is given in ppm while NO_x is given in ppb. To convert the NO_x to mass it is assumed that all NO_x corresponds to NO_2, and to convert the NO_x emission value to NO_x emission per kWh, Equation 3, as given in the IMO annex VI, the fuel efficiency of the specific engine has to be included through the specific fuel oil consumption. This value can vary from 160 g/kWh for slow stroke engines to 220 g/kWh for medium stroke engines but for the value in equation 3 it includes a default value 200 g fuel per kWh of axial power. In the associated papers we have used data from the ship emission model named STEAM (Jalkanen, 2009), if available, otherwise the default value above.

$$\frac{NO_x\,[g]}{fuel\,[kg]} = \frac{\sum NO_x}{\sum CO_2} \cdot 3.48 \qquad \text{Eq.2}$$

$$\frac{NO_x\,[g]}{kWh} = \frac{\sum NO_x}{\sum CO_2} \cdot 0.667 \qquad \text{Eq.4}$$

A custom software named *IGPS-real*, is being used that detects ship plumes which blows across the instrument and then automatically calculates emission factors of various species and identifies the corresponding ship. A view from the *IGPS-real* program is shown in Figure 4 and Figure 15. In the latter figure the measured mixing ratio values of NO_x, SO_2 and CO_2 (bottom up) are shown when the emission plume from a ship (Stena Scandinavica) blows over the measurement site. The FSC and specific NO_x emission factor are derived by integrating across each plume and then calculating the FSC and NO_x emission factor using equation 1 and 4. The derived values correspond to 0.75 % and 11 g/kWh, respectively.

In Figure 16 results from sniffer measurements in the inlet channel of Göteborg (Älvsborgsfästning) are shown for several years, i.e. 2007, 2010, 2012 and 2013. The data correspond to the average FSC value for a certain ship and year. In Figure 17 the same data has been divided into 10 %, 25 %, median, 75% and 90 % percentiles, respectively. In addition the SECA limits, for the different years are shown as the green dashed line. As can be seen, both in Figure 16 and Figure 17 the ships in the harbor obey the SECA values rather well with only a few ships above. The uncertainty of single ship measurement is around 20 % at 1 % FSC but better for the average of several measurements.
Noteworthy is that the frequency of ships running MGO, i.e. FSC below 0.1 %, has increased strongly when comparing the years 2010-2013 to 2007.

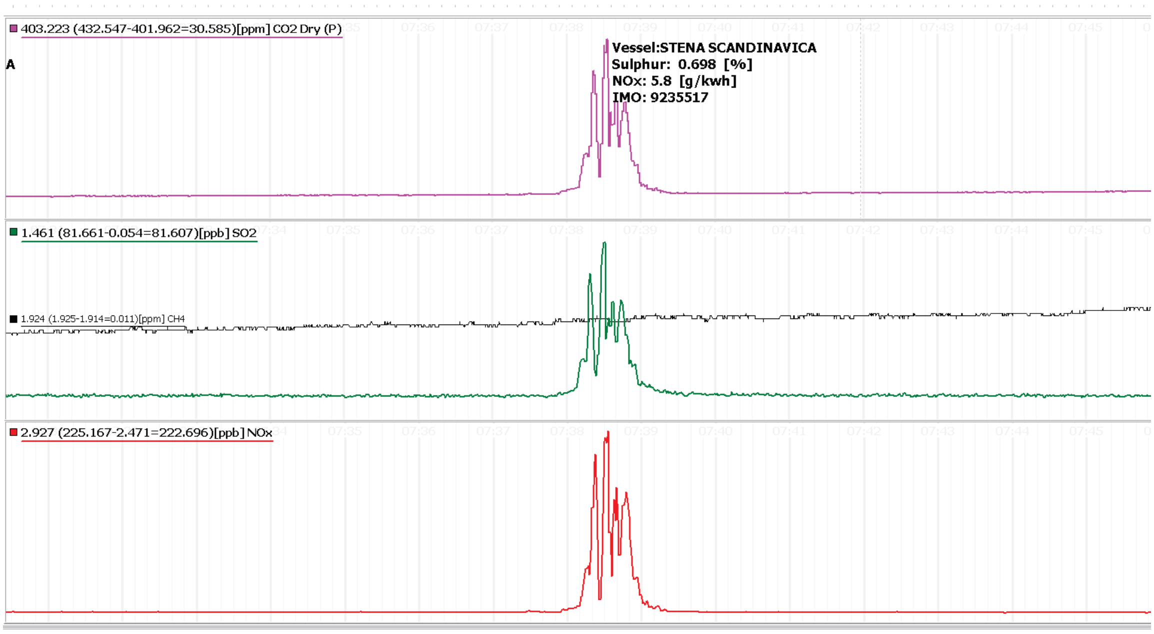

Figure 15. A view from the real time program *IGPS-real* when running sniffer measurements from the yellow box in Figure 3 in the inlet channel of Göteborg. Figure 4 shows the passage of the ship Stena Scandinavica and it's modeled smoke plume (blue). This figure shows the measured data of CO_2 (pink), SO_2 (green) and NO_x (red)during the passage. From the ratio of SO_2 and NO_x, respectively, against CO_2, the FSC (0.7%) and the NO_x emission (5 g/kWh) is obtained.

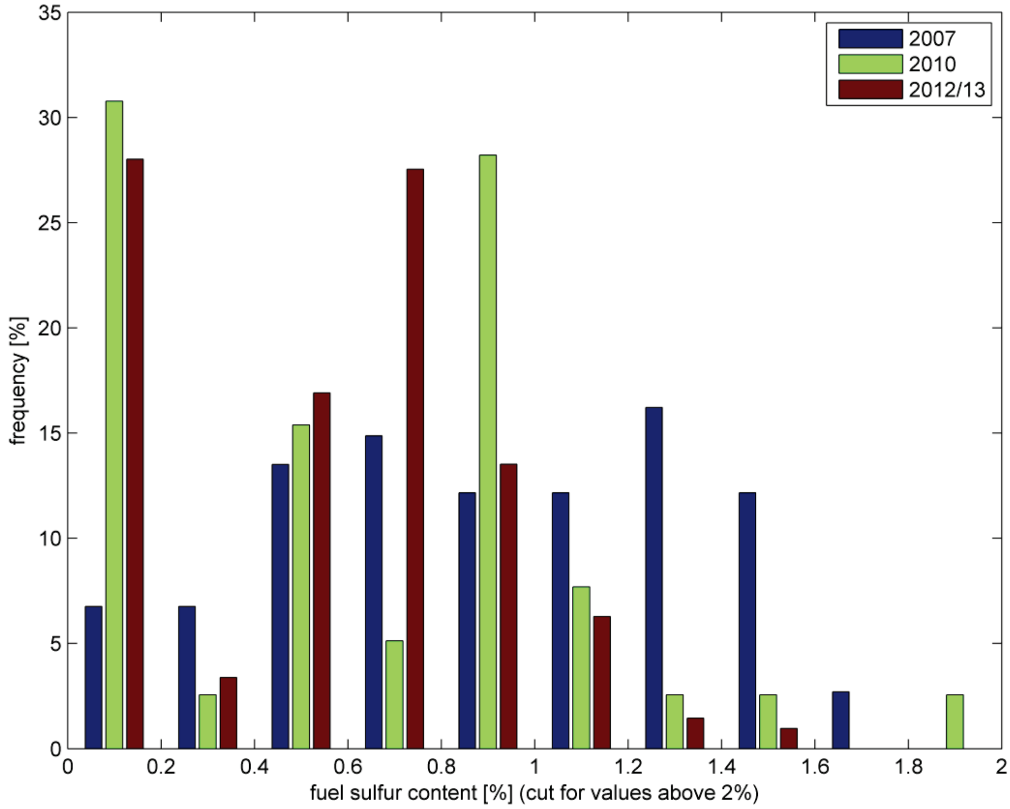

Figure 16. Results from automatic sniffer measurements of FSC in individual ships at the inlet channel of Göteborg (Älvsborgsfästning) within the IGPS project during several years. The data correspond to the average value for a certain ship and year.

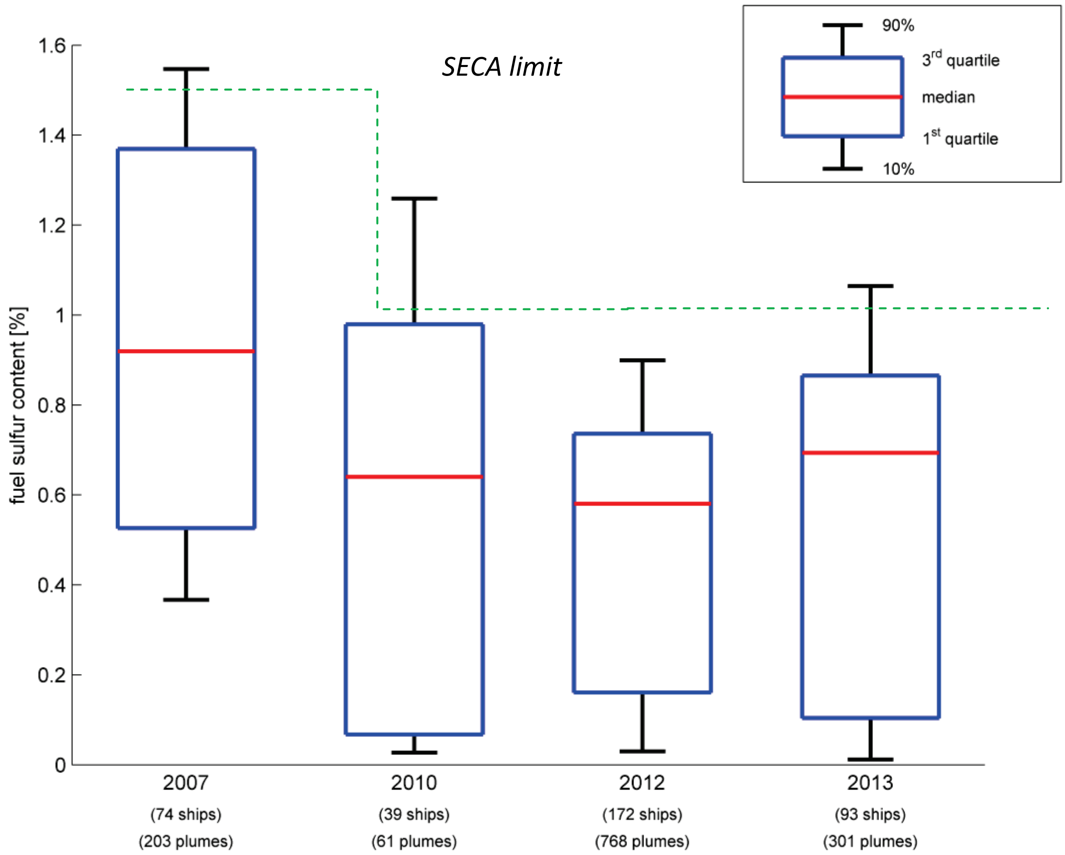

Figure 17. Measurements of FSC in individual ships in Göteborg, same as in Figure 16. The data correspond to the average yearly FSC measured for each ship, based on numerous measurements. It is shown a 10%, 25 %, median, 75% and 90% percentiles, respectively. In addition the SECA limits, i.e. 1.5% and 1, for the different years I shown as the green dashed line.

4.2 Air borne measurements

The main objective in this project was to develop and test an airborne method for compliance monitoring of ships with respect to FSC, NO_x and particulate matter. The advantage with airborne surveillance is the capability to check ships that are operating in the main shipping lanes. Due to the speed of the flight measurements it is not possible for the ships to switch their fuel as in the case for the fixed sites. It is speculated among PSC authorities that some ships may systematically operate on high sulfur fuel in the open sea, especially when their destination is outside the SECA region. The flight measurements will be able to detect these ships and determine the frequency of such a behavior. The disadvantage with flight surveillance is the high cost (2000-3000 kEuro/h) but since the measurements are carried out in locations with a higher probability of finding ships that use noncompliant fuel these measurements may still be cost effective compared to the 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.

The airborne surveillance scheme that has been developed and tested in this project is illustrated in Figure 18 and consists of two parts. First optical measurements of reflected solar light from the water surface are carried out, from which the path integrated concentration of SO_2 and NO_2 along the light path can be retrieved (Berg 2012). This value is recalculated to the mass flux in g/s using the wind and ship speed. In addition the CO_2

emission of the measured ships is calculated using a ship emission model named STEAM (Jalkanen, 2009). The estimated FSC is obtained from the ratio of the measured SO_2 and calculated CO_2 according to Equation 1.

The other part in the surveillance corresponds to s*niffer measurements*, in which the exhaust plumes from the ship is extracted trough a gas inlet (sonde) on the airplane and then further analyzed by onboard instruments for SO_2, CO_2 and NO_x.

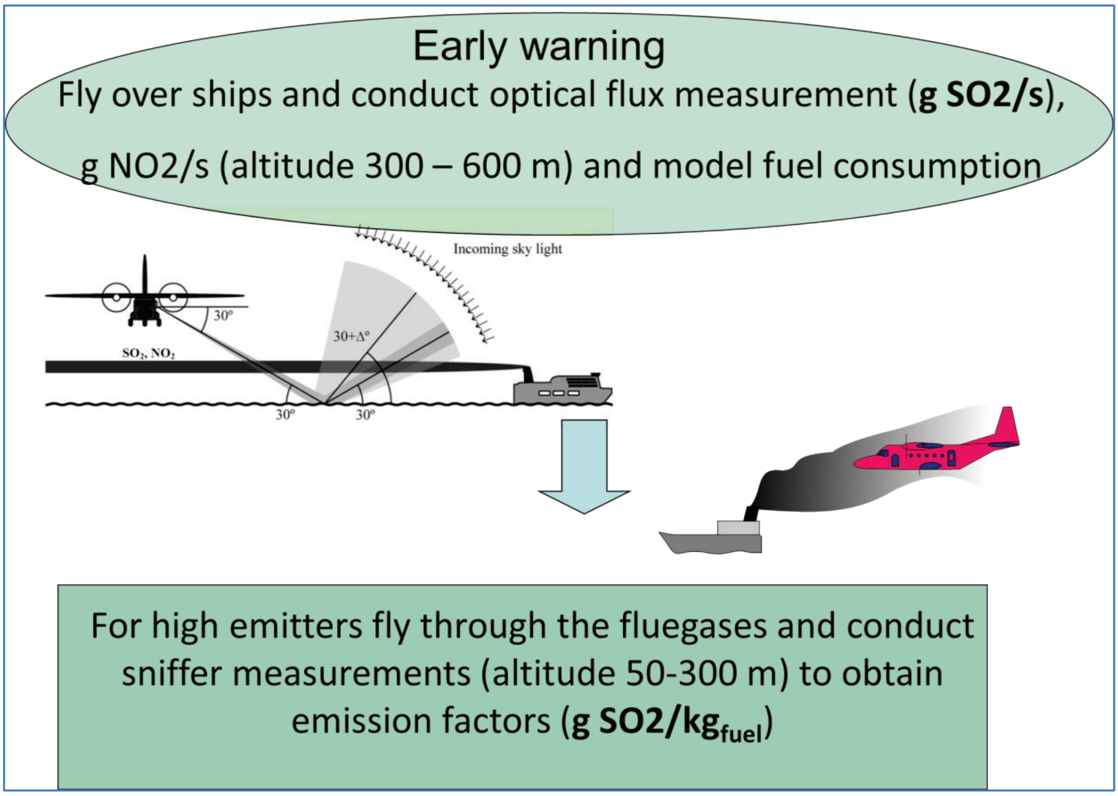

Figure 18. Schematic of the airborne surveillance methodology.

The general idea is that the remote optical system measures SO_2 or NO_2 in the ship plumes from an altitude of 300-400 m. When the values reach a certain threshold the airplane will drop to the lower altitude of 50-100 m to reach the ship plume and then a few transects through the plume are conducted measuring with the sniffer system from which the FSC and NO_x per fuel unit is obtained instantaneously. The data are stored together with information from an Automatic Identification System (AIS) which provides the name and speed of the target ship.

This can directly be transferred to a database for further usage by ship inspection authorities to target which ships to inspect once they are in harbors. A suitable data base is *THETIS-S* which is developed by the European Maritime Safety Agency (EMSA) to flag ships that are found to use noncompliant fuel with regard to the EU sulfur directive. With the optical measurements it is possible, under day light conditions, to check the FSC of 10-20 ships, depending on how close they are, while for the sniffer system 4-8 ships can be checked.

The program *IGPS-real* has been developed to track the movement of ships and aircraft, based on AIS and GPS-information, and automatically calculate the FSC and NO_x emission when intercepting the ship plume with the aircraft in the manner shown in Figure 18. The operator window of the program when in flight mode is shown in Figure 19, including some explanations of the given information. The program also controls the optical sensors and calculates emissions according to the description above.

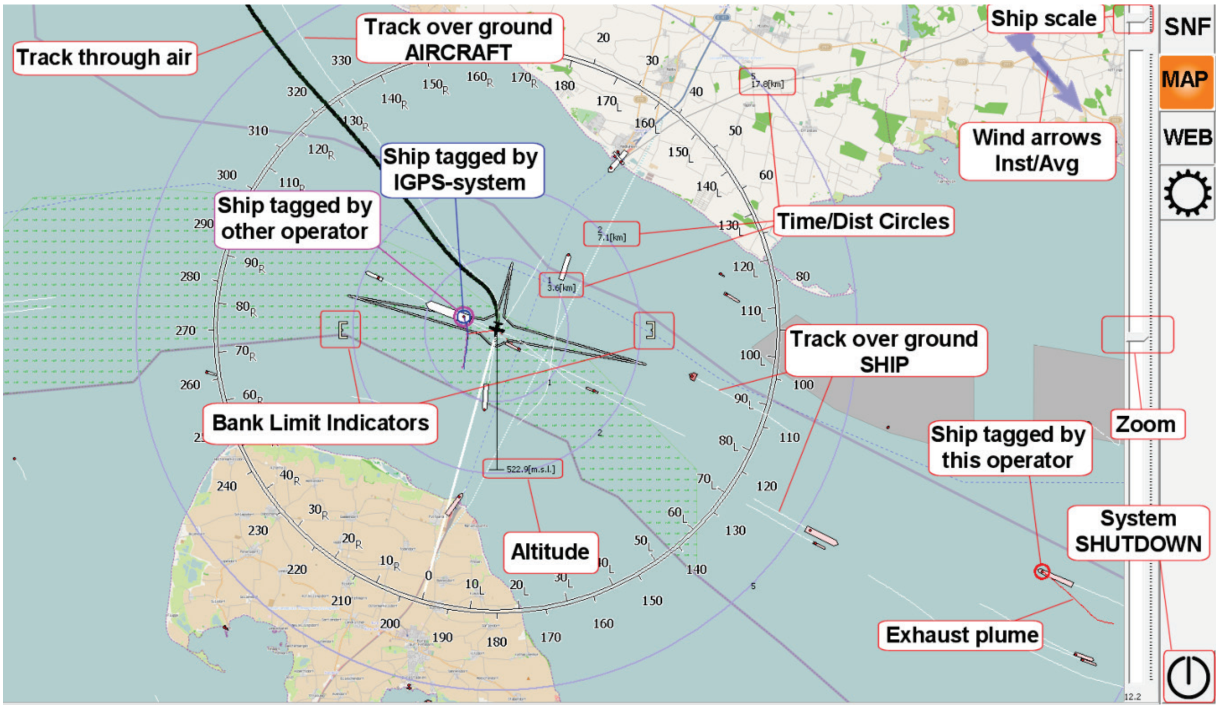

Figure 19. The program IGPSreal when carrying out airborne compliance control. Different type of information that is displayed is explained in the picture.

Optical measurements from a Dauphine helicopter measuring on a Stena ferry in the North Sea are shown in Figure 20 (Berg 2012). In this case the average SO_2 emission obtained with the optical sensor is 87±13 kg/h, to be compares to 97 kg/h that was measured on board. The emission rate is obtained by multiplying the optical measurement across the plume with the apparent wind (the wind felt on board the ship and which corresponds to the sum between true wind speed and direction and the wind due to the movement of the ship). The optical measurement is associated with a high uncertainty due to the difficulty of calculating the optical path of the light which is affected by light scattering in the waves and reflection on particles in the ship plume (Berg 2012). However, it is estimated that the technique combined with ship emission modeling is capable of distinguishing between ships running with 0.1 % and 1% FSC.

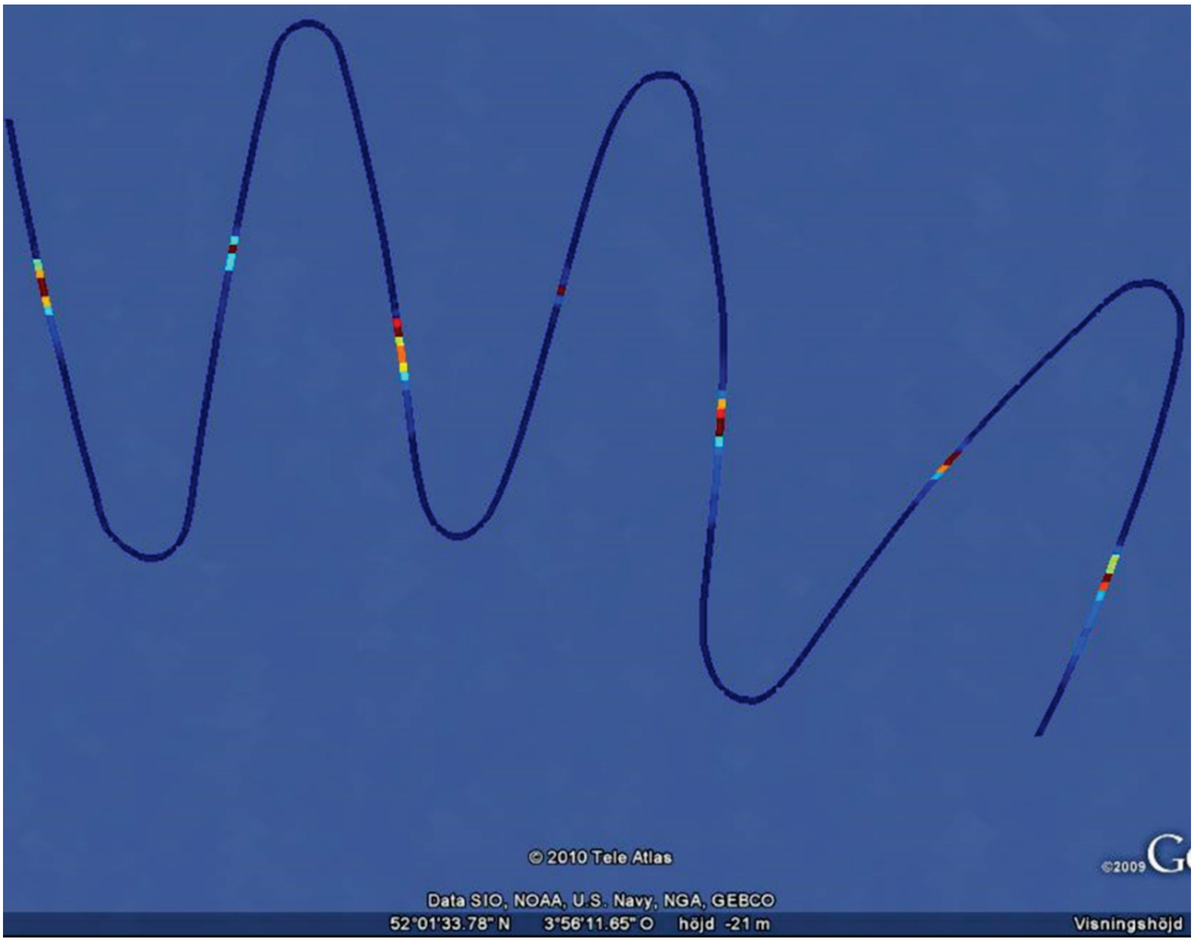

Figure 20. Optical measurements of SO_2 through the flue gas plume of Stena Hollandica (blue to red scale) from a Dauphin helicopter (Berg 2012) in the North Sea. The optical measurements correspond to an emission a rate of 87±13 kg/g, to be compares to 97 kg/h that was measured on board.

The airborne sniffer measurement are similar to the ones at the fixed sites, with the difference that the instruments are pressure controlled and rebuilt into smaller boxes as described in section 3.3. Measurements of 162 ships in the Baltic and North sea 2011/2012 during several campaigns using the IGPS equipment is shown in Figure 21 and Figure 22 below (Beecken, 2014a). These two figures show the distribution of FSC and mass specific NOx emission, respectively. In the upper right corner of Figure 21 additional measurements are shown from a CASA airplane and Dauphine helicopter in 2008 and 2009. Note that the SECA limits until mid-2010 was 1.5 % FSC and then 1 % FSC. Hence during last years, about 5 % of the ships used noncompliant fuel on the open sea, considering a relative measurement uncertainty of 20 % at 1 % FSC (Beecken 2014a).

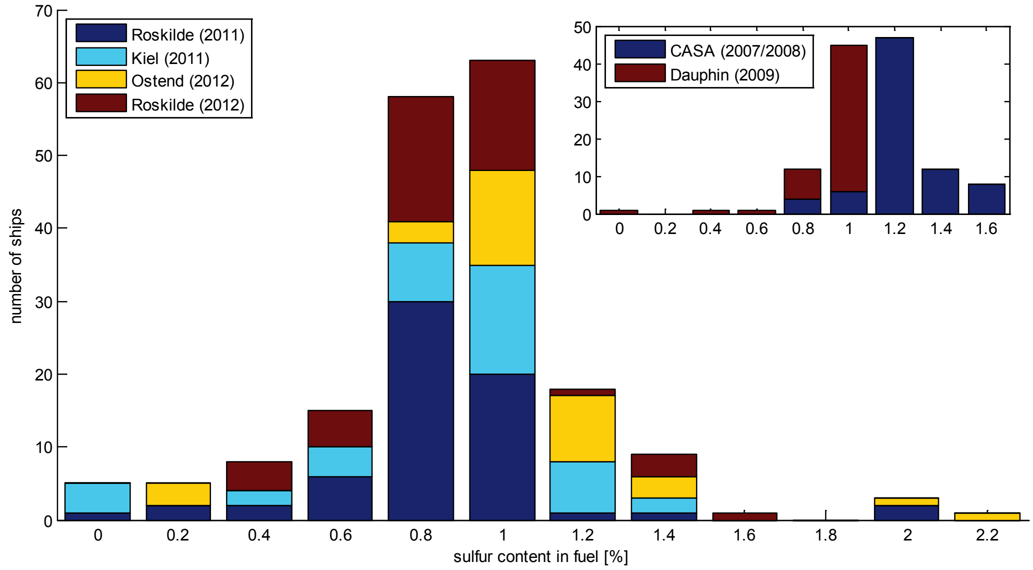

Figure 21. The frequency distribution of the FSC of 162 ships on the Baltic and North sea 2011/2012 (Beecken, 2014a), lower left, and the Baltic sea in 2007 (Mellqvist, 2010), upper right. The measurements were obtained from various airborne platforms. The SECA FSC limit until 2010 was 1.5 % and 1 % thereafter.

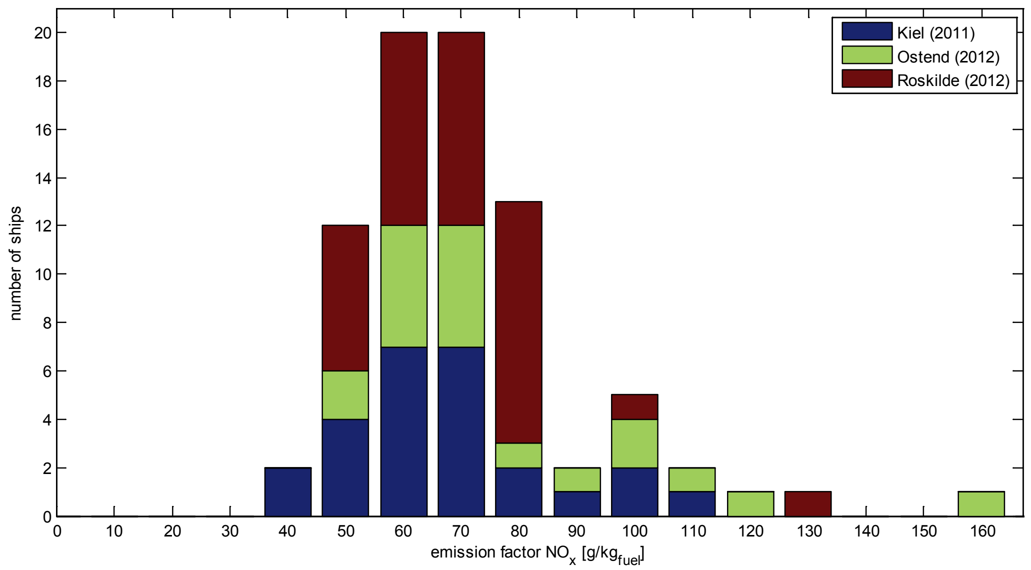

Figure 22. Frequency distribution of the mass specific NO_x emission of 162 ships on the Baltic and North sea 2011/2012 (Beecken, 2014a). The measurements were obtained from various airborne platforms.

5. Complementary particle measurements

In this project the main objective was to develop measurements tools for compliance measurements of ships. The main parameter to measure is FSC for which there is already a new EU directive at place. For the sniffer measurements of FSC it is assumed that all sulfur in the fuel is converted to SO_2. However, a fraction of the SO_2 will, either in the flue gas channel, or downwind in the plume, chemically transfer to SO_3^- and then further to sulfate (SO_4^{2-}).

Previous measurements on ship engines shows that only a few percent of the sulfur is in particulate form (Moldanova, 2009) and this has been confirmed by measurement downwind the plumes of the average particle levels from several ships by collecting filter samples over a full day (Alföldy, 2013), showing a particulate sulfur fraction of around 5 %. However, measurements directly on ship engines require that the plume is diluted in the same manner as when the flue gas is emitted in the atmosphere. This is a difficult task and the results appear rather dependent on dilution method, wherefore such results are associated with considerable uncertainty.

Another related uncertainty issue is the fact that there are several studies that indicate that the SO_2/CO_2 ratio as an indicator for the FSC yield values that are on the low side by 15-20 % (Balzani, 2014). Part, but not all, of this difference can be explained by particles.

All in all, considering the fact that particles is a potential uncertainty source for the FSC measurements and that particle emissions are very important for health related air quality issues, we carried out several activities within the IGPS project with focus on particle emissions.

First of all, instruments were acquired with the capability of conducting fast measurements of the number and size distribution of particles from 10 nm to 10 µm. These instruments correspond to an instrument which is based on electrostatic mobility named EEPS (Engine Exhaust Particle Sizer) and an instrument which is based on light scattering named OPS, see section 3.1. The data of number and size distribution are converted to mass, assuming unit density, and in this manner it is possible to quantify mass emission factors. In most cases the emitted particles are very small, 80 % of them smaller than 65 nm, which is typical for combustion processes. In the associated papers (Beecken 2014a, Beecken 2014b) detailed information about particle emission factors can be found with comparison to other studies

Secondly, given the few, rather uncertain measurements of the sulfate fraction in ship flue gases, we decided to investigate the sulfate fraction for single individual ships. A measurement method was developed to sample the fraction of sulfate in individual ship plumes, and presently a paper on this is in manuscript by Salo et al., according to the title given in section 1. The method, which has been applied from fixed sites, is based on using a large sampling chamber (150 l) (MEGA chamber) with a high flow through (300 ls^{-1}). When the ship plume arrives at the site the flow is stopped and then the volume of the chamber can be analyzed. The analysis of the sulfate is conducted by a Particle Into Liquid sampler (PILS) which is based on that particles pass through a supersaturated environment and function as vapor seeds. Thus the particles are grown to droplets which impact on a collector plate. The collector plate is continuously rinsed by a stream of distilled water taking up sampled particles. The sampled liquid is stored in small vials for later analysis by an ion chromatograph.

Together with the PILS the number size distribution of particles in sample chamber is measured using the EEPS and OPS instruments described above. A third particle instrument, an aethalometer, measures the mass concentration of soot from it's optical properties. In Figure 23 an example of such a measurement at the site Älvsborgsfästning is shown of a Stena rail ferry. The graph shows the mass fraction of sulfate and soot relative to the total mass as derived from the mass obtained from the EEPS instruments. The ratio between the sulfate and SO_2 concentration in the sampling chamber shows that 4 % of the sulfur is in particulate phase. This result is typical for our study and the data are hence consistent with earlier studies. This means that the potential uncertainty using the SO_2/CO_2 ratio as an indicator of FSC remains, and that the FSC numbers obtained with the IGPS-sniffer method potentially are 10-15 % too low. This should be investigated further but in the case of compliance monitoring it is not a big issue, since this will simply give non-compliers a 10 % discount, still within the estimated uncertainty.

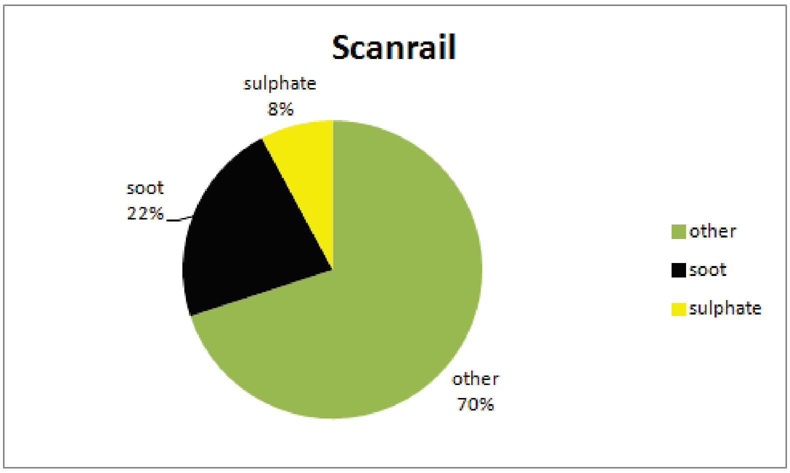

Figure 23. Example of the particle composition for a single ship, Stena Scanrail, measured using aethalometer, EEPS and PILS/IC in connection with the MEGA-chamber.

Another particle study that has been carried out within the project is to investigate the relationship between particle emissions and FSC. According to a reference study used by IMO (Buhaug, 2009) and a study by Alföldy (2013) there should be a distinct relationship between particle emissions in number and FSC. We have tried to find this relationship in our extensive data set by studying similar type of ships operating in a similar manner. The conclusion from this is that the variability between ships is rather large concerning particle emissions and in most cases this hides the relationship between particle emission and FSC. The IGPS- data hence indicates that particle emissions will remain to be a very important topic also after the introduction of the low sulfur fuel in 2015. This topic is discussed in the PhD thesis by Jörg Beecken.

6. Conclusion and outlook

Four unique tools for compliance measurements of gas emissions from ships have been developed, corresponding to (1) an automatic FSC sniffer for fixed measurements, (2) a FSC sniffer box for flight measurements, (3) an optical system for airborne measurements of FSC and (4) software that logs data, shows ships on a map and that calculates FSC and NO_x emission per kWh, and SO2 emission in g/s automatically. The software can be used on various instrument configurations.
The developed instruments have been tested successfully by real measurements, both from fixed sites (several thousand individual ship inspections) and airborne measurements from various platforms at the main shipping lanes in Baltic and North sea (several hundred ship inspections), with an estimated accuracy of around 20% at 1 % FSC.
Extensive certification work has been carried to be able to install the IGPS equipment for permanent use in airplanes. A request for approval to modify a Danish Navajo Piper was requested from the European Air Safety Agency (EASA) and which was issued in Dec 2014 (Supplemental Type Certificate 10051623). The preparatory work required extensive activities by a certified design and production organization and included design of dedicated IGPS instruments and equipment that were tested extensively regarding electromagnetic interference and magnetic properties. The certification will make it easier to install equipment in other planes. The Navajo Piper is presently certified to fly with a full IGPS system (FSC, NO_x and particles) and upon request this plane is available and ready to carry out compliance monitoring work.
As part of the project, particle measurements have been carried out for quality assurance and research purposes showing that the ships probably will emit considerable amounts of particles even after the introduction of cleaner fuel in 2015, in contrast to predictions.
The FSC data shows that around 95 % of the ships on the open sea have been using complying with the EU sulfur directive during the last years while the corresponding number is around 98 % for the ships entering the harbor of Göteborg. It hence appears that the historic 10 % price difference between 1 % and 1.5 % FSC has been low enough to prevent te shipping industry from using noncompliant fuel. The situation will be different during 2015 when the projected fuel price difference between 0.1 % and 1% FSC is 50 % or more.

To conclude the technique developed in this project is mature enough to become implemented on a full scale compliance monitoring program, both for measurements from fixed sites and airborne ones.

7. Acknowledgements

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8. References

Alfoldy B., ..., Mellqvist J., et al. (2013). Measurements of air pollution emission factors for marine transportation, Atmos. Meas. Tech., 6, 1777-1791

Balzani-Lööv, J M…. J. Mellqvist, et al. (2014). Field test of available methods to measure remotely SO_x and NO_x emissions from ships, Atmos. Meas. Tech., 7, 2597-2613, 2014, www.atmos-meas-tech.net/7/2597/2014/ doi:10.5194/amt-7-2597-2014

Beecken, J., Mellqvist, J., Salo, K., Ekholm, J., and Jalkanen, J.-P (2014a). Airborne emission measurements of SO2, NOx and particles from individual ships using sniffer technique, Atmos. Meas. Tech., 7, 1957–1968, , www.atmos-meas-tech.net/7/1957/2014/doi:10.5194/amt-7-1957-2014.

Beecken J. et al. (2014b), Emission Factors of SO_2, NO_x and Particles from Ships in Neva Bay from Ground-Based and Helicopter-Borne Measurements and AIS-Based Model, Atmos. Chem. Phys. Discuss., 14, 25931-25965 ,www.atmos-chem-phys-discuss.net/14/25931/2014/doi:10.5194/acpd-14-25931-2014

Berg, N., Mellqvist, J. et al. (2012). Ship emissions of SO2 and NO2: DOAS measurements from airborne platforms, Atmos. Meas. Tech., 5, 1–14, doi:10.5194/amt-5-1-2012 www.atmos-meas-tech.net/6/1777/2013/doi:10.5194/amt-6-1777-2013

Buhaug, Ø., J. Corbett, et al. (2009). "Second imo ghg study 2009." International Maritime Organization (IMO), London, UK 24.

Corbett, J., Winebrake, J., et al., e. (2007). Mortality from ship emissions: A global assessment. Published online in the American Chemical Society journal Environmental Science and Technology on 7 November .

Mellqvist, J and Berg N. (2010), Final report to Vinnova: IDENTIFICATION OF GROSS POLLUTING SHIPS RG Report (Göteborg) No. 4, ISSN 1653 333X, Chalmers University of Technology

Moldanova, J. et al. (2009), Characterization of particulate matter and gaseous emissions froma large ship diesel engine, Atmospheric Environment 43, 2632–2641

Commission, E. (2002). Quantification of emissions from ships associated with ship movements between ports in the European Community. Entec UK Limited

EMEP. (2002). Effects of international shipping on European pollution levels. Hämtat från http://www.emp.int/reports/dnmi_note_5_2000.pdf

Jalkanen, J.-P. (2009). A modeling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area. Atmospheric Chemistry and Physics (9), 9209-9223