CHALMERS

IDENTIFICATION OF GROSS POLLUTING SHIPS

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Executive Summary

The aim in this project is to develop and test techniques for the surveillance of gas emissions of SO_2 and NO_x from ships, to enforce new low sulfur regulation within the International Maritime Organization (IMO). The regulation puts a cap on the sulfur fuel content of 1.5% for ships traveling on the Baltic Sea, North Sea and the English Channel. It is driven by the fact that the emissions of sulfur and NO_x in Europe are projected to exceed the land based emissions by 2020. Low sulfur fuel is expensive and since surveillance methods for ship emissions are missing it is questionable whether the new legislation will be respected. This project has been funded by Vinnova, the provincial government of Västra Götaland and the Swedish Maritime Organization.

Two types of instrument systems have been employed: The *optical system* which measures SO_2 and NO_2 in the flue gases of the ships remotely, by spectral analysis of direct or reflected solar light. From this it is possible to derive the emission rate in *mass per time unit*. The other system, denoted the *sniffer system*, is based on the extraction of flue gases through a sonde into the instruments located either in the airplane or in the stationary measurement location. The concentration ratio of SO_2 to CO_2 is measured and this value is directly proportional to the sulfur fuel content in the ship plume. The system also measures the NO_x to CO_2 ratio from which the emission in *mass per fuel unit* is obtained and emission per kWh as given in legislation. The sniffer measurement requires direct contact with the ship plume. The optical system is unique although a similar technique is applied for global satellite monitoring. Similar systems to the sniffer one have been employed by other research groups for airborne measurements of ship emissions. However, their work has been limited to measurements of a few ships, as part of air pollution campaigns, with no focus on surveillance and legal enforcement.

The sniffer system, when operated in this project, had a measurement uncertainty of 15% for the sulfur content, with a negative bias of 5%, and a 21% uncertainty for the measurements of NOx emission versus axial power (g NOx/kWh). For the optical system the uncertainty is difficult to assess but roughly it corresponds to 30-50%. If one considers the overall uncertainty for SO_2, then the sniffer measurement has to be above 1.8% sulfur fuel content to e able to tell that a ship is a non complier with the IMO limit. For the NO_x emissions It is uncertain whether the measurement accuracy of the IGPS system is sufficient to check compliance with the Tier II regulation (20% reduction), but whenever it is decided to introduce environmental control areas for NO_x then the Tier 3 limit, with 80% reduction, will be rather easy to control.

In May and June 2007, stationary measurements with the Sniffer and optical system were carried out at Nya Älvsborgs fästning, an old fortress, on the north side of the ship channel into Göteborg. From these measurements, 220 ship plumes corresponding to 80 individual ships, were identified and analyzed. A large fraction of the ship plumes (50 out of 220) corresponded to plumes from ferry boats, predominately from *Stena line*. The measured data was compared to certain ships for which the sulfur fuel content was known. All in all, a good agreement was obtained when comparing the results to ships with known sulfur fuel values of 0.1%, 0.5% and 1.1%, respectively. The data for the passenger ferries, with known sulfur fuel content of 0.5%, showed that the Sniffer instrument on average, shows 10-15% too low values.

In August 2007 and 2008, respectively, the IGPS (Identification of Gross Polluting Ships) measurement system was installed in the CASA-212 airplane KBV-583 of the Swedish

coastguard and 20 test flights with a duration of 2 hours were conducted in the Baltic sea, east of the Island of Gotland, and between Denmark and Sweden. A total of 343 measurements were done with the sniffer instrument corresponding to 95 individual ships. The measurements were shared about equal between SO_2 and NO_x, being able to measure only these species one at a time in the experimental setup. On average the ships had a sulfur content of 1.28% and only 3 ships were with certainty above the IMO SECA limit of 1.5%, when considering the measurement uncertainty. The ships, on average, emitted 13 gNO_x/kWh (66 g NOx/kg fuel) and the ships seemed in general to comply with the Tier I IMO standard, considering the uncertainties. A thorough investigation of emission versus crankshaft speed has not been done, however.

The optical instrument was able to obtain fluxes in 66% of the ship measurements; 70 flux measurements [kg/h] of SO_2 or NO_2 were conducted on 35 individual ships. On average the SO_2 and NOx emission were 54 kg/h and 33 kg/h.

The Sniffer method has the disadvantage that one has to fly at low altitudes around 50-100 m, with the height depending on the meteorological conditions and the travel direction of the ships relative to the wind. However, already now we have demonstrated that this method works for surveillance, but by choosing optimal conditions for the surveillance we believe this method will become even more efficient. The optical flux measurements needs more research but the results show that it is possible to calculate kg/h SO_2 and NO_2 emissions from ships. Difficulties lie in multiple scattering in the plume and light reflection due to waves.

By combining the sniffer and optical measurements it is possible to obtain the fuel consumption per time unit for the ships measured. The results from this project show that oil products and crude oil tankers have a better fuel efficiency than ferries and ro-ro cargo ships.

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1. Introduction

The aim in this feasibility project was to develop and conduct field tests of new instrumentation that in the future can be used for cost effective surveillance of ship emissions of SO_2 and NO_x (NO_2 and NO). Such surveillance should be used to enforce the use of low sulfur oil and NO_x abatement equipment according to new conventions within the International Maritime Organization (IMO).

During 2006 and 2007 a measurement system was built together, which is denoted the IGPS system (Identification of Gross Polluting Ships). In the spring and early summer of 2007, stationary measurements of ships were conducted with this system downwind of the ship channel of Göteborg by analyzing the flue gases which blew across the station. From these measurements the sulfur fuel content of the ships was directly obtained. Between August 2007 and September 2008 the 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, east of the Island of Gotland, and between Denmark and Sweden.

The sulfur measurements were complemented by NO_x emission measurements in 2008. The work relating to the stationary measurements was financed by the provincial government of Västra Götaland (project P27477-1), as part of the larger project IGPS (Identification of Gross Polluting Ships) which mainly was financed by Vinnova and the Swedish Maritime Organization. This report covers the stationary measurements and airborne measurements. The IGPS system has also been utilized from a Dolphin helicopter on the North Sea and from a ground station in the shipchannel of the Rotterdam harbor. These measurements were conducted in an EU project, aimed at testing techniques for ship surveillance. An EU report from this campaign will be available during 2010.

2. Background

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 N_2, 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 (Jonson, Tarrason, & Bartnicki, 2000) 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 by (Corbett, Winebrake, & al., 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.

In contrast to fuels used on land, there are no sulfur limits for marine heavy fuel oils, these contain a high amount of sulfur relative to other fuels. 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 for the (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.

This topic has been recognized within *the International Convention for the Prevention of Pollution from Ships* (MARPOL), administrated by the IMO. In this convention there is an annex VI denoted *Regulations on Prevention of Air Pollution from ships,* which recently was ratified by more than 50% of the member states. This annex includes a global cap of 4.5% on SO_2 and contains provisions allowing for special *SO_x Emission Control Areas* (SECA) to be established with more stringent controls on sulfur emissions. In these areas, the sulfur content of fuel oil used on board ships must not exceed 1.5%. Alternatively, ships must fit an exhaust gas cleaning system or use any other technological method to limit SO_x emissions.

The Baltic Sea Area, the North Sea and English Channel are designated as a SECA in the Protocol, from the end of 2007.

In 2010 the maximum SECA sulfur level was decreased to 1% and then it will be further taken down to 0.1% in 2015. This is illustrated in Figure 1 were both a global cap and SECA limit of sulfur content is plotted. The coastal waters around USA and Canada will become an ECA from 2012 requiring that fuel used by the vessels is below 1.0 percent sulfur. Beginning in 2015, fuel used by vessels operating in these areas cannot exceed 0.1 percent sulfur. Beginning in 2016, NOx after treatment requirements become applicable.

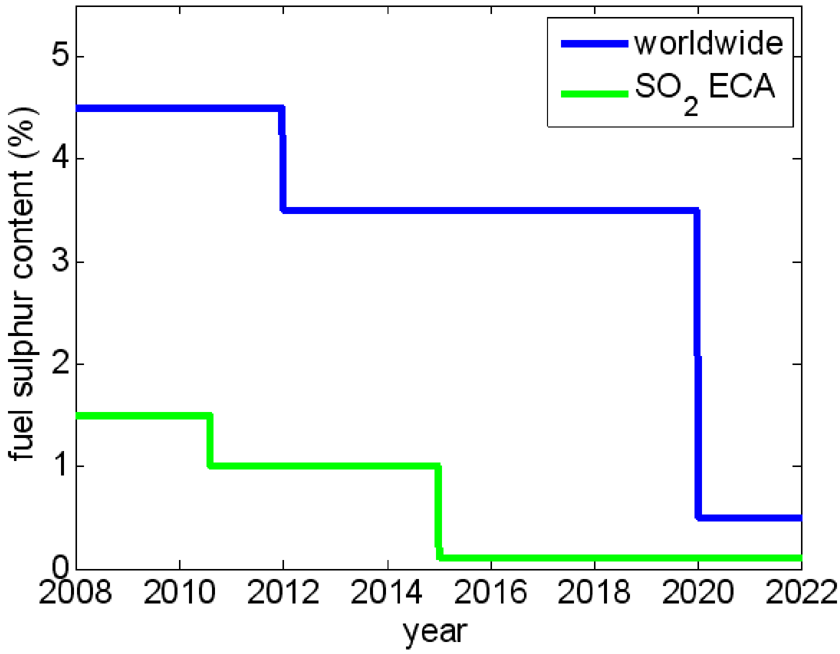

Figure 1. Fuel sulfur content (%) for the world and in SECA areas. Limits is going down and in 2020 the world wide limit is 0.5 % and in SECA areas 0.1%.

The IMO regulation regarding ship emissions is more complicated for NO_x than for sulfur. Since NO_x is produced from the combustion itself, IMO has chosen a limit that corresponds to the total emissions per axial power produced from the engine. 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 crankshaft speed of around 100 rev/min. These ships are fuel efficient (down to 160 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 crankshaft speed of around 500 rev/min and these engines are less fuel efficient (180-200 g/kWh) but on the other hand produce less NO_x compared to the slow stroke engines. An emission curve as a function of crankshaft speed has therefore been put forward by IMO, as shown in Figure 2. The IMO NO_x regulation requires all ships built after year 2000 to fulfill the IMO Tier 1 emission values, and by 2011 the emission for new ships should be even 20% lower, Tier 2. Also ships built between 1990 and 2000 will be forced to retrofit NO_x abatement equipment, if a cost effective upgrade is available. Tier 3 is not yet ratified but hopefully this limit will be valid in special NO_x emission control areas (ECA, environmental control area).

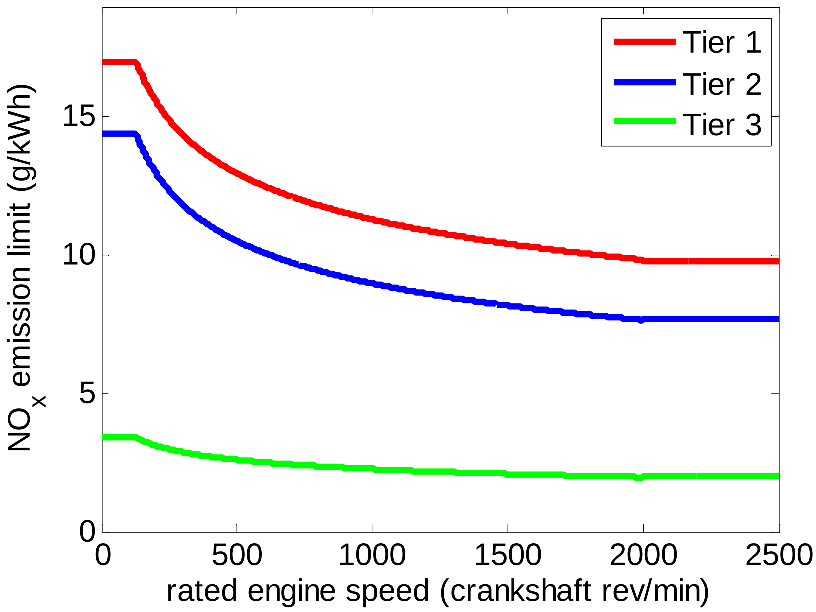

Figure 2: NO_x emission limits versus engine speed (rev/min) for ships built after 2000, Tier 1. Tier 2 corresponds to the limit for 2011 and Tier 3 for future foreseen limits for NO_x Emission Control Areas (2016).

Worth noting is that Russia and several other Baltic Sea states have not ratified Annex VI in the protocol, although obliged to adapt to it. The EU has added to the annex VI (Directive 2005/33) and included a legislation on the sulfur content in fuels requiring a maximum level of 1.5% S on ships trafficking the North and Baltic sea by 2006 and 0.1% sulfur for ships anchored longer than 2 hours in harbors. In addition, the Swedish Maritime Organization is running a program with reduced harbor fees and fairways for ferry boats that use sulfuric levels of 0.5%, respectively. There are also voluntary initiative, for instance by the Swedish pulp and paper industry which require there freighters to run on 1% sulfur in the fuel.

There is a considerable price difference between low and high sulfur oil and this difference will increase further with increasing demand for low sulfur oil. Since a large proportion of the costs for shipping relates directly to fuel cost, there is economic incitement to disobey the legislation and run with cheaper residual fuel containing high concentrations of sulfur. Shipping companies that disobey rules will hence have considerable economic advantages wherefore fair competition and quality shipping will not be promoted. The success of the environmental control areas will depend on how well they are respected, and this requires the possibility of controlling individual ships. Ships have the capability to carry different qualities of fuel in separate tanks and since the introduction of the SECAs, ocean going ships probably switch from high to low sulfur fuel when entering the North sea and Baltic sea. If this really occurs is today impossible to control. Authorities presently conduct inspections by stepping onboard the ships in harbors. This is rather expensive and only few such inspections are conducted. On international waters, there is no good way of controlling whether ships in real traffic are running on low or high sulfur oil. 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 ability to conduct checks of ships in real traffic from a distance, something like a *speed camera* but for emissions. If such a device could be used from an airplane, for instance on coast guard airplanes which are constantly in the air, this would provide an excellent tool for surveillance of ship emissions.

3. Overall method

The IGPS system surveillance system that has been developed and tested in this project is illustrated in Figure 3. One part is composed of an *optical system* measuring reflected solar light from the water surface, from which the concentration of SO_2 and NO_2 along the light path can be retrieved. The other part corresponds to a *Sniffer system*, in which the exhaust plumes from the ships are extracted trough a gas inlet (sonde) on the airplane and then further analyzed by onboard instruments for SO_2, CO_2 and NO_x.

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 lower itself to an altitude of 50-100 m to reach the ship plume and then a few transects through the plume will be conducted measuring with the sniffer system from which the sulfur fuel content 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 if above 300 ton. This can be transferred to a database for further usage, for instance by ship inspection authorities when choosing ships to enter onboard.

In this project the system has been used in airborne mode for about 40 flight hours, measuring about 70 ships on international waters around the coastline of southern Sweden, as described in section 4 and 5. The system has also been used in stationary automatic mode from a station downwind of the ship channel of Göteborg, as described in section 6.

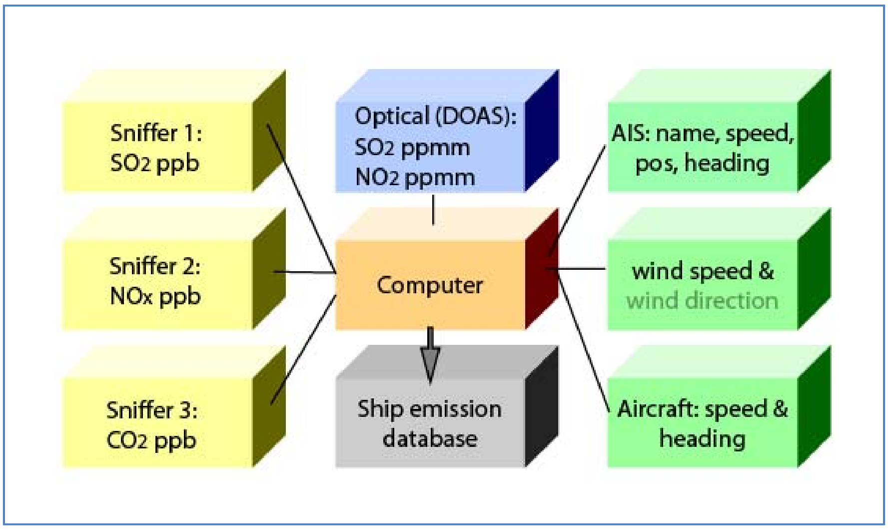

Figure 3. An overview of the IGPS surveillance system. The optical system measures reflected solar light to detect SO_2. If high concentrations are detected the sniffer system is used, sampling the plume of the ship and measuring the ratio of SO_2-to-CO_2. Information from the Automatic Identification System is merged together with the ratio measurements in a computer to be put in a database.

4. Airborne sniffer measurements

The sniffer measurements are carried out by extracting the plume of the ships into the instruments through a sonde 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 per produced axial power can be derived. Similar measurements have been conducted by other research groups both from the air (Parikhit, 2003) and the ground (Williams & al., 2006).

4.1. Hardware

The Sniffer system is based on three extractive techniques: *fluorescence* for SO_2, *chemiluminiscence* for NO_x and *nondispersive infrared absorption* for CO_2. These techniques are available in commercial instruments but in the IGPS system we have modified these instruments and integrated them in to a common system together with an AIS (Automatic identification system) for the identification of the ships, similar to (Peischl, Ryerson, & al., 2010). The system is shown in Figure 4 and for all instruments the rate of the sample flow has been increased to obtain a time response of about 1 s, by using stronger pumps and decreased cavity pressures. The time delay for the gas, before entering the gas analysis cells is around 3 seconds. All three instruments have pressure regulators at the inlets to compensate for varying flight altitude. The system has an arrangement for automatic calibration, by so called *standard addition*. A gas stream of about 1 lit/min, controlled by a massflow controller is then added into the sample gas flow of 9-14 lit/min, measured by a flow meter, hence diluting the calibration gas by about a factor of 10.
The air entering into the CO_2 instrument is first dried using a Nafion tube (Permapure). The instruments are controlled by a computer and a self developed software recording all measurement data for calculation of NO_x g/kWh and sulfur content. The data read from the instruments is the one that is processed by the software of each instrument. For instance are the Li-COR values corrected for H_2O interference.

In Figure 5 the actual setup in the CASA-212 aircraft is illustrated. The system was built into three aluminium boxes (Zarges) that were installed in the airplane. Due to weight and power restrictions it was not possible to measure simultaneously with the SO_2 and NO_x instruments. The outside air was extracted through a sonde that was installed in the cabin floor. Here also the exhaust from the NO_x instruments was going out since this instrument produces ozone.

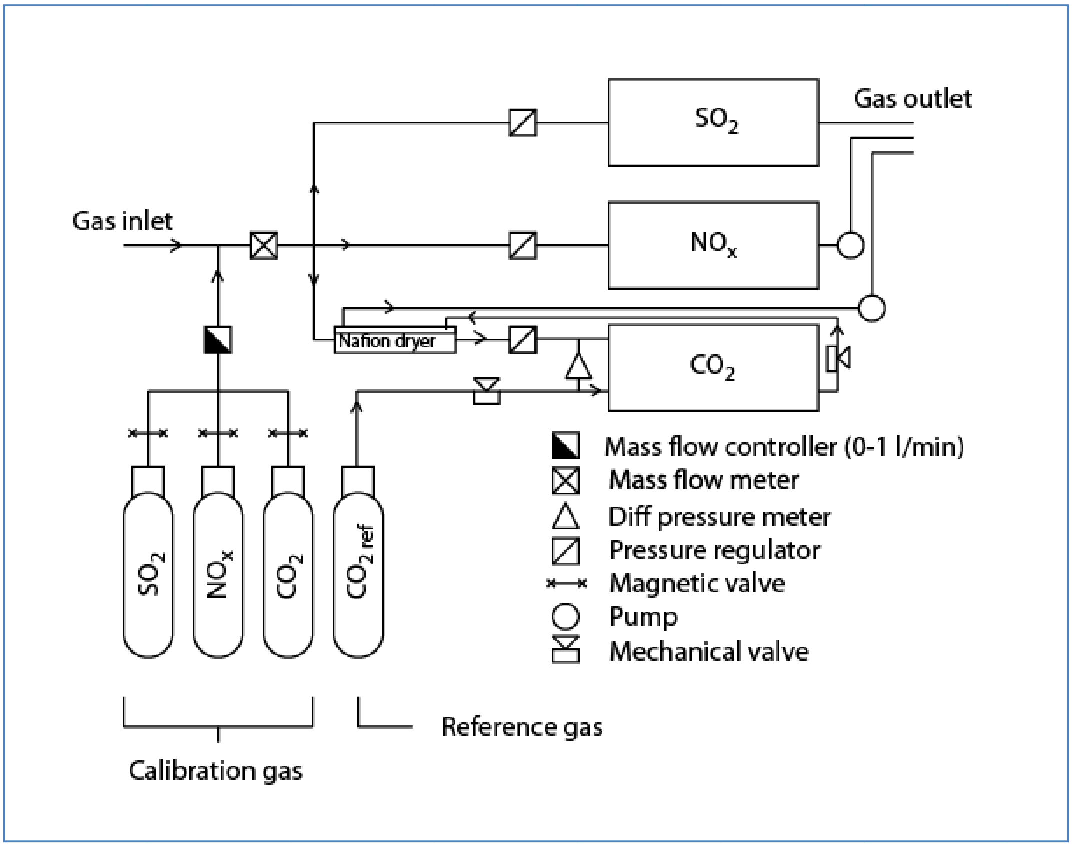

Figure 4. A flow chart of the Sniffer system.

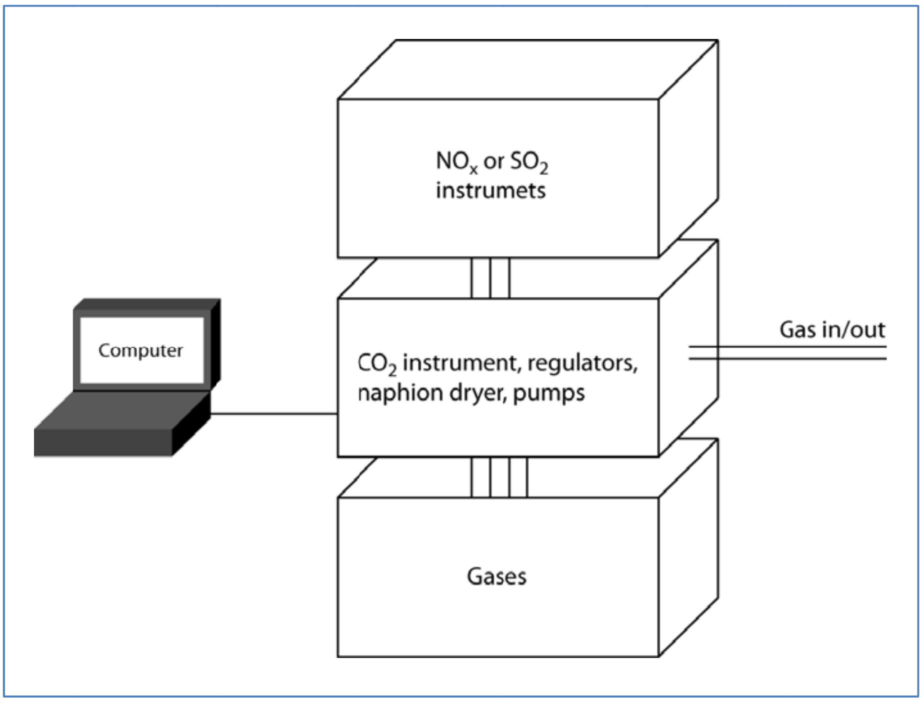

Figure 5. Airplane set up of the IGPS instrumentation in the CASA airplane. The NO_x and SO_2 were not measured simultaneously due to weight restrictions.

Some more details about the instruments are given below:

The CO_2 instrument (LI-COR – 7000) is an optical instrument that measures infrared absorption in two wavelength bands around 5 µm using a broad band light source and bandpass filters. In these wavelength bands the species H_2O and CO_2 absorb rather strongly. The instrument includes two measurement cells, one sample cell and one reference cell containing a known concentration of CO_2 and H_2O. The concentration in the former cell is obtained by calculating the light absorption due to CO_2 and H_2O by comparing the intensities in the two cells. The absorption is nonlinear (does not follow Beer lamberts law) and therefore the instrument has been calibrated by 13 gas concentrations when manufactured. Furthermore, when operated in the field in this project, the calibration curve has been corrected by a span gas calibration between two or three known gas concentrations. The H_2O obtained from the instrument is used by the LI-COR software to correct the CO_2 concentration values, since H_2O interferes weakly with CO_2. Even with this correction the impact of the water is about 1-2% (personal comm. Friedrich Lagier JRC). In the measurements in this project, Figure 4, the air was dried with a Nafion tube to minimize this effect. The inlet pressure to the LI-COR was set at 80 hPa. A reference gas of 364 ppm or 372 ppm was flowed into the reference cell (100 ml/min). As already described above the air entering into the CO_2 instrument was first dried using a Nafion tube (Permapure) to minimize the impact of H_2O interference. The amount of humidity removed by this device depends on the pressure and temperature conditions for the tube, and since these parameters varied, the amount of H_2O varied. This caused a variation in the absolute reading of the LICOR of about 2-5 ppm. The span was not affected however, and this is what is relevant for the ship measurements. The flow through the LI-COR instrument was around 5 lit/min and this instrument was very quick in responding, around 0.5 s.

The SO_2 instrument (Thermo Electron model 43*i* – Trace Level Enhanced) is based on a pulsed UV lamp, and a bandpass filter, that excites the SO_2 in the measurement cell by light in the wavelength region 220-230 nm. This causes the SO_2 to fluoresce around 300 nm and this is detected by a photomultiplier tube and then recalculated to a SO_2 gas concentration. Also other gases, such as NO and aromatic hydrocarbons reacts in similar manner and hence cause interference, Typically NO causes an interference of 2-3% of the NO reading (personal comm. Friedrich Lagier JRC), hence 100 ppm NO will be interpreted as 2-3 ppm SO_2. There is also an interference with aromatic hydrocarbons, especially since we, to augment the flow, have removed the so called “kicker”, a diffusion tube that absorbs aromatic VOCs before the gas enters the instrument. Since ship plumes have negligible levels of aromatic hydrocarbons this is a small problem, but more so if the measurements are conducted in the vicinity of a refinery. The SO_2 instrument is run with a large flow (about 5 lit/min) through the system to get a reasonably fast response. Even so, this instrument yields the slowest response of the ones used, i.e. about 2 s. The inlet pressure to the SO_2 instrument was set to 80 hPa.

The NO_x instrument (Thermo Electron model 42*i* – Trace Level) measures the sum of NO and NO_2. This is conducted, first, by flowing the gas through a heated stainless steel converter that converts NO_2 to NO. The NO is then measured by the chemiluminiscence reaction in which ozone is reacted with NO to excited NO_2 (NO_2*), which emits green light (luminescence) that can be measured by a photomultiplier and which is proportional to the concentration. The response of the instrument is favored by low pressure and is affected by humidity. The inlet pressure to the NO_x instrument was set to 50 hPa. This increased the sensitivity of the instrument and the response time to about 0.5 s.

4.2. Calibration

The calibrations have been carried out in two manners, by *standard addition* (adding a subflow of a gas standard to the main flow of the instruments) and by *standard replacement* (replacing the whole flow by a gas standard). The CO_2 instrument was calibrated on the ground before each set of 2 to 3 days of flight measurements, by standard replacement, while for the SO_2 and NO_x instruments the original calibration settings were kept. All instruments were calibrated by standard addition during the airplane missions, with exception for most of 2007 when only CO_2 could be calibrated in this manner and SO_2 was calibrated solely on the ground.

Standard replacement is the most precise calibration, but it requires considerable amount of gas being used. In addition, since the calibration gas is dry the influence of water is not captured by these calibrations. Tests show that when calibrating in dry and humid air, respectively, a 1-2% lower CO_2 reading is obtained with the LI-COR and a 3-7% lower NO_x reading is obtained with the chemiluminiscence instrument (pers comm. Friedrich Lagier).

Standard addition, adding 1 lit/min of gas standard into the mainflow of approximately 10 lit/min, has the advantage that most of the background parameters in the measurement situation, such as humidity and background species composition, are kept the same, since only 10% of the gas is replaced. It also reduces the amount of gas needed for the calibration. The reading of the instrument when calibrating is shown in the equation below. The background concentration of the gas species may have significant impact on the gas reading, since the background flow is 10 times larger than the calibration flow. This causes an uncertainty, especially when calibrating for species such as CO_2 which has a high background concentrations.

$$Gas\ reading = \frac{1}{flow}\left(flow_{cal} \cdot concentration_{cal} \cdot + flow_{background} \cdot concentration_{background}\right)$$

When calibrating sniffer instruments one, typically, uses two gases or more to investigate the span factor of the instruments, i.e. how the instruments respond to changes, and how large the offsets in the values of the instruments are. However, in the ship measurements only the span is of interest, since one wants to measure the extra gas in the plume above the background, and it is unimportant if the absolute values are correct. For NO_x and SO_2 the background is low compared to the typical amount in the ship plumes, 1 ppb and 100 ppb, respectively, while for CO_2 it is high, 370 ppm and 20 ppm, respectively. For NO_x and SO_2 one therefore, typically, uses a zero gas (clean air) as one of the two calibration gases while for CO_2 two gases around the background value are being used. The number of calibration gases used depends on the linearity of the instrument. The SO_2 fluorescence and NO_x chemiluminiscence techniques are known to be linear, and tests we have conducted show linearity at least up to 500 ppb, which is above the range of the measurements in this study. The non dispersive CO_2 technique is in contrast quite nonlinear and the manufacturer LI-COR for this reason carries out a factory calibration using up to 13 different concentrations, as earlier described. In this study we therefore assume that the calibration by LI-COR corrects for most of the nonlinearity and that the instrument therefore is linear in the measurement range.

In Table 1, the secondary calibration gases used in this study are shown. The concentrations of these were derived from the primary standards also shown in the table. The uncertainties of the secondary calibration gases are estimates based on the analysis procedure when deriving the concentrations from the primary gases. An uncertainty of 0.5 ppm has been assumed in the CO_2 analysis, and 30 ppb for SO_2 and NO_x from the variability from several analyses. The primary CO_2 gas standards were lent from the US agency NOAA (National Oceanic and Atmospheric Administration, acknowledgement to Tom Ryerson) and were referenced to the NOAA/ESRL/Global Monitoring Division standards before the field campaign. For SO_2 and NO_x the main standards correspond to gases from the EU Joint Research center in ISPRA that were compared against our calibration gases one year after the campaign (acknowledgement to Friedrich Lagier).

To save weight and space in the air, the calibrations for SO_2 and NO_x were conducted without zero gas, using one calibration span gas that was diluted to 30-40 ppb for both gases in the standard addition procedure. For SO_2 we relied on the fact that the background concentration over the ocean should be less than 1 ppb, hence the background air as zero gas, while for the NO_x instrument a so called prereactor[1] was used to obtain the zero values.

For the CO_2 instrument, two gas concentrations were used to obtain the span factor in the last part of the campaign in 2008. At other occasions only one CO_2 calibration gas was utilized. To obtain the calibration gas reading in the standard addition, as shown in the equation above, the background concentration value measured by the CO_2 instrument was taken as the true background. This is not true since this value also relies on the calibration and we estimate that this procedure causes a 3-5% added uncertainty in the span value of the CO_2 instrument, assuming 5-10 ppm uncertainty in the background value.

The calibration factors, by which the measured ship plume values have been multiplied with, are shown in Table 2, together with the calibration gases used. Most of these calibrations were carried out by standard addition. The factors correspond to the corrections to apply to the measured value relative to the background value. Noteworthy, is that there is about 7% variability in the obtained correction factors for a certain flight, for all species. We do not understand this variability but it could be caused by varying conditions along the flight transect (humidity, temperature) or be of system specific nature, such as variability in the gas flow or instrument drift. We have conducted a relatively large number of CO_2 standard replacement measurements in a parallel project, in Rotterdam in 2009, and here the variability was considerably smaller. Hence, it seems that the variability is related to the standard addition calibration procedure.

In Table 2 there are two occasions when it was possible to conduct both standard replacement and addition calibration for the same flight. On August 21, 2008, the standard replacement and addition yielded 0.95 and 1.029±0.05, respectively, while on August 22 the correction factors were 0.992 and 0.997±0.09, respectively. Again there is considerable variability in the standard addition values, but all in all the values seems to agree within 5-7%. The NO_x correction is surprisingly large in the beginning of the measurements 2008, this we do not understand. Since this is a feasibility project we had relatively limited focus towards calibration issues in the beginning of the project but this improved later on, and the IGPS system was therefore best calibrated during the last three days of the campaign in August, 2008.

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[1] In the prereactor of the NO_x instrument all NO is converted to NO_2 by ozone before entering the chemiluminiscence chamber. Since only NO is measured this will provide a zero reading. A caveat here is that the gas does not go through the catalyst that converts NO_2 to NO and will not reflect this part of the system.

Table 1. The secondary calibration gases used in the campaigns, together with the primary standard gases from The primary CO_2 standard gas mixtures were referenced to NOAA/ESRL/Global Monitoring Division standards and the SO_2 and NO_x to JRC-Ispra standards.

	Analys	Comment
CO_2	376.48±0.01 ppm	Primary CO_2 standard, referenced to NOAA
CO_2	422.40±0.02 ppm,	Primary CO_2 standard, referenced to NOAA
SO_2	83.5 ppb ±2%	Primary standard SO_2, referenced to JRC-ISPRA
NO_x	210 ppb ±1.5%	Primary standard NO_x, referenced to JRC ISPRA
CO_2_1	3919 ppm±1.7%	Secondary calibration gas used
CO_2_2	364 ppm±0.15%	Secondary cal gas used, also reference cell gas
CO_2_3	396.5 ppm±0.15%	Secondary calibration gas used
CO_2_4	534.86 ppm ±1%	Secondary calibration gas used
CO_2_5	655 ppm±1%	Secondary calibration gas used
SO_2	420 ppb±7%	Secondary calibration gas used
NO_x	435 ppb ±7%	Secondary calibration gas used

Table 2. Average correction factors, obtained from calibrations in the airplane and calibration gases used. Most of these were obtained by standard addition while a few were conducted by standard replacement.

Date	SO_2 std add	SO2 ppb Cal gas	NO_x std add	NOx ppb cal gas	CO_2 std add	CO2 ppm Cal gas	CO_2 std repl	CO2 gas ppm
07-08-21	0.92±0.07**	420			0.780±0.09	3919*		
07-08-22	1.04±0.13**				0.820±0.06	3919*		
07-09-18	1.07±0.06	420			1.076±0.03	3919*		
08-08-11			1.220±0.06	435	1.144±0.07	536		
08-08-12			1.515±0.07	435	1.380±0.11	536		
08-08-13	1.043±0.05	420			1.093±0.06	536		
08-08-14	1.007±0.07	420			1.177±0.07	536		
08-08-21	1.043±0.08	420			1.029±0.05	536,655	0.956	364, 396.5
08-08-22			1.098±0.09	435	0.997±0.09	536,655	0.992	364, 396,5
08-08-23			1.098±0.07	435	1.000±0.08	536,655		
08-08-24			1.128±0.06	435	1.062±0.06	536,655		

*The calibration gas flow was 0.05 lit/min compared to 1 lit/min for all other cases **Calibration from ground prior to flight.

4.3. Method

The sniffer measurements are carried out by extracting the plume of the ships into the instruments through a sonde, gas in/out in Figure 5, and the ratio between SO_2 and CO_2 and NO_x and CO_2, respectively, is consequently measured. The aircraft has to be inside the exhaust plume of the ship to be able to measure with the sniffer and the flight altitude is usually between 50 to 100 meters. When a ship has been targeted a flight path is chosen; for ships moving towards the wind an "S" turn approach with multiple turns is favorable starting about 5 km downwind and then moving towards the ship. This makes it possible to obtain multiple transects trough the plume without measuring the own exhaust. The flight speed used has been the lowest possible cruise speed of the CASA-212 corresponding to 65 m/s, to increase the time in the plume.

The exhaust plume from a ship, points in various directions relative to the ship depending on the meteorological conditions. The exhaust plume follows the apparent wind[2], which has a direction and speed which is the combination of the true wind and the wind created from the speed of the ship, Figure 22. If the apparent wind is low, which is the case for ships traveling with the wind, the plume rises at a steeper angle from the ship and is therefore easier to find at higher flight altitudes (150 m). If the apparent wind speed is high, which is the case for ship traveling against the wind, the plume tends to drop behind the vessel and stay at low altitude for a long time, i.e. 50 m altitude also at 3000 m distance. For sniffer measurements knowledge about the apparent wind is of less importance than for the optical method. The apparent wind is therefore discussed more in detail in section 5.

The installation of the sniffer system is shown in Figure 6. The instruments are carried in aluminum boxes. A sonde is pushed out through a hole in the airplane floor, sampling the air 50 cm below the airplane.

Figure 6. Installation of the sonde for the Sniffer measurement system (Photo J-O Yxell). The sonde is pushed out through a hole in the airplane floor, sampling the air 50 cm below the airplane. Calibration gas is flown out to the entrance of the sonde.

An example of an airborne sniffer measurement with the CASA 212 airplane on August 21 2008 is shown in Figure 7, corresponding to information from the automatic identification system (AIS) of the airplane. The position and flight track of the airplane is shown as the large black circle and the black dotted lines. Shown is also the ship Eagle Turin (triangles) and its traveling direction with green lines. The sniffer measurement showed a fuel sulfur content of 1.37%. The ship has also been measured with the optical system with a corresponding SO_2 emission of 53 kg/h. By combining the sniffer and the optical measurements one can also calculate that the fuel consumption of the ship is 2 T/h.

[2] The apparent wind corresponds to the wind one feels onboard of a moving ship.

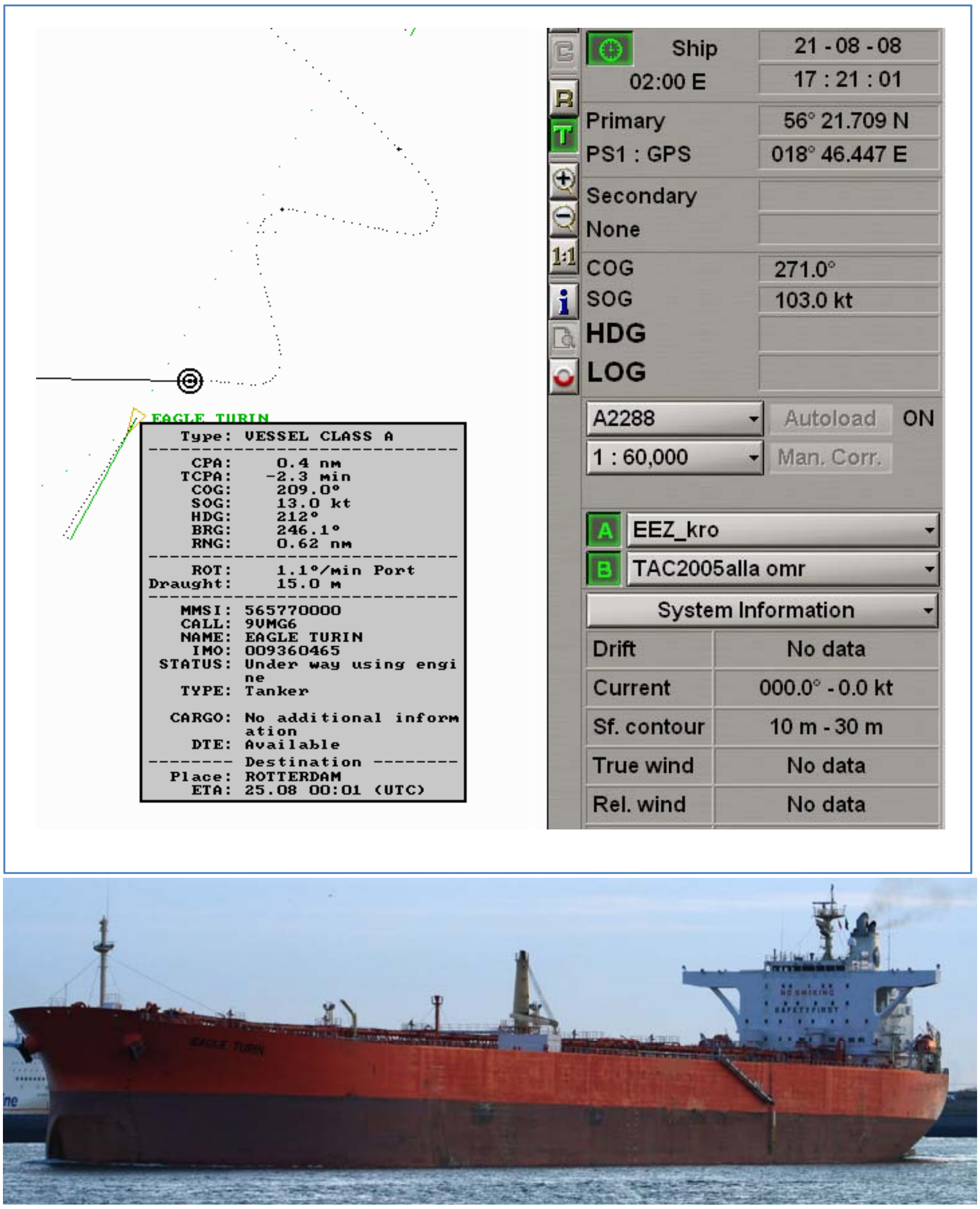

Figure 7. (Upper) Information from the automatic identification system (AIS) when conducting airborne measurements with a CASA airplane from the Swedish coastguard, August 21 2008. The position and flight track of the airplane is shown as the large black circle and the black dotted lines. Shown is also the ship Eagle Turin (triangles) and its traveling direction with green lines. (Lower) A photo of the oil tanker Eagle Turin.

The main principle for the sniffer measurements conducted here, is the assumption 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, Eq. 1 and Eq. 2. The amount of carbon in the fuel is about 87% for both residual fuel and diesel oil, and hence the sulfur the S to C ratio normalized with 87% directly corresponds to the S to fuel content, (Tuttle & al., 1995). Similar measurements have been conducted recently in the ship channel of Houston by (Williams & al., 2006). Other sulfur species in the exhaust, except SO_2, includes SO_3 and SO_4 particles but a recent study (Moldanova & al., 2009) indicates that these species only correspond to a few percent of the sulfur. For carbon in the exhaust, except CO_2, both gaseous CO and particulate phase and is present, but the same study as above shows that particulates correspond to less than a percent of the carbon, while another study shows that CO is less than 0.05% (Williams & al., 2006). This indicates that the main assumption for the sniffer measurements is fairly robust.

$$S\ in\ fuel = \frac{S\,[kg]}{fuel\,[kg]} = \frac{\sum SO_2\,[ppb]\cdot V\cdot M(S)/_{1000}}{\sum CO_2\,[ppm]\cdot V\cdot M(C)/_{87\%}} = \frac{\sum SO_2\cdot M(S)}{\sum CO_2\cdot 1000\cdot M(C)}\cdot 87\% \qquad \text{Eq.1}$$

$$\%S\ in\ fuel = \frac{\sum SO_2}{\sum CO_2}\cdot 0.232 \qquad \text{Eq.2}$$

From the NO_x to CO_2 ratio, that is also measured, the emission of NO_x per mass of fuel is obtained, Eq.3 and Eq 4. To convert the NO_x to mass we assume that all NO_x corresponds to NO_2, since this is what is done in the IMO legislation. To convert the NOx emission value to NO_x emission per kWh, as given in the legislation, the fuel efficiency of the specific engine has to be included. This is done through the brake specific fuel consumption which corresponds to the amount of fuel burnt per obtained axial power, Eq. 5. Slow speed engines, typically used by large ships (oil tankers, container vessels), have values between 160 to 170 g/kWh when new and tested in favorable conditions. The medium stroke engines, such as the passenger ferry Stena Danica, have higher values on the other hand, about 180 g/kWh (Tuttle & al., 1995). In reality, the fuel efficiency is worse; for instance in a recent study in Rotterdam a ferry with medium stroke engines, which was supposed to have 180 g/kWh efficiency, had a fuel efficiency of about 250 g /kWh (pers. comm. J.P Jalkanen). Here we have used a value of 200 g fuel per kWh of axial power for all ships corresponding to an assumed average for the fleet, based on the experience of other work(Jalkanen, 2009).

$$\frac{NO_x\,[g]}{fuel\,[kg]} = \frac{\sum NO_x\,[ppb]\cdot V\cdot M(NO_2)}{\sum CO_2\,[ppm]\cdot V\cdot M(C)/_{87\%}} = \frac{\sum NO_x\cdot M(NO_2)}{\sum CO_2\cdot M(C)}\cdot 87\% = \frac{\sum NO_x}{\sum CO_2}\cdot 3.48 \qquad \text{Eq.3}$$

$$specific\ fuel\ oil\ consumption = \ ^{200g\ fuel}/_{kWh} \qquad \text{Eq.4}$$

$$\frac{NO_x\,[g]}{kWh} = \frac{NO_x\,[g]}{fuel\,[kg]}\cdot\frac{0.2\,[kg]\,fuel}{kWh} \qquad \text{Eq.5}$$

In Figure 8 an example of three flight transects across the plume of the ship Betis is shown, with values obtained with sniffer corresponding to above ambient for SO_2 in ppb and for CO_2 in ppm. To obtain the sulfur fuel content of the ship the gas in the plume for each species is first integrated, instead of comparing individual values. The integration is done by summing up all values that are above the background in the plume, corresponding to the grey area in the figure. The background is here calculated as a linear function between the average of the two pink areas surrounding each plume. The reason for integrating is that the different instruments have different response times as can be seen in Figure 8; the CO_2 plumes are much narrower than the SO_2 ones.

The integrated values are corrected with the calibration factors in Table 2 and then Eq.2 is applied. In the case of the ship Betis this procedure resulted in obtained fuel sulfur contents of 1.88%, 2.05% and 2.02% (average 1.98%), respectively, for the 3 plumes in Figure 8. Hence this ship very likely used oil above the IMO SECA limit.

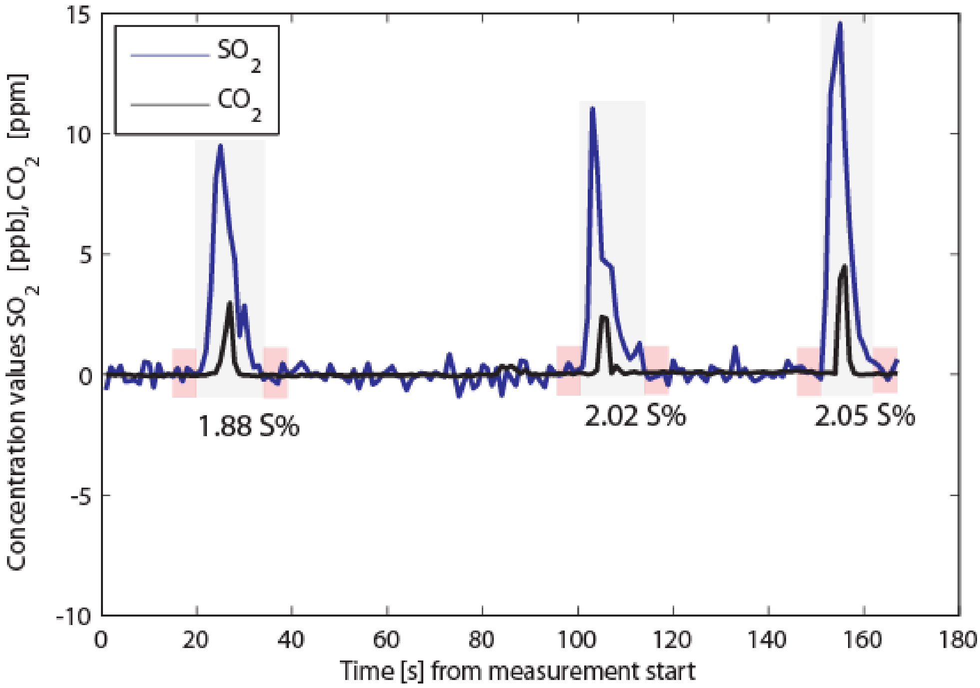

Figure 8. (Upper) Three transects across the plume of Betis are shown on August 24 , 2008 at 15:20, together with the obtained sulfur values. The concentration values are above ambient. (Lower) A picture of the ship.

4.4. Results of the sniffer measurements.

In this study data for 95 ships have been collected, based on 342 individual airborne sniffer measurements taken with the CASA 212, as shown in appendix I. The data was collected both 2007 and 2008 on the international shipping lanes surrounding Sweden. For this data set the fleet average sulfur content in the fuel is 1.28% (25.6 g/kg fuel) and NO_x emission is 13.14 gNO_x/kWh (65.7 g/kg fuel). Below in Table 3 an extract from appendix I of the high emitters of SO_2 and NO_x are shown. More discussion about these data can be found in section 7 and below. Our data can be compared to measurements outside Houston, in 2008, (Williams & al., 2006) showing emissions of NO_x of around 60 g/kg for container vessels and 80-90 g/kg NO_x for bulk freight carriers and oil tankers. In the same papers the average sulfur emissions are 1.4% (28 g SO_2/kg fuel).

Table 3: Draft of measurements done 2007-2008 both sulfur fuel content and gNO_x/kWh.

Ship Name	Flag	Ship Type	gNOX/kWh	Sulfur fuel content
VITTA THERESA	Denmark	Chemical and Product Tankers		1.82%
STADIONGRACHT	NETHERLANDS	CARGO		1.62%
ENGLISH BAY	HONG KONG (CHINA)	BULK CARRIER		1.57%
ENERGIZER	PANAMA	OIL PRODUCTS TANKER		1.65%
MONTEGO	GREECE	OIL PRODUCTS TANKER		1.56%
BALTIC BREEZE	SINGAPORE	VEHICLES CARRIER		1.55%
WEC MAJORELLE	CYPRUS	CONTAINER SHIP		1.67%
AMUR 2514	RUSSIA	CARGO		1.65%
SEABOURN PRIDE	BAHAMAS	PASSENGERS SHIP		1.69%
ICELAND CEMENT	BAHAMAS	CEMENT CARRIER		2.28%
MASTERA	FINLAND	CRUDE OIL TANKER		1.62%
BETIS	HONG KONG (CHINA)	BULK CARRIER		1.98%
FINNSTRAUM	NORWAY INTERNATIONAL REGISTER	OIL/CHEMICAL TANKER	17.5	
HANS LEHMANN	ANTIGUA & BARBUDA	CARGO	16.2	
URANUS	ANTIGUA & BARBUDA	CONTAINER SHIP	16.42	
FINNMAID	FINLAND	FERRY	15.2	
TRANSEUROPA	GERMANY	RO-RO CARGO	15.7	
GRIGORIY ALEKSANDROV	RUSSIA	BULK CARRIER	15	
MARE ACTION	MARSHALL ISLANDS	OIL/CHEMICAL TANKER	20.1	
KANG HONG	HONG KONG (CHINA)	BULK CARRIER	18.2	
JORK	CYPRUS	CONTAINER SHIP	15.5	

The sulfur content in the fuel is shown in Figure 9 with respect to ship type and in Figure 10 with respect to measurement day. As can be seen there are only a few ships exceeding 1.5%.

Regarding ship type it looks like the bulk carriers and oil ships tend to be around 1.5% while cargo ships are more spread out in sulfur fuel content, i.e. 0.53 – 1.65 %. As can be seen in both figures the highest measurement was 2.28% and this sulfur fuel content was measured for the cement carrier Iceland Clement from Bahamas, home port Nassau. A measurement transect of this ship is shown in Figure 11. The second largest emitter in the data set is the Bulk carrier Betis, for which three measurements was already shown in Figure

8. This ship is a 225 m long bulk carrier from Hong Kong (single engine of 9230 kW, 106 RPM). The time data in Figure 10 indicates a similar sulfur fuel content and spread on all dates, and this indicates that the calibration corrections worked reasonably well. Before the correction the 2007 data were actually considerably lower on several dates.

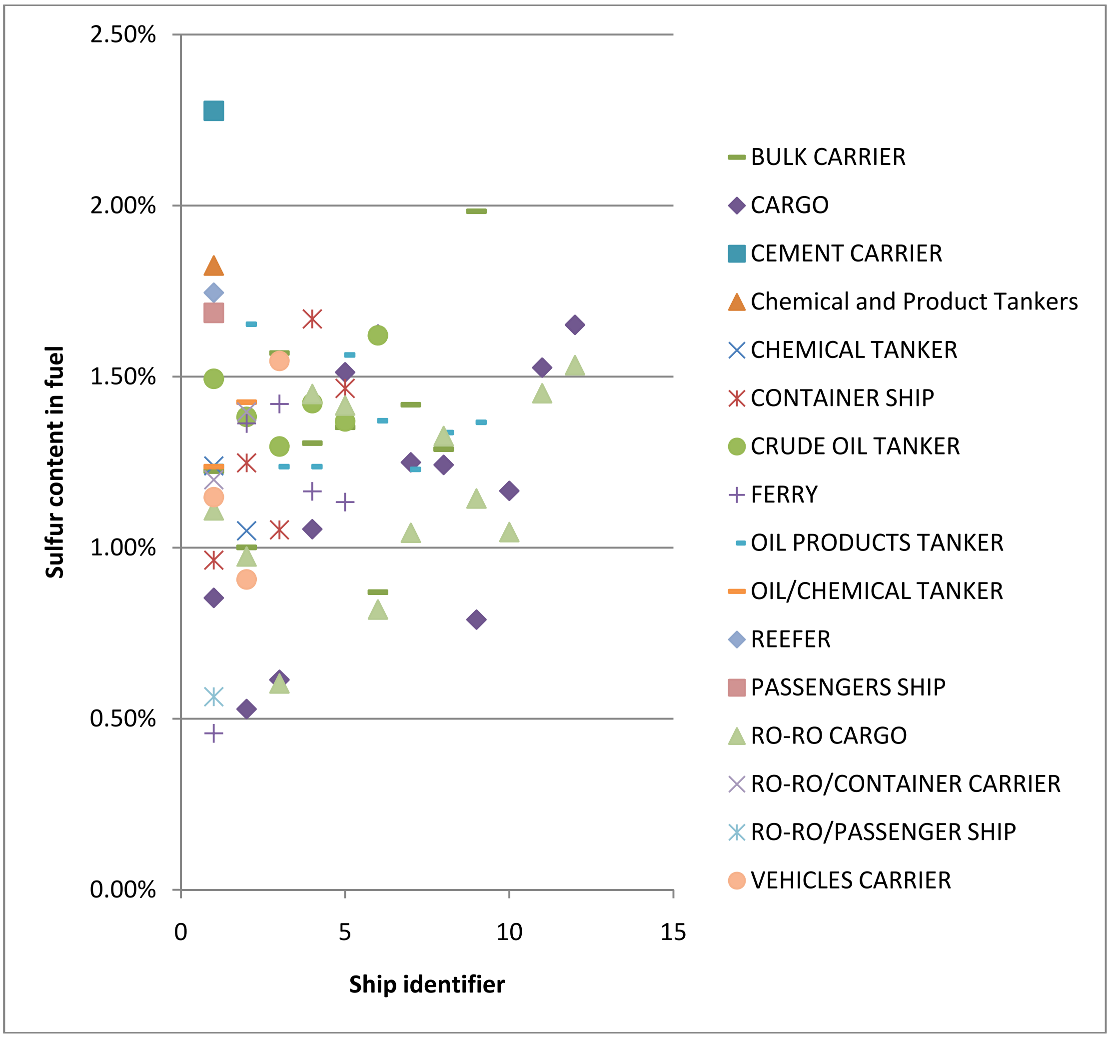

Figure 9. Sulfur fuel content for different ship types derived from the IGPS sniffer system.

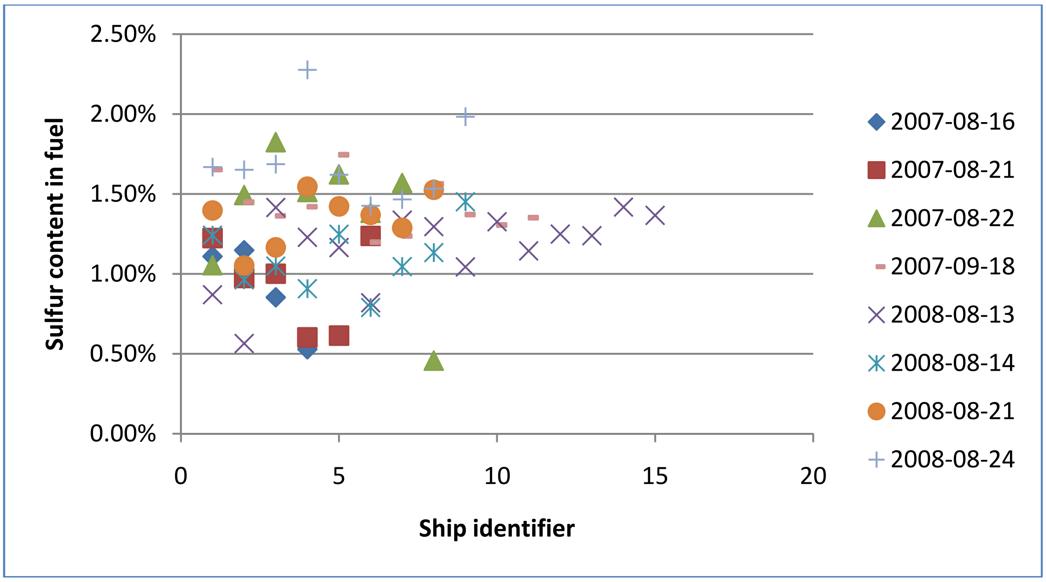

Figure 10. Sulfur fuel content for different measurement days derived from the IGPS sniffer system.

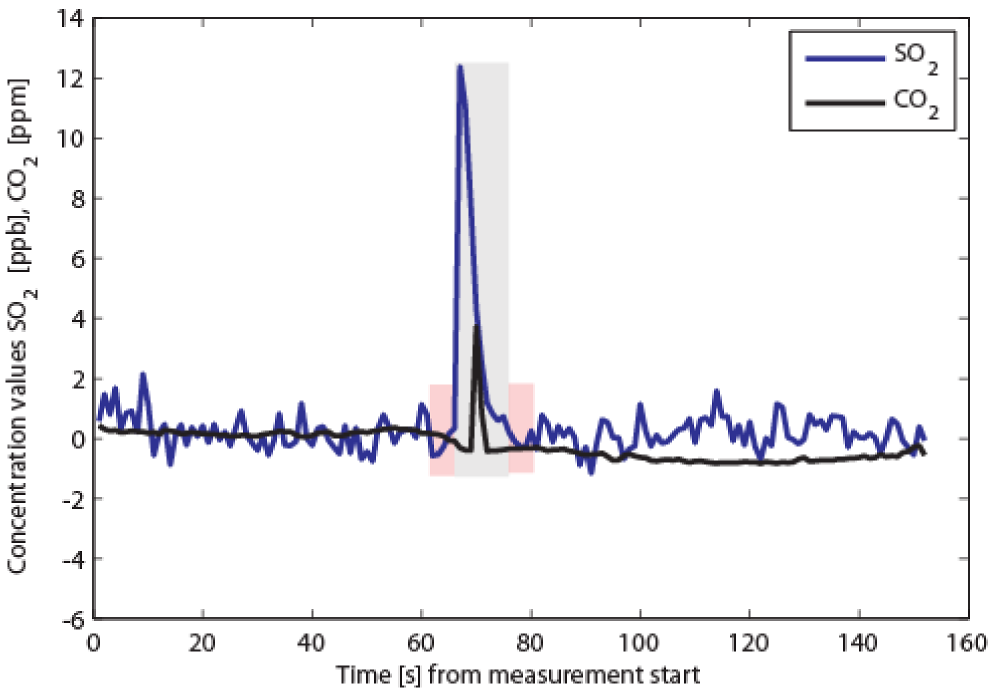

Figure 11. A flight transect across the plume of the cement carrier Iceland Clement, August 24 at 13:40. This ship had the highest sulfur content of all measured ships, i.e. 2.28%. The concentration values are above ambient.

NO_x emission data from the airborne sniffer measurements are shown in Figure 12 and Figure 13 for different days, for the emission units gNO_x/kg fuel and gNO_x/kWh, respectively. In the latter case a standard engine efficiency of 200 g fuel/kWh was assumed for all measurement, as discussed in section 4.3. The average emission is 13.14 gNO_x/kWh (65.7 g/kg fuel). In Figure 14 the individual ship emissions in gNO_x/kWh for different ship types and build year is shown. As can be seen there are two ships with very low emissions corresponding to the ferry Stena Carisma with a gas turbine engine and the the oil/chemical tanker Finnstraum (Wärtsila 9 L 38, 5940 kW/600 rpm), but the reason for this could be that they run at reduced speed etc, and this will be further investigated.

Another ship of interest is Kang Hong, Figure 15, which has an emission of 18.6 gNO_x/kWh (93 g/kg fuel) and low variability between the two measurements, 18.4 and 18.8 gNO_x/kWh. This ship is hence just at the Tier 1 limit of17 gNO_x/kWh, see section 2. Noteworthy, is that this emission is similar to measurement of bulk carriers 87 kg NO_x / kg fuel) from another study in Houston (Williams & al., 2006).

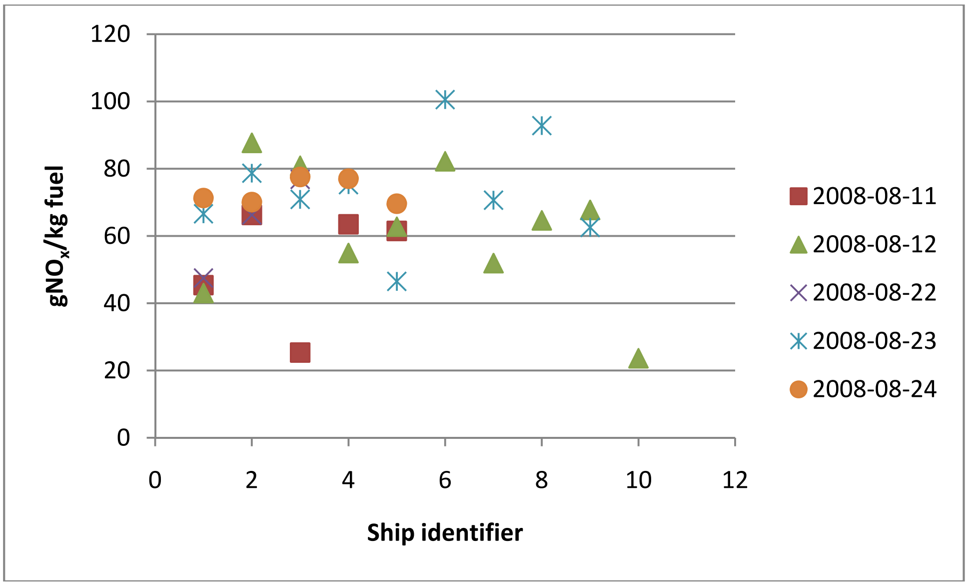

Figure 12. Individual ship emission data in gNO_x/kg fuel with respect to measurement days, derived from the IGPS sniffer system.

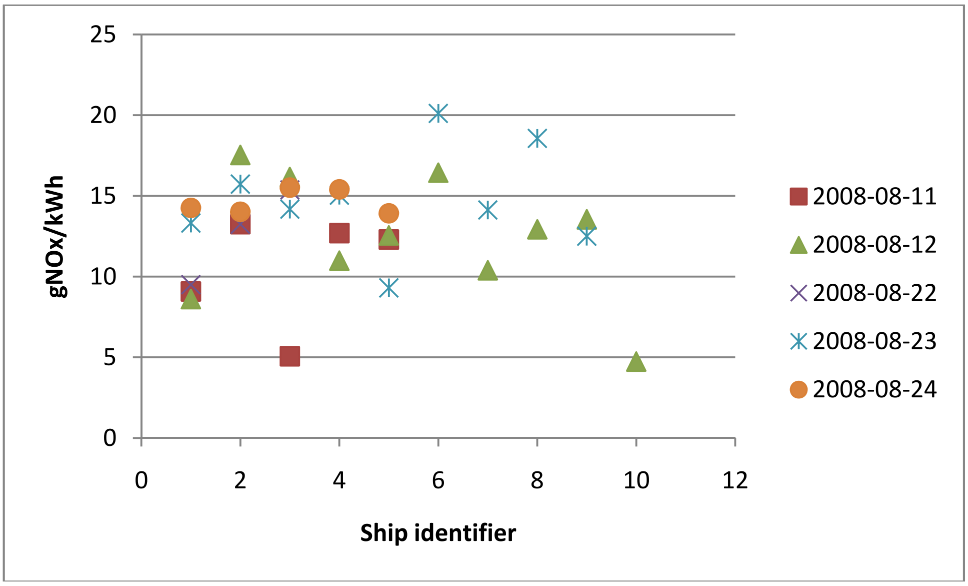

Figure 13. Individual ship emission data in gNO_x/kWh of axial power with respect to measurement days, derived from the IGPS sniffer system. Here we assume a fuel efficiency of 200 g/kWh.

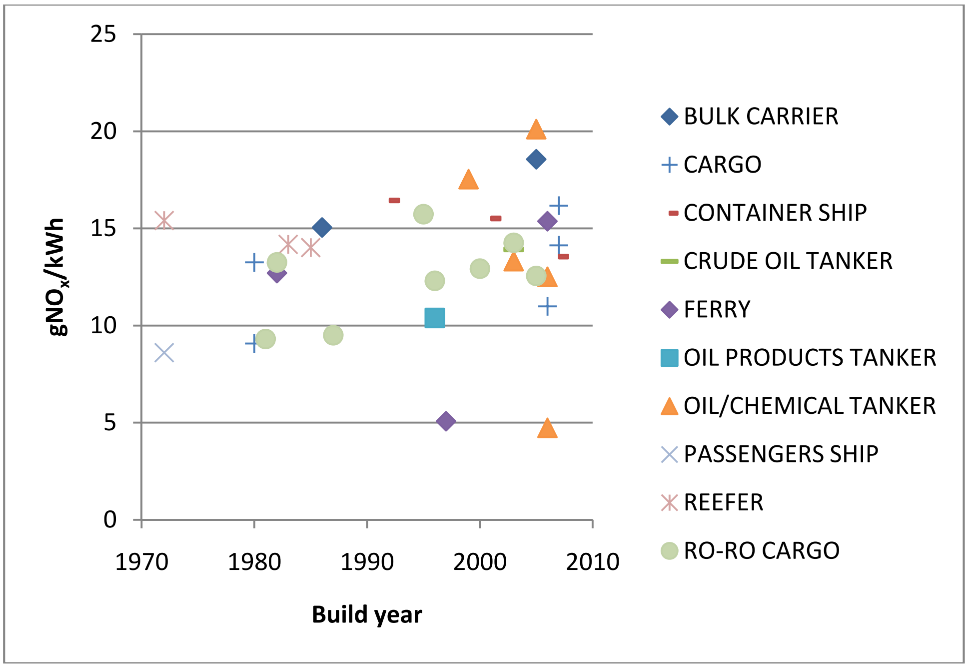

Figure 14. Ship emission data in gNO_x/kWh for different ship types.

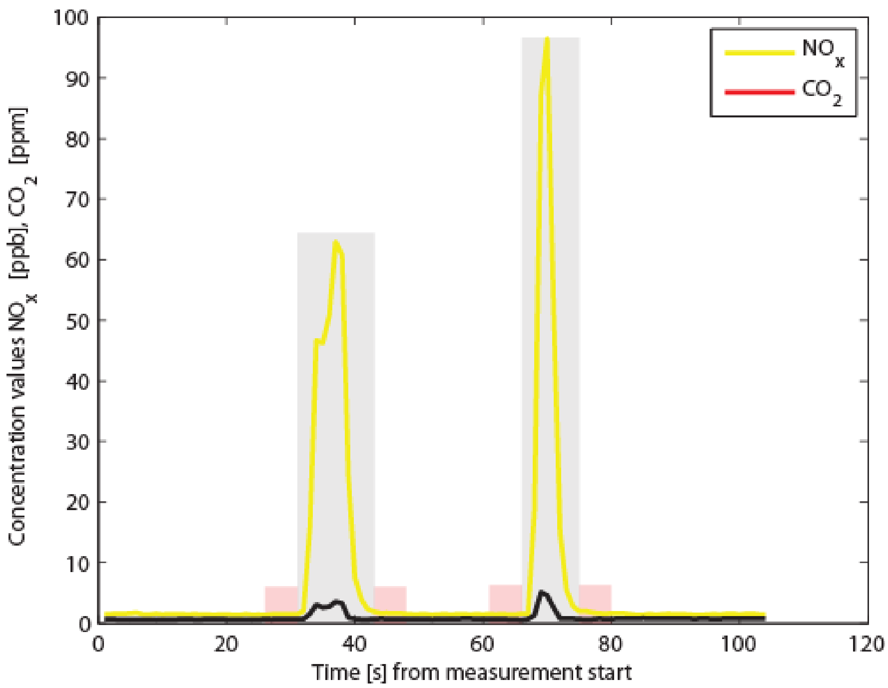

Figure 15. A flight transect across the plume of the ship Kang Hong, a bulk carrier from Hong Kong (China) with the second largest gNO_x/kWh of the measured ships. The engine type is 1D 2 SA 6 CY with 8 kW power.. The two measurements yield a NOx emissions of 18.4 and 18.8 gNO_x/kW, respectively.

4.5. Error discussion sniffer

In this study multiple measurements have been carried out on most ships. From the obtained data set, using measurements with more than 6 repetitions, the 1-σ variability of a the measurement has been derived, corresponding to 14% for the sulfur fuel content, and 18% for the gNO_x/kg fuel (or g NO_x/kWh).

This random uncertainty applies for a single measurement, and when conducting several measurements, as we have done in this study, the random uncertainty is lowered by the square root of the number of samples, assuming a normal distribution of the uncertainties. In addition to the random errors there are systematic uncertainties of the calibration gas mixtures and in the calibrations themselves as discussed in section 4.2. In accordance with Table 1 the calibration gas uncertainty is 7% for both SO_2 and NO_x. For CO_2 it is 1% but when applied for standard addition it scales up to 3%.

The errors in the calibration procedure are mostly due to the fact that zero gas and multiple CO_2 gases were missing during part of the project. This causes an uncertainty of about 3% in the CO_2 value assuming an error in the background value of 5 ppm. For SO_2 and NO_x the uncertainty is instead 5% assuming 2 ppb error in the assumed zero value. An additional error source corresponds to the variability in the calibration factors observed from the standard addition calibrations as discussed in section 4.2. Here we assume that this uncertainty is lowered with the square root of the number of samples taken.

An additional bias in the SO_2 measurements is interference by NO. As described in section 4.1 there is a 2-3% interference of NO on the SO_2 reading and this causes a reading of 2- 3 ppb SO_2 for 100 ppb of NO. The emission factors of NO, measured in appendix I seems to be almost double those of SO_2 on a mole by mole basis and this actually causes 4% apparent SO_2.

In Eq. 6 the uncertainty in the sulfur fuel content is calculated from the error sources discussed above. Estimates of these uncertainties are also shown in Table 4 and here also the overall uncertainty is shown, hence corresponding to 16% and 17% for SO_2 (S%) and NO_x (g/kg fuel), respectively. For the emission factors of NO_x versus axial power, g/kWh, the uncertainty is 23%.

If one considers the overall uncertainty for SO_2, including also the bias from NO, then the measurement has to be above 1.8% sulfur fuel content for a ship to violate the IMO limit. Similarly for NOx per kWh the Tier I limit, Figure 2, corresponds to 21 g NO/kWh for slow stroke vessels, considering the uncertainties and 16 g NO/kWh for medium stroke ones.

$$\sigma_{\%S} = \sqrt{\left(\left(\frac{\sigma_{Random_S}}{\sqrt{N}}\right)^2 + {\sigma_{gas_S}}^2 + {\sigma_{gas_C}}^2 + {\sigma_{CP_S}}^2 + {\sigma_{CP_C}}^2 + \left(\frac{\sigma_{CF_S}}{\sqrt{N}}\right)^2 + \left(\frac{\sigma_{CF_{SC}}}{\sqrt{N}}\right)^2\right)} \quad \text{Eq.6}$$

Table 4. Uncertainty sources for measuring a single ship using the IGPS sniffer system.

		Estimated value		
		SO_2 (S)	NO_x (N)	CO_2 (C)
N	Number of ship measurements	3	3	3
$\sigma_{random, S or N}$	Random measurement uncertainty in SO_2/CO_2 or NO_x/CO_2	13.7%	18%	
$\sigma_{gas, S,N, or C}$	Gas calibration uncertainty,	7%	7%	3%
$\sigma_{CP, S, N or C}$	Calibration procedure, uncertainty in background/zero	5%	5%	3%
$\sigma_{CF, S, N or C}$	Variability in calibration correction factors	7%	7%	7%
Resulting uncertainty Sulfur fuel content% NOx g/kg fuel	**Eq, 6**	**14%**	**15%**	
σ_{Fuel}	Uncertainty in ship fuel efficiency	15%	15%	15%
Resulting uncertainty (NOx g/kWh)	Eq. 6		**21%**	
Systematic Bias	NO interference	+4%		
Overall uncertainty		4%±14%		

5. Optical airborne measurements

In the optical system spectra of reflected light from the water surface are measured with high time resolution (1s) by a spectrometer via a telescope and an optical fiber. From the spectra the gas species SO_2 and NO_2 are retrieved around the wavelengths 300 nm and 430 nm, respectively. The system has been custom designed but is based on a commercial spectrometer and a CCD detector from Andor Technology. In the optical measurement the airplane, which is at a few hundred meters altitude, is moved in such a way that the field of view of the optical telescope transects the plume of interest, Figure 16. From these measurements the amount of gas across the plume can be derived, and then recalculated to an *absolute emission in kg/h.* In Figure 17 the optical system is shown when installed in the CASA-212 airplane of the Swedish coast guard.

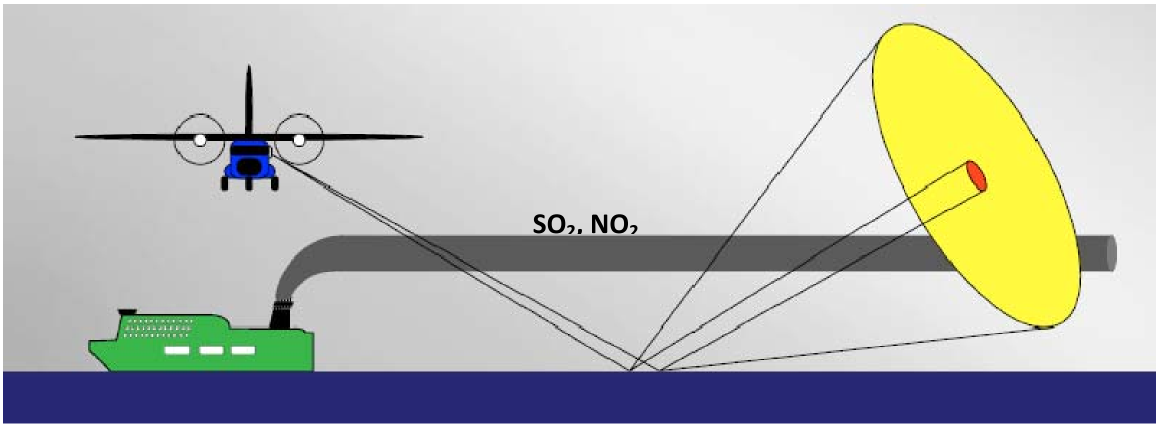

Figure 16. Measurement geometry for the optical method utilizing solar light reflected from the ocean.

Figure 17. The optical system measuring SO_2 and NO_2 in the reflected solar light.

5.1. Hardware and spectroscopy

The optical system consists of a UV spectrometer (Andor Shamrock 303i spectrometer, 303 mm focal length, 300 µm slit) equipped with a CCD detector (Andor Newton DU920N-BU2, 1024 by 255 pixels, thermoelectrically cooled to -70^{o}C). The spectrometer covers the wavelengths between 294 and 324 nm for SO_2 and has a spectral resolution of 0.47 nm (2400 grooves/mm grating). For NO_2 the wavelength interval 424 to 450 nm is instead used (1800 grooves/mm holographic grating).

The spectrometer is connected to a quartz telescope (20 mrad field of view, diameter 7.5 cm) via an optical fiber (liquid guide, diameter 3 mm). Two optical band pass filters (Hoya and a custom made one from Layertec) is used to prevent stray light in the spectrometer by blocking wavelengths longer than 325 nm.

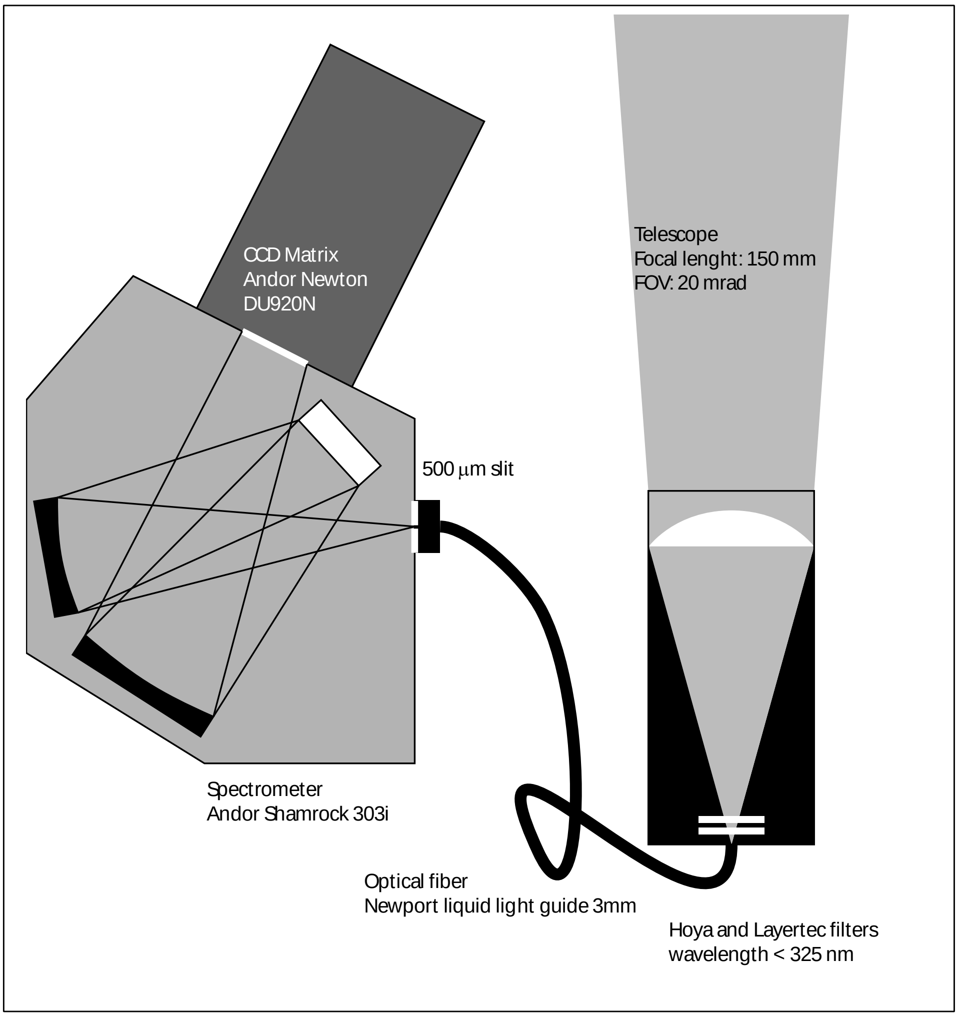

Figure 18. Overview of a mobile DOAS system. Scattered solar light is transmitted through a telescope, and an optical fiber to a UV/visible spectrometer. From the measured spectra the amount of NO_2 and SO_2 in the solar light can be retrieved.

In the spectral evaluation procedure the recorded spectra along the measurement transect are first normalized against a reference spectrum measured outside the ship plume. In this way most of the absorption features of the atmospheric background and the inherent structure of the sun is eliminated. The normalized spectra are further high pass filtered according to algorithms proposed by (Platt, Perner, & Pätz, 1979) and then absorption spectra for the species are scaled to the measured spectra by multivariate fitting. Here we have used a software package denoted DOASIS (Kraus, 2005) to do that.

The absorption spectra used here for NO_2 and SO_2 were obtained from laboratory spectra by (Vandaele, 1998) which were adapted to the instrument used in our study by the software WinDOAS (Van Roozendael & Fayt, 2001). In addition, to the above mentioned absorption spectrum it is also necessary to fit so called "ring spectra", corresponding to spectral structures coming from inelastic atmospheric scattering (Fish & Jones, 1995). This has been done through the DOASIS software which calculates a ring spectrum from the Raman scattering processes of atmospheric nitrogen and oxygen applied on the intensities of the reference spectrum. An example of a fit can be seen in Figure 19 and Figure 20, in which a sample spectrum, corresponding to a ship plume measurement, has been normalized to a reference spectrum. An absorption spectrum of SO_2 has then been fitted to the measured differential absorbance yielding a SO_2 column of $9 \cdot 10^{16}$ molecules/cm^2, as can be seen in Figure 20.

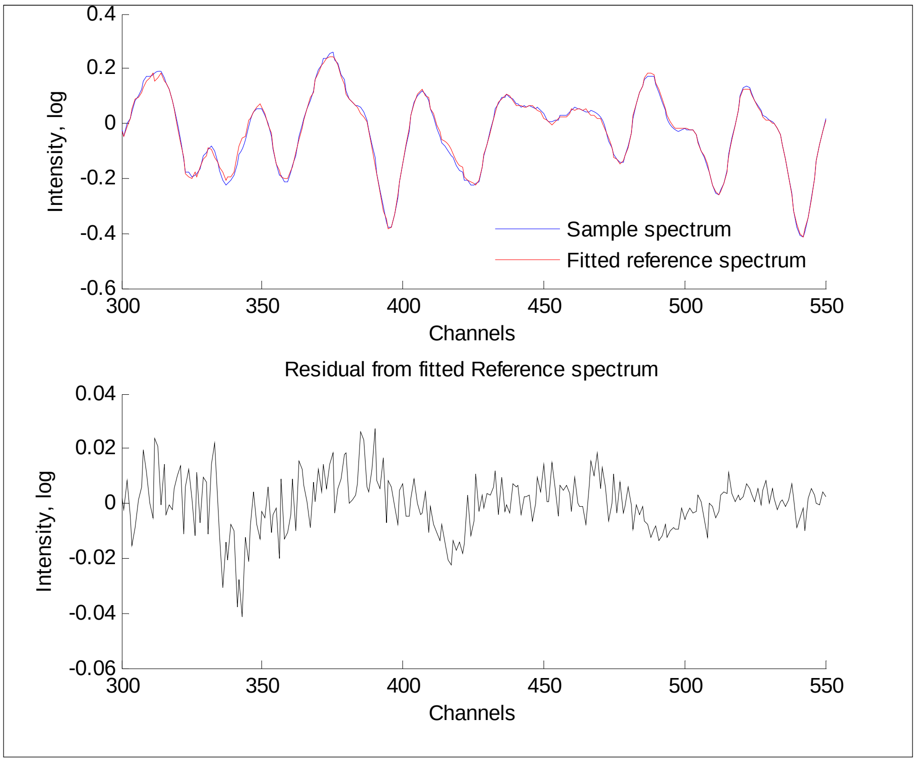

Figure 19. The upper figure shows two ultraviolet spectra (Intensity counts versus channels in the spectrometer) measured from the CASA airplane when conducting a flight transect across a ship plume in the North sea. The reference spectrum was measured in the clean air outside the ship plume while the sample spectrum was measured inside. The difference between the two spectra corresponds to the residual containing absorption features of SO_2 from the ship plume.

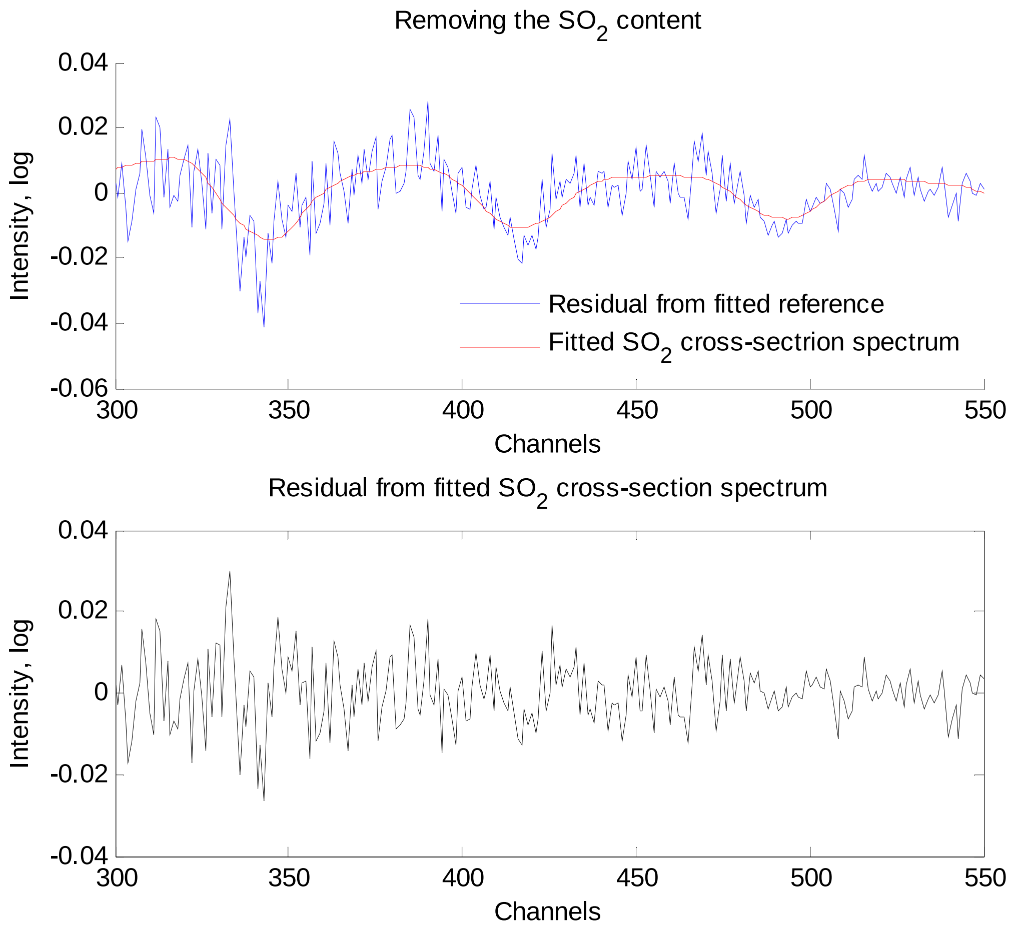

Figure 20. From the differential absorption spectrum a SO_2 column of 9 $\cdot 10^{16}$ molecules/cm^2 was derived by fitting the absorption cross-section for SO_2.

5.2. General method

The main purpose of the optical system is to measure the gas flux from the corresponding to the *emission rate of kg emitted species (SO_2, NO_2) per time unit.* The flux measurements are carried out by conducting flight transects across the plume, as shown in Figure 21, with the telescope of the optical system pointed at 30° angle from the horizon. From the spectra, which are measured every second, the gas column of SO_2 or NO_2 across the plume is obtained.

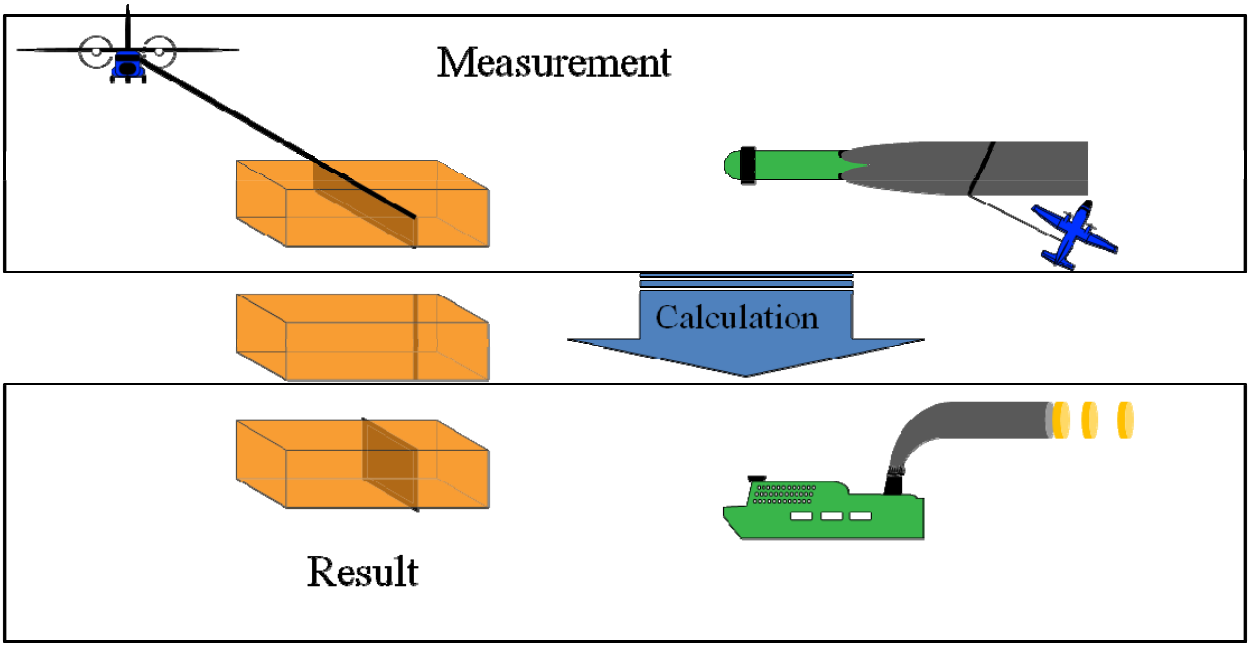

Figure 21. An illustration of a flight transect across the ship plume. The field of view of the telescope and spectral interval is illustrated by the cones standing out from the aircraft. The plume bearing is pushed out from the contra course line of the ship by the wind speed and direction.

The emission of the ship is diluted by the *apparent wind*, which is the resulting wind of the created wind by the travel velocity of the ship combined with the true wind speed and its direction. The apparent wind is the wind felt when standing on the ship and it is the one that dilutes the plume, resulting in a plume bearing and velocity, as shown in

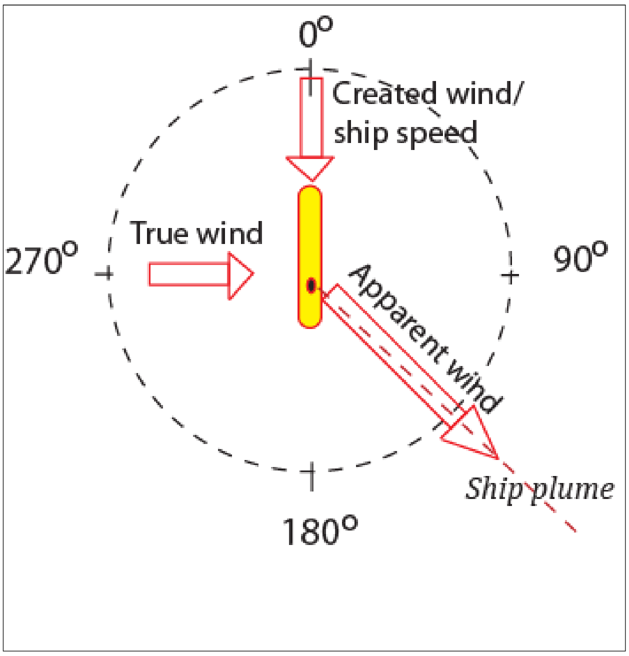

Figure 22.

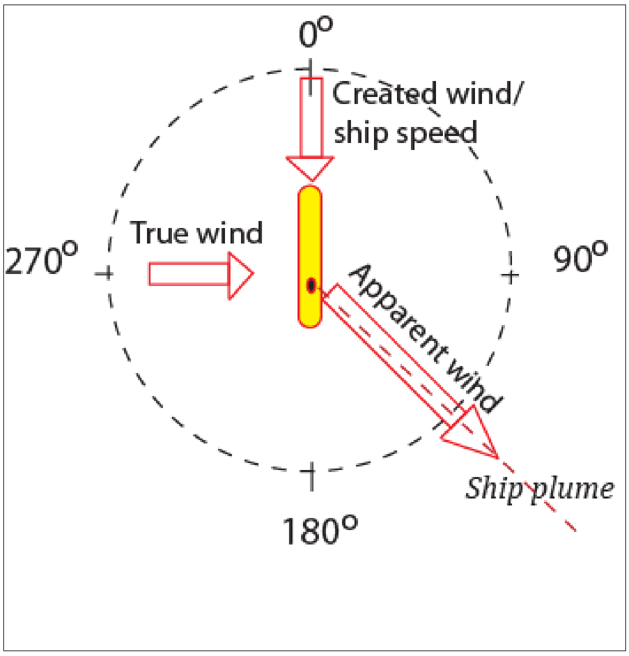

Figure 22. The apparent wind is the resulting wind from the created wind from the speed of the boat and the true wind, as illustrated here. The ship exhaust follows the apparent wind.

In Figure 23 a flight transect across the exhaust plumes from three ships, i.e. Jork, Scottish Star and Beachy Head, is shown with data taken from the AIS system of the Swedish Coast Guard CASA-212 airplane. This measurement was carried out in August 2008 in the Baltic sea, outside the island of Gotland.

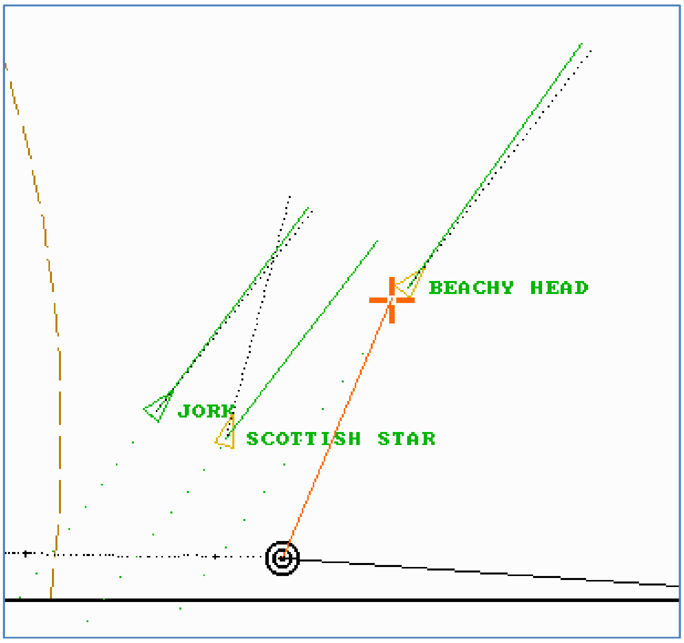

Figure 23. A *screen dump* made from the coast guard computer on Aug 24 2008. It shows the airplane and heading, in double black rings and solid black line with the ships Jork, Scottish Star and Beachy Head as triangles with their heading as green solid lines.

An NO_2 measurement with the optical system, for the flight transect in Figure 23, is shown in Figure 24. In this measurement, downward looking spectra at the wavelength 430 nm have been collected every second. From each spectrum the path integrated concentration of NO_2 (also denoted column) along the solar light is retrieved in the unit ppm·m or mg/m^2. To calculate the flux, the gas columns from the individual spectra are first summed up (integrated) across the exhaust plume, subtracting the background value which is obtained as the linear function between the sides of the exhaust plume. The integrated value is multiplied with the plume width and this yields the total mass across the plume in mass NO_2 per meter unit [kg·m]. This value is multiplied with the plume speed [m/s] (i.e. apparent wind) and this corresponds to the gas flux [kg NO_2/h]. The calculation of the gas flux is used in a similar application for volcanic and industrial monitoring (Galle, Oppenheimer, & al., 2003).

The optical measurements are carried out in the same way for SO_2 but these measurements are more sensitive to the ambient light conditions since they are carried out further down in the ultraviolet spectral region at 312 nm where there is less light due to the atmospheric absorption.

One problem with the optical system concerning NO_x is the fact that it only measures NO_2 and not the species NO. The latter species is actually the dominant part of the NO_x (90%) when leaving the chimney but when entering the atmosphere it is fairly rapidly converted to NO_2 by atmospheric reactions. Hence, the fact that the optical instrument measures a minor NO_x constituent in the fresh plume, and the fact that the ratio between this component (NO_2) and the major one (NO) changes along the plume causes a relatively large uncertainty in the ability of the optical measurements to predict the total NO_x emission.

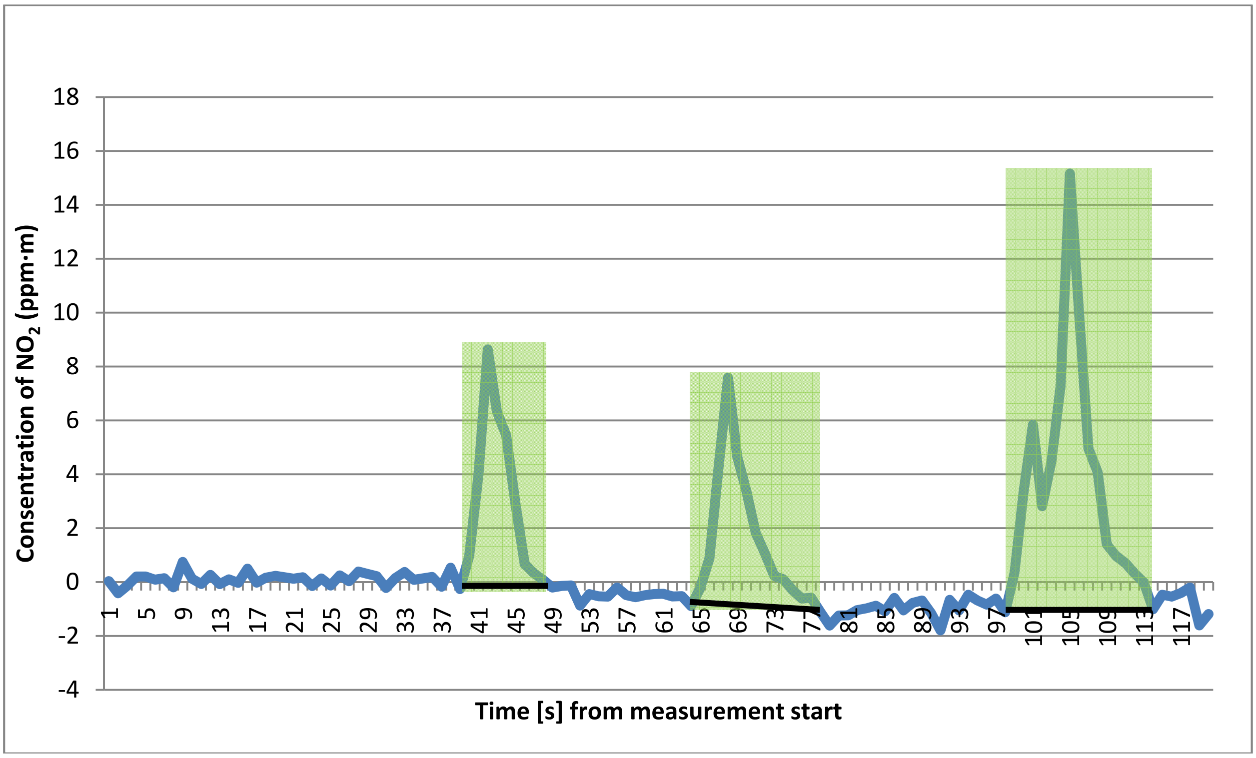

Figure 24. An optical NO_2 measurements across the exhaust plumes of the ships Jork, Scottish Star and Beachy Head. The peaks are marked with green rectangles while the assumed back ground is marked with a black line.

5.3. Details of the flux calculation

Several parameters have to be accounted for in the emission calculation:

a) The course of the aircraft and the direction of the plume are not always orthogonal to each other and the difference between the two corresponds to a *wind factor* [k_{wind}].

b) The sky light passes twice trough the gas plume as illustrated in Figure 27 with a slant angle of 30° below the horizon. In addition, due to waves the angle of the light from the sky to the water surface does not correspond to the angle of the telescope, described further down in *Reflection angle changes due to waves*. The above-mentioned factors are corrected for by the *telescope factor* [$k_{telescope}$].

c) The 1 second accumulation time of each spectrum combined with the aircraft velocity gives the *distance* along the flight transect of the gas, which each gas column corresponds to.

d) Velocity of the plume [$v_{apparent\ wind}$] is the resultant velocity from the ship speed and heading and wind speed and bearing. This gives the apparent wind speed and heading which is needed for the flux calculation.

e) The *mass Column* is calculated from the measurement column to have the unit kg/m^2.

In equation 8 below the gas emission in kg/s from the ship is obtained by adding up the gas column measurements across the plume. Equation 9-11 describes the calculation for the apparent wind both angle and velocity. Equation 12 shows the telescope factor ($k_{telescope}$) and equation 13 the wind factor (k_{wind}).

$$flux = \sum massColumn \cdot distance \cdot v_{apparent\ wind} \cdot k_{wind} \cdot k_{telescope} \qquad \text{Eq. 8}$$
$$[kg/s] = [kg/m^2] \cdot [m] \cdot [m/s] \cdot [-] \cdot [-]$$

$$\begin{Bmatrix} ship_x = v_{ship} \cdot \cos\left(-\theta_{ship} + \pi\right) \\ ship_y = v_{ship} \cdot \sin\left(-\theta_{ship} + \pi\right) \\ wind_x = v_{ship} \cdot \cos(-\theta_{wind} + \pi) \\ wind_y = v_{ship} \cdot \sin(-\theta_{wind} + \pi) \end{Bmatrix} \qquad \text{Eq.9}$$

$$\theta_{apparent\ wind} = -\tan^{-1}\left(\frac{ship_y + wind_y}{ship_x + wind_x}\right) \qquad \text{Eq.10}$$

$$v_{apparent\ wind} = \sqrt{(ship_x + wind_x)^2 + \left(ship_y + wind_y\right)^2} \qquad \text{Eq.11}$$

$$k_{telescope} = \frac{1}{\frac{1}{\sin\left(\theta_{telescope}\right)} + \frac{1}{\sin\left(\theta_{reflection}\right)}} \qquad \text{Eq.12}$$

$$k_{wind} = abs\left(\cos\left(\theta_{travel} + 1.5\pi - \theta_{apparentwind}\right)\right) \qquad \text{Eq.13}$$

5.4. Results of the optical measurements

Various test flight with the optical IGPS equipment were carried out in 2007 from a rented Cessna airplane operated by *Västkustflyg* and in the CASA 212. These test measurements were useful for the development of the optical method but lack necessary input data for quantifying the ship emissions. We have therefore, in this report, focused on the 2008 flights which were of better quality. These measurements were conducted during 7 days between August 12 and 24, 2008. During this period a large number of optical ship measurement were carried out, and for these it was possible to calculate the ship emission (flux) in 66% of the cases (70 measurements), for 32 individual ships. In many cases, multiple emission measurements were carried out for the ships. For two of the ships it was possible to measure emissions of both SO_2 and NO_2 and for one ship the emission of SO_2 was measured twice, with the measurements 9 days apart. In Table 5 and Table 6 the results of these measurements are shown with some additional information about the ships.

Table 5. Flux calculation results of SO_2 with the optical measurements, during 5 days between 13 and 24 of August 2008.

SHIP NAME	MMSI	MEAN FLUX SO_2 [kg/h]	VESSEL TYPE	DWT [kton]	BUILD YEAR	VELOCITY [kts]
Sten Aurora	258953000	8	OIL/CHEMICAL TANKER	16.596	2007	13.3
SCF Yenisei	636012912	33	OIL PRODUCTS TANKER	47.187	2007	15.1
Superfast VII	276647000	102	FERRY	5.915	2001	22.8
Isabella	215545000	43	OIL PRODUCTS TANKER	89.999	2004	13.3
Baltic Meridian	375304000	57	REEFER	9.728	1980	17.5
Finnpulp	266295000	48	RO-RO CARGO	10.3	2002	16.2
Liteyny Prospect	636011642	44	OIL PRODUCTS TANKER	104.707	2003	14.3
Pulpca	245097000	111	RO-RO CARGO	17.5	2008	20.8
Birka Carrier	230367000	92	RO-RO CARGO	8.853	1998	16.3
Finnmaid	230982000	133	FERRY	9.653	2006	23.6
Merchant	218252000	37	RO-RO CARGO	13.09	1982	16.2
Timca	246521000	77	RORO/CONTAINER CARRIER	18.25	2006	20
Cartagena	304753000	8	CONTAINER SHIP	5.218	1995	14.7
Rusich-5	273317430	10	CARGO	5.485	2005	9.5
Minerva Astra	237841000	36	CRUDE OIL TANKER	105.946	2001	12.9
Eagle Turin	565770000	53	CRUDE OIL TANKER	107.123	2008	12.5
Navigator II	353269000	42	BULK CARRIER	69.174	1998	11.5
Superfast VII	276647000	62	FERRY	5.915	2001	22.7
Snow Land	518173000	45	REEFER	15.588	1972	17
Pirita	210716000	34	CONTAINER SHIP	7.946	1995	17.6
Seabourn Pride	311084000	42	PASSENGERS SHIP	800	1988	14.6
Petersburg	636090780	76	RO-RO CARGO	8.036	1986	15.7

Table 6. Flux calculation results of NO_2 with optical measurements, during 4 days between 12 and 24 of August 2008.

Ship Name	MMSI	MEAN FLUX NO_2 [kg/h]	VESSEL TYPE	DWT [kton]	BUILD	VELOCITY [kts]
HANS LEHMANN	236424000	16	CARGO	12	2007	11.7
KALKVIK	258909000	22	CARGO	7.67	2006	13.6
GERD KNUTSEN	235807000	19	OIL PRODUCTS TANKER	146.273	1996	10
FROSTA	308269000	5	OIL/CHEMICAL TANKER	5.675	2006	14.8
Aurora	211622000	6	RO-RO CARGO	13.09	1982	17.3
Glacier Point	212100000	7	OIL/CHEMICAL TANKER	37.288	2003	14.3
Green Atlantic	325350000	8	REEFER	3.75	1985	12.1
Kang Hong	477995400	34	BULK CARRIER	55.589	2005	14.8
Jork	209715000	45	CONTAINER SHIP	11.385	2001	17.2
Scottish Star	309053000	43	REEFER	13.058	1985	16.8
Beachy Head	235573000	143	RO-RO CARGO	10.09	2003	21
Snow Land	518173000	40	REEFER	15.588	1972	17.1
Pirita	210716000	42	CONTAINER SHIP	7.946	1995	17.2

The average SO_2 emission of the measured ships is 54 kg/h with a standard deviation of 13 kg/h for NO_2 the average emission corresponds to 33 kg/h with a standard deviation of 8 kg/h. In Figure 25 and Figure 26 the SO_2 and NO_2 emission measurements obtained from the optical measurements have been plotted versus a proxy for the power consumption, corresponding to the cube of the velocity times the ship weight. This type of calculation is included in recent modeling attempts of ship emissions (Jalkanen, 2009). The ship emission data in Figure 25 and Figure 26 have also been divided into ship types.

Indicated with ovals are ships which are measured for both species. The red oval corresponds to the reefer ship Snow Land and the blue oval is the container ship Pirita.

In the two figures it is obvious that the ship types follow different patterns, and that the optical data looks rather reasonable.

For instance, in Figure 25 the bulk carrier cargo ships, container ships, passenger ships, reefers and RO-RO cargo ships (Roll On Roll Off) seem to follow the relationship indicated by the green line while crude oil tankers, oil products tankers and oil/chemical tanker follows the black line. Ferries and RO-RO /container carriers are somewhat in between. In the same manner in Figure 26 for NO_2 one can see that cargo ships , container ships, reefers and one of the RO-RO cargo ships are well correlated (green arrow) while there rest (bulk carriers, oil products tankers, oil/chemical tankers and the other of the RO-RO cargo ships) are correlated along the black line.

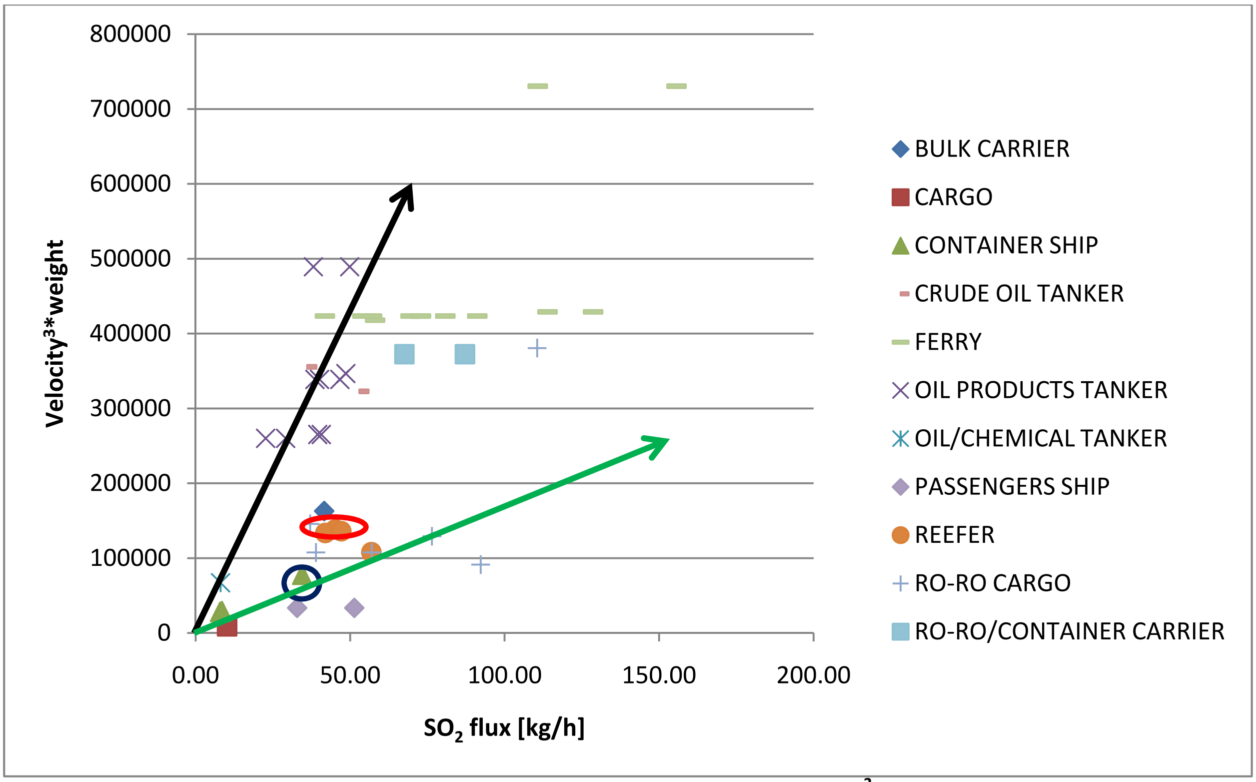

Figure 25. SO_2 measurements plotted against the fuel consumption proxy (velocity^3*weight), with the ship types as legend. The marked ships are Pirata (blue) and Snow Land (red).

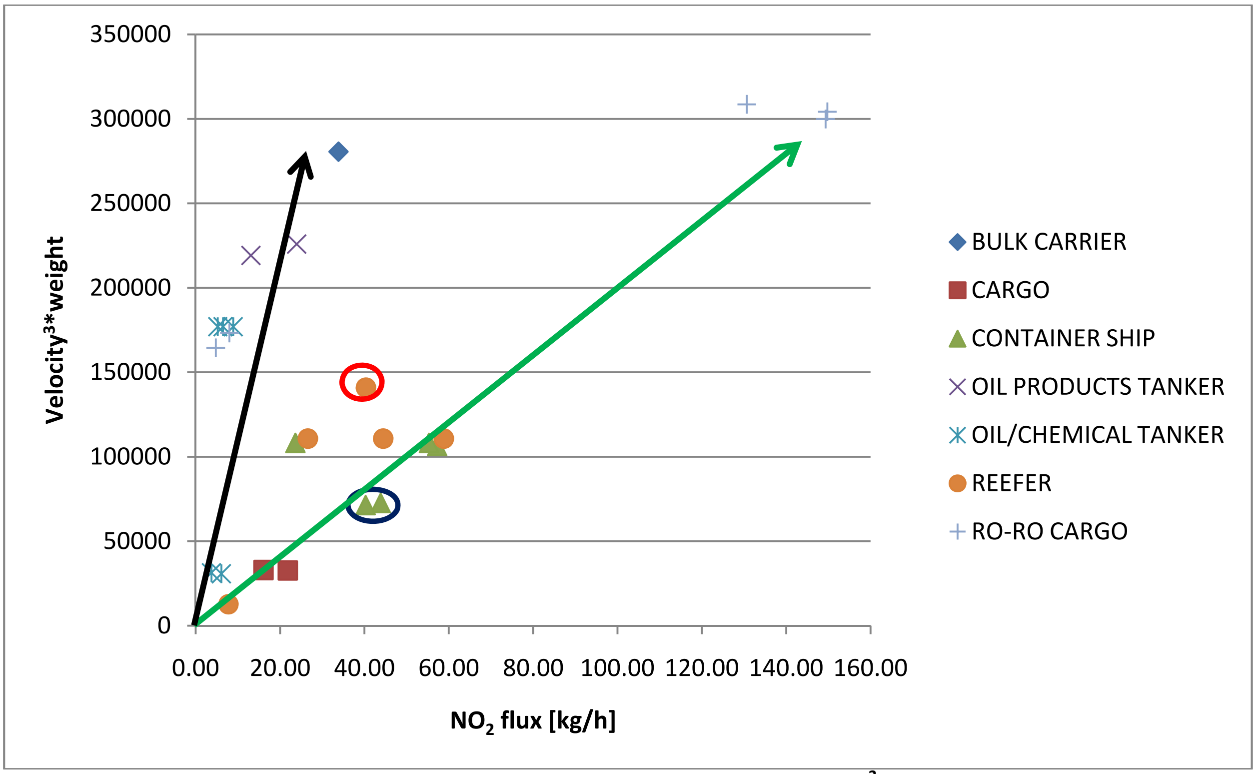

Figure 26. NO_2 measurements plotted against the fuel consumption proxy (velocity^3*weight), with the ship types as legend. The ships marked with circles correspond to Pirata (navy blue) and Snow Land (red).

5.5. Error discussion optical measurement

The optical measurements conducted here have not been carried out elsewhere to our knowledge. Due to the novelty of this approach it is, at this stage, not possible to carry out a good error estimation and further work is needed to make realistic estimates. But roughly we estimate the uncertainty to be in the range 30-50%. In this section we point out several error sources that has emerged during the project, which should be considered in more detail in the future. This mainly includes the difficulty in estimating the optical path of the ocean scattered light due to waves and direct and multiple scattering in the exhaust plume.

5.5.1. Impact of waves

In the optical method it is assumed that the skylight is reflected on the water surface like in a mirror (specular reflection). This means that the light will pass the gas plume twice as illustrated in Figure 27.

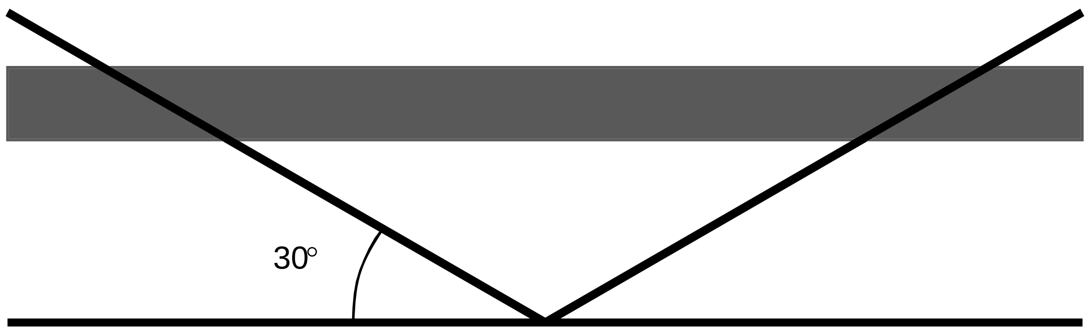

Figure 27. Illustration of light path through the plume. The black line is the main light path for the light reaching the detector and the grey rectangle is the illustrated flue gas.

Due to the presence of waves the slant angle of 30° will not have the corresponding reflection angle as of a plane surface. In Figure 28 an example is illustrated were the field of view of the telescope covers approximately 1.5 waves with the corresponding reflection lines from the water surface.

In Figure 29 the same case as in Figure 28 is shown but zoomed out. The average of all incoming reflection lines corresponds to the grey line, this is to be compared to the thick black line corresponding to specular reflection on a flat surface, as shown in Figure 27. This indicates that there is a difference between the slant angle and the reflection angle due to the waves on the water surface, which gives rise to a smaller path difference through the plume. This difference is denoted the telescope factor as shown in Eq.5. In the flux calculations this wave dependent reflection angle is not taken into account but it is regarded as an error.

For future calculations a wave model has to be used which takes into account the wind speed and calculates the corresponding telescope factor more correct.

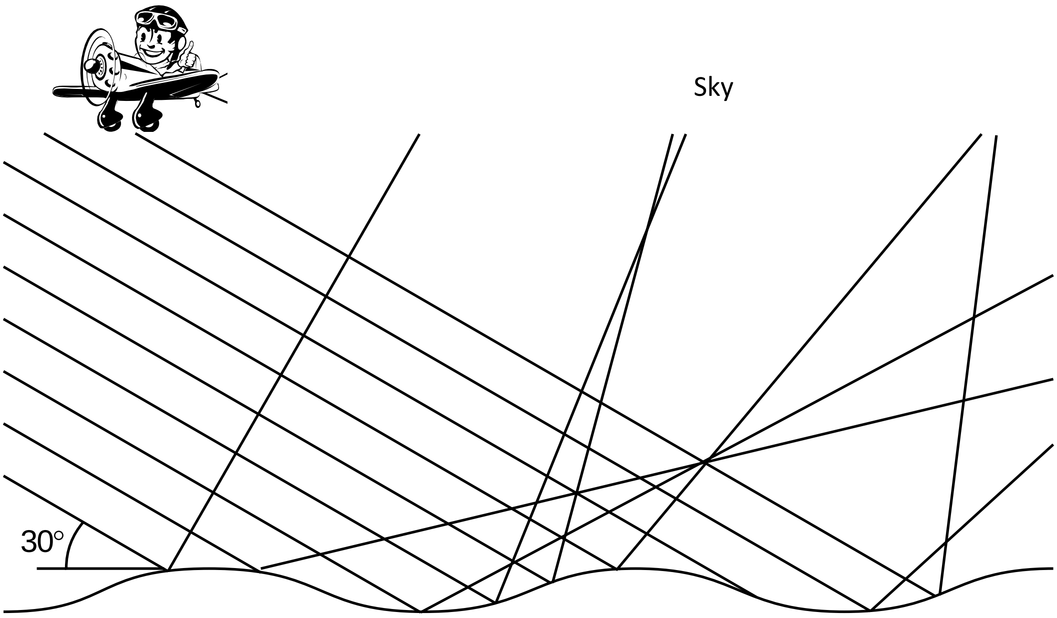

Figure 28. The incoming lines to the left illustrates the field of view of the telescope. The reflection on the water gives the scattered lines which due to the waves are not in the same direction.

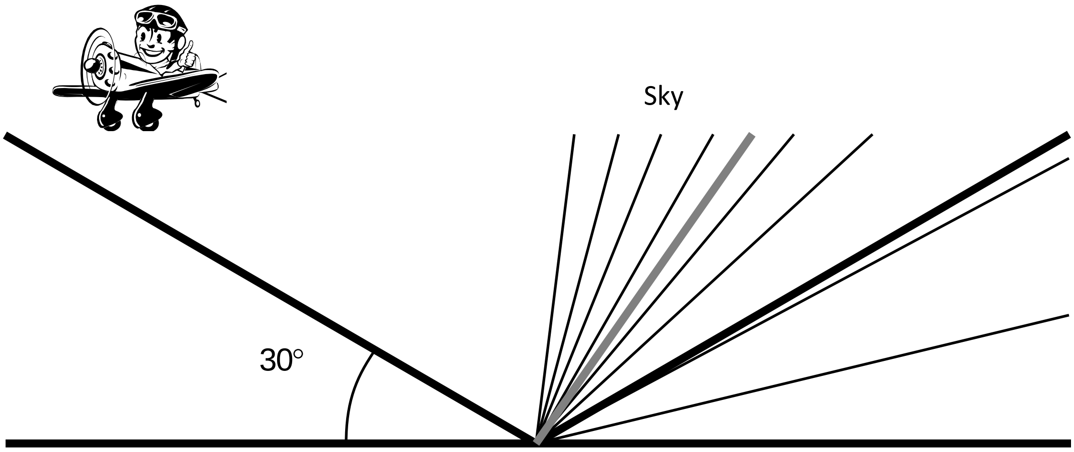

Figure 29. The average of all reflection lines, thin lines, corresponds to the gray line. This gray line is to be compared with the black thick reflection line which illustrates the reflection from a flat surface. Depending on wave characteristics the wave reflection angle changes.

5.5.2. Impact of direct scattering in the plume

Ship plumes seen from above often appear white, as observed during this field work. This means that they reflect more light than the ocean surface due to direct light scattering on particles in the plume. Hence the assumption of the light path, as illustrated in Figure 27, is partly incorrect and this will in turn cause an uncertainty in the derived gas column.

The light scattering in the gas plume is even more evident when using a UV camera which we have done in another study in Rotterdam.

To study the problem with scattering in the plume further the increase of the measured UV light intensity inside the plume relative to the outside has been studied for all flight transects. In Figure 30 the relative increase of the intensity inside the plume is plotted against the obtained gas flux for all optical ship measurements. Two wavelengths, 312 and 430 nm, have been studied corresponding to the wavelengths were SO_2 and NO_2 are measured. It is evident that most measurements correspond to a relatively small increase in the intensity, within 10%, although a few measurements, inside the green oval, have much higher increase in light intensity, clearly indicating large plume scattering and hence associated with large uncertainties in the derived flux values. It can also be seen that more scattering occurs for SO_2 than for NO_2 and this is with high certainty caused by the fact that shorter wavelengths, as used for the SO_2 measurement, scatter more light. The ships with large light scattering, indicated with an oval, are Superfast VII (ferry), Finnmaid (ferry) and Birka Carrier (RO-RO) for SO_2 and Glacier Point measured for NO_2. In Figure 32 several individual optical measurements versus change in light intensity inside the plume is shown for the Superfast VII ferry. It appears that the flux has a weak dependence on the light intensity. To understand more about the scattering problem we believe it is needed to conduct modelling studies of the radiative transfer.

Figure 30. Ship emission gas plume seen from above. It appears white due to direct scattering in the plume.

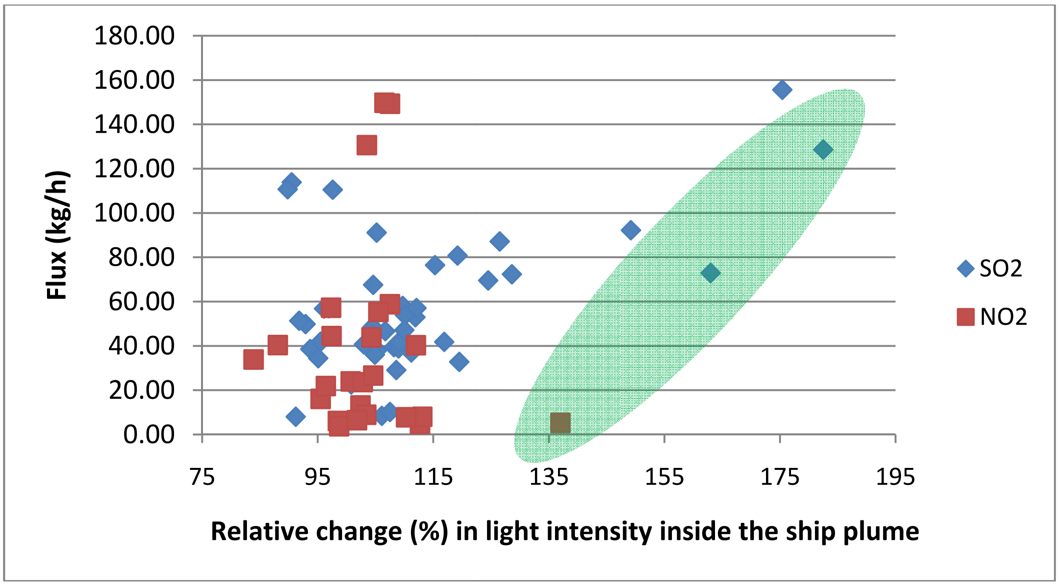

Figure 31. Measured gas flux versus relative change in light intensity due to light scattering in the plume. The green oval shows measurements with high plume scattering.

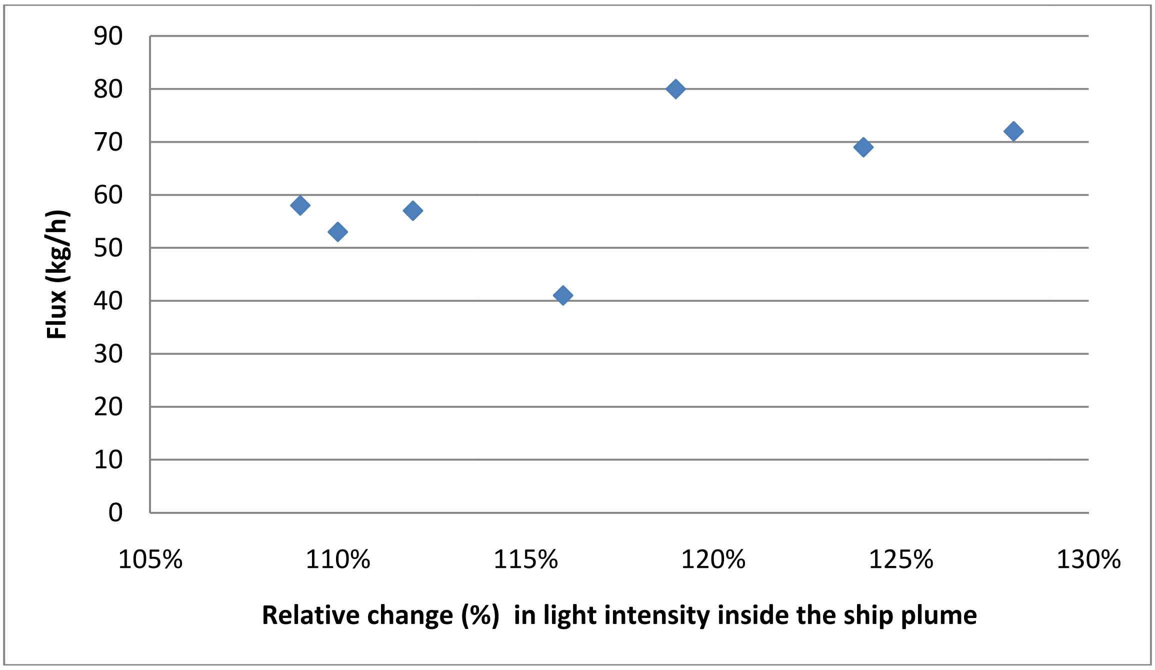

Figure 32. The measured gas flux versus relative change in light intensity is shown here for the passenger ferry Superfast-VII.

6. Stationary measurements

During May and June 2007 unattended continuous measurements where conducted using the Sniffer system at Nya Älvsborg fästning, a fortress, in the north of the ship channel to the harbor of Göteborg, see Figure 33. In these measurements we analyzed the sulfur fuel content but neither NO_x sniffer measurements nor optical measurements were carried out.

Figure 33. The measurements site at New Älvsborg Fortress, in the north of the ship channel to Göteborg, view towards east.

Approximately 200 ship plumes corresponding to 80 individual ships were measured by the Sniffer method for the wind sector southwest to southeast, see Appendix I. Several ships were measured on numerous occasions (up to 20 times), for instance the passenger ferries Stena Danica, Stena Germanica, Stena Jutlandica and Stena Scanrail. For some of these ships the sulfur fuel analysis is available from Stena line (0.49%, 0.49% and 1.12% for Danica, Jutlandica, and Scanrail, respectively).

6.1. Hardware

The Sniffer instrument hardware is the same as for the airborne system without the NO_x instrument. The system was combined with a digital camera, a wind meter and an AIS system (Automatic Identification System) to interpret which ships were measured at a certain time. In Figure 34 the measurement equipment is shown together with calibration gases.

Figure 34. The Sniffer system measuring SO_2 and CO_2 is shown together with calibration bottles.

6.2. Method and Calibrations

The Fortress Nya Älvsborg is situated near the shipping channel of the Göteborg harbor, just north of it. With southerly winds plumes from the ships passing in the lane will blow towards the fortress and our measurements equipment. In Figure 35 the gas intake, wind meter and location of the measurement station is shown.

Figure 35. The measurement site at New Älvsborg Fortress, in the vicinity of the ship channel to Göteborg, view towards SW. The inlet probe and windmeter were installed on top of the roof, as shown in the left picture.

In Figure 36 information from the Automatic Identification System (AIS) is shown. The circle indicates the measurement location. Here the passenger ferry Stena Danica is passing, with the traveling direction indicated by the line.

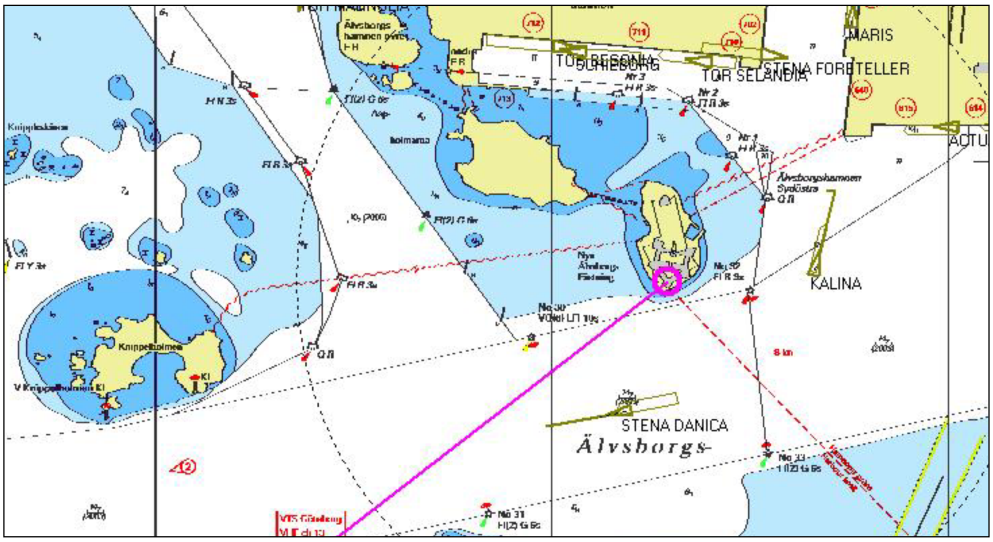

Figure 36. Information from the Automatic Identification System, when conducting stationary measurements at New Älvsborg Fortress. The circle indicates the measurement location. Here a passenger ferry Stena Danica is passing, with the traveling direction indicated by the line.

For the stationary measurements only few calibrations were conducted since most measurements were conducted in an automated unattended manner. This gives added uncertainty to the measurements. In Figure 37 correction factors (by which the measured values should be multiplied by) are shown and these have been used in the evaluation. In the calibration SO_2 changed by about 10% over 1 month, while CO_2 stayed much more constant. This is consistent with the correction factors in Table 2.

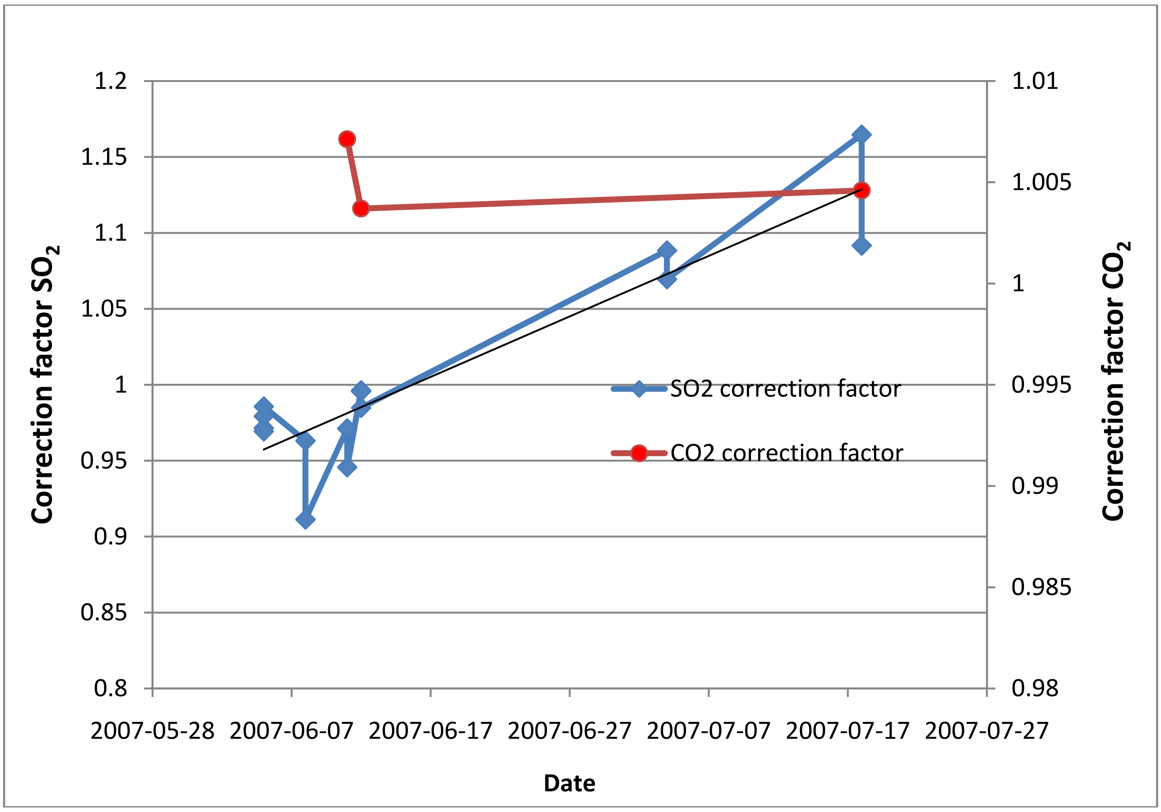

Figure 37. Calibration correction factors of SO_2 and CO_2 for the IGPS equipment.

6.3. Results

In Figure 38 an example of a measurement on June 25, 2007, is shown, when the plume from the Stena Danica ferry blew over the inlet probe of the sniffer instrument. The mixing ratio values of CO_2 and SO_2 are shown. The sulfur fuel content was derived to 0.52% to be compared 0.49% which corresponds to the fuel analysis from the bunker delivery notes. All measurements for Stena Danica are shown in Figure 39 and summarized in Table 7. The derived average fuel concentration for the whole period is (0.39±0.07)% which is 20% lower than the fuel analysis obtained from the bunker delivery notes. It can also be seen in Figure 39 that the derived sulfur content for Stena Danica over the measurements period is variable and that the values are rather low in the end of May, rather stable most of June and then variable again. The sulfur fuel content was constant at 0.49% according to the fuel analysis so most of the variability should be due to measurement artifacts. It could also be misinterpretations of the origin of the plume. These artifacts could have been sorted out if we would have had frequent calibration data, but this is unfortunately not the case.

In Figure 39 and Table 7 is also shown measurement data from other Stena ships. These ships were operating with three distinct classes of sulfur fuel content: The high speed vessel Stena Carisma, runs on gasoil, with virtually no sulfur, while the passenger ferries (Stena Danica, Stena Germanica, Stena Scandinavica, Stena Jutlandica) operate on 0.5% sulfur fuel content and the cargo ferry Stena Scanrail operates on around 1.1%. The latter actually runs 1.5% S fuel on the main engines and 0.08% on the auxiliary ones, with an assumed 80%/20% distribution at full load. The distribution will depend on the load of the main engines and this may explain some of the variability in the graph in Figure 39, especially around the end of May. This highlights a problem when conducting measurements close to harbors for ships that have different sulfur fuel content for the main and auxiliary engines, which is quite typical. This may explain some of the variability seen in Figure 39. Noteworthy, is that the measurements of Stena Danica in the end of June are considerably more variable than the data for several of the other ships.

There are also two combined cargo and passenger ferries in the data in Figure 39 (Stena freighter and Stena Carrier) for which the sulfur fuel content information is not available. The measurements indicate that they should operate on 0.5% sulfur fuel content.

All in all, Figure 39 gives confidence in the sniffer measurements and can actually be used to validate the performance of the sniffer instruments, assuming that one can trust the fiel analysis from the bunker receipts. It is also evident that it is possible to pin point ships running on different classes of sulfur fuel content (very low -0.1% S, low - 0.5% and medium - 1%). The average data in Table 7 shows that the sniffer instrument in general underestimated the sulfur fuel content with 14% (-0.06 S% units) for the ships operating with 0.5% S and 10% (-0.1 S% units) for the one at 1.1%.

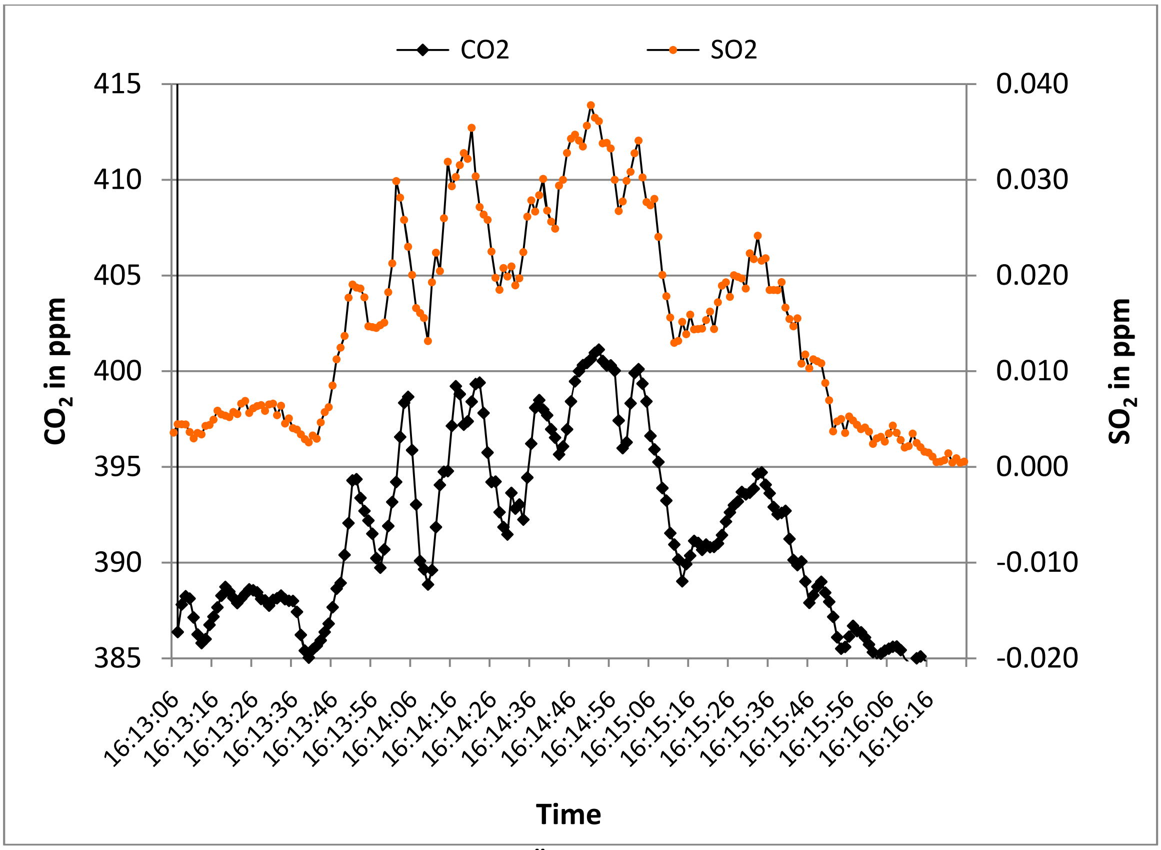

Figure 38. Measurement of SO_2 and CO_2 at New Älvsborg Fortress in the plume of the passenger ferry Stena Danica on June 30 2007 in South easterly wind. The derived fuel sulfur content is here 0.52%, to be compared to the sulfur fuel analysis of 0.49%.

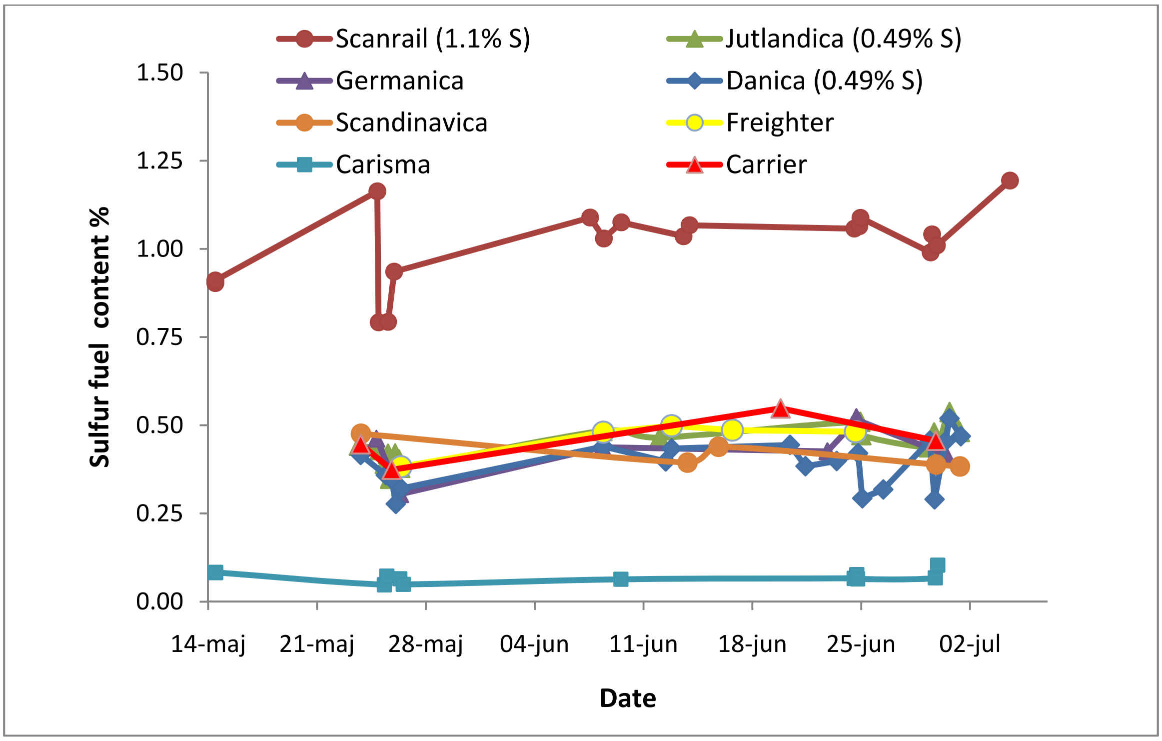

Figure 39. Measurements of Sulfur fuel content in various Stena ships at New Älvsborg Fortress using the IGPS extractive system.

Table 7. Average sulfur fuel content and standard variability derived from sniffer measurements at New Älvsborg Fortress.

	# meas	S%	Fuel analysis S%*	Probable fuel content S%
Stena Scanrail	18	1.01±0.11	1.12	
Stena Jutlandica	17	0.44±0.05	0.49	
Stena Germanica	9	0.44±0.07		0.5
Stena Danica	18	0.39±0.07	0.49	
Stena Scandinavica	5	0.42±0.04		0.5
Stena Freighter	5	0.47±0.05		0.5
Stena Carrier	4	0.46±0.07		0.5
Stena Carisma	13	0.07±0.01*		<0.1

- *Fuel analysis from bunker receipts obtained from Stena line*

In Figure 40 an overview of the sulfur fuel content in the 220 ship plumes measured (80 individual ships) is shown, as a histogram, with the number of measurements grouped into different sulfur fuel content intervals. One can see two peaks in the histogram, at 0.5% and 1%, and that only few ships are higher than the SECA limit of 1.5%. The ships that were higher was an oil tanker (80 m) registered in Denmark with a derived sulfur fuel content of 2.6%, a cargo vessel registered in Antigua-Barbado (100) with a 2.1% sulfur fuel content and a 100 m long container vessel, also registered in Antigua Barbados. The peaks at 0.5% are interpreted as the passenger ferries, which corresponded to 50 of the 220 ship plumes. The 1% peak is the scanrail ferry together with other ships, for instance the freighters Schieborg and Slingeborg running pulp and paper for Stora Enso, with lower sulfur content on a voluntary basis.

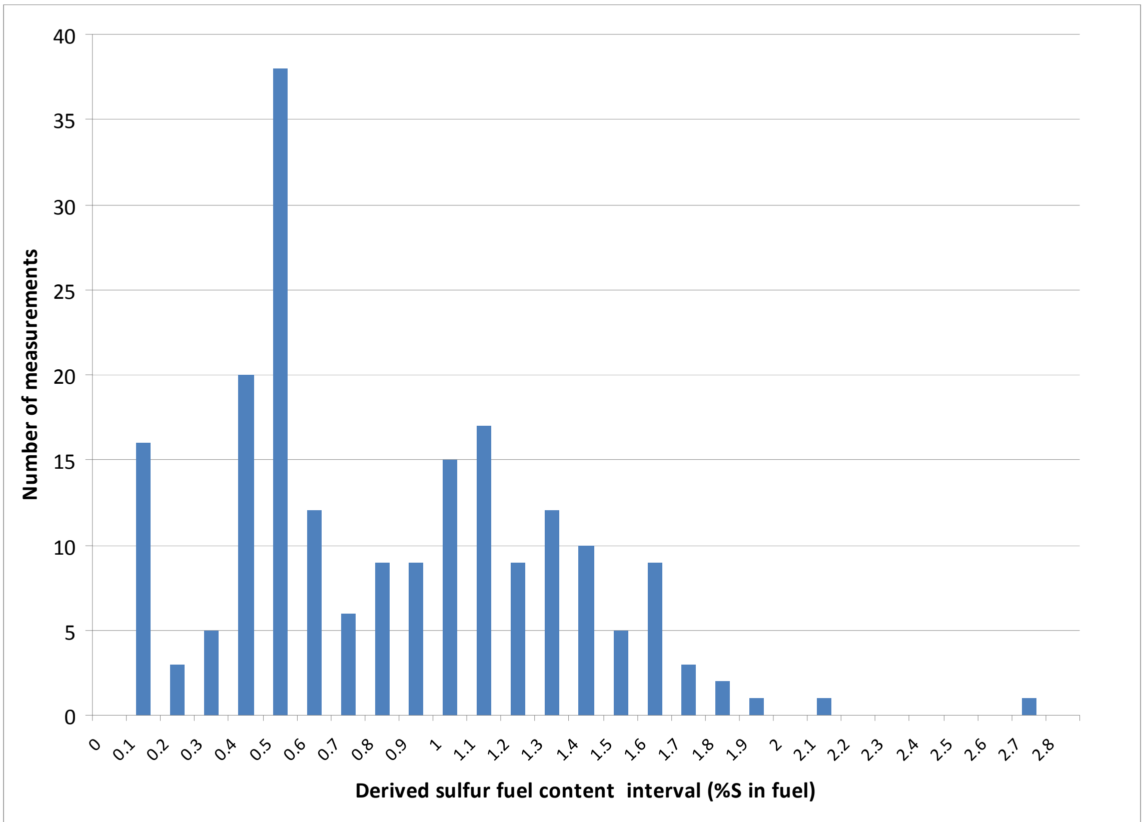

Figure 40. Histogram (number of measurements grouped into different sulfur fuel content intervals) of 220 ship measurements by the IGPS sniffer system at the fortess Nya Älvsborg, in the ship channel of Göteborg.

7. Overall discussion

In this study it is clearly demonstrated that remote surveillance of ship emissions, for enforcing the IMO emission legislation, can be carried out using the sniffer and the optical method techniques that have been developed and tested. These methods have sufficient sensitivities for both airborne and stationary measurements of ship plumes. The sniffer method has the advantage that it provides a direct measurement of the parameters that are relevant for the IMO legislation, with a demonstrated accuracy of about 15%. The main disadvantage is that one has to fly at low altitudes around 50-100 m, with the height depending on the meteorological conditions, but by choosing optimal conditions with low wind speed and measuring on ships that travel with the wind we believe this method will become even more efficient. For instance in several sniffer measurements the gas plume were encountered at a height of 250 m. The optical method on the other hand measures the absolute emission, of large environmental relevance, but to use the data for investigating compliance with the IMO limits needs to estimate the fuel consumption.

The mean sulfur fuel content in the airborne dataset obtained during the project corresponds to 1.28% and in Figure 41 a histogram of all measured ships is shown. Here a small peak at 0.5% is visible and one at 1.25 %. Only 3 ships exceeded 1.8%, which is the IMO limit when considering the uncertainty of the technique, and the measurements hence indicates that these ships run on fuel with higher sulfur fuel content than 1.5%. The data in Figure 41 are similar to the ones form the stationary measurements in Göteborg, Figure 40.

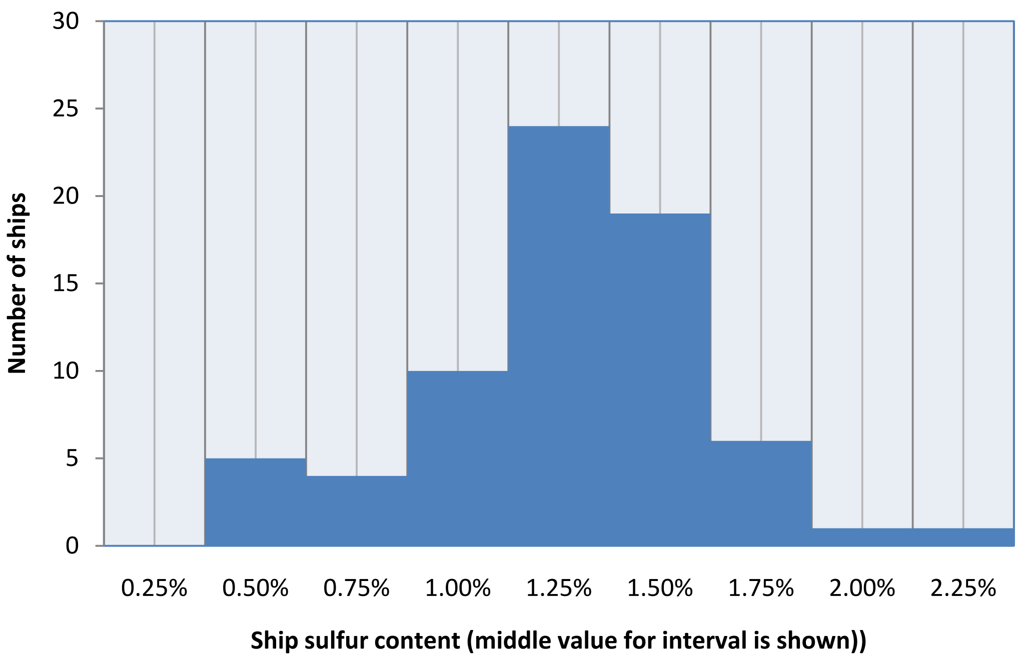

Figure 41. Histogram corresponding to the number of ships in different sulfur content intervals. The middle value in the interval is indicated. A total of 70 ships were measured using the IGPS sniffer system from the Swedish coast guard CASA 212 airplane during 2007 and 2008 on international water along the coast of Sweden.

In Figure 42 a histogram of the airborne NO_x emission measurements is shown, corresponding to the number of ships in different NO_x emission intervals. The average emission is here 13.14 gNO_x/kWh (65.7 g NOx/kg fuel) with the highest ship corresponding to 20.1 gNO_x/kWh, which is just within the Tier 1 IMO limit for slow stroke engines, considering the measurements uncertainty.

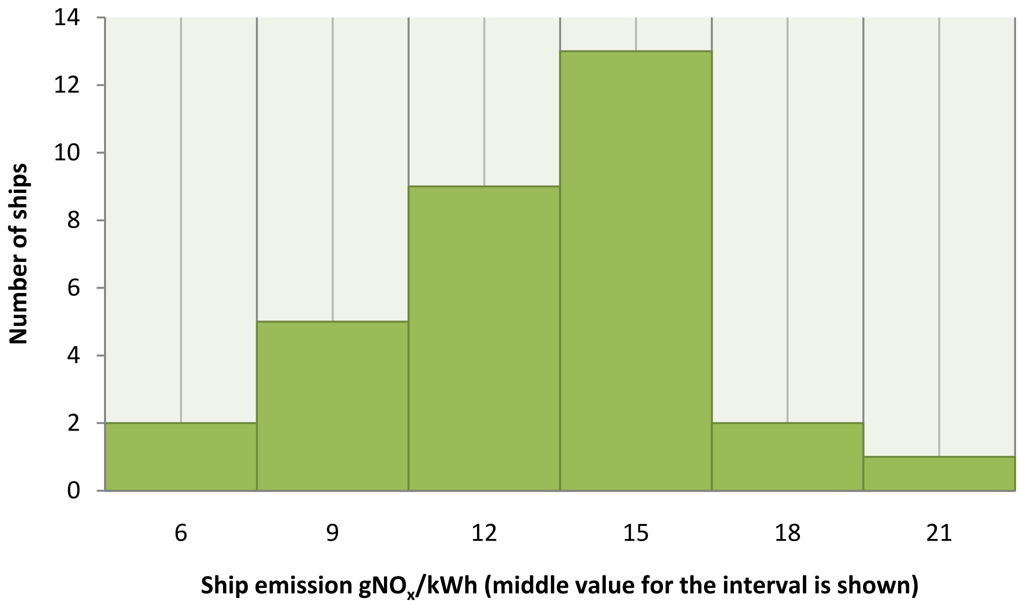

Figure 42. Histogram corresponding to the number of ships in different NO_x emission intervals. The middle value in the interval is indicated. A total of 32 ships were measured using the IGPS sniffer system from the Swedish coast guard CASA 212 airplane during 2008 on international waters along the coast of Sweden.

The sniffer and optical instruments both measure SO_2 while the sniffer also measures CO_2. By combining these two measurements, for the same ship it is hence possible to derive the CO_2 emission in kg CO_2/hour or the fuel consumption in kg fuel/hour, assuming that 87% of the fuel corresponds to carbon. In Figure 43, such results are shown for several ships. The graph actually shows predicted fuel consumption versus measured fuel consumption. The fuel consumption is here a proxy calculated from the cube of ship speed of the ship multiplied by the weight.

In the figure one can see that that oil products tanker and crude oil tanker seem to be able to have a higher speed or carry higher mass (the proxy is proportional to speed) for the same measured fuel consumption compared to ferries and ro-ro cargo ships. The former ships hence show better engine efficiency.

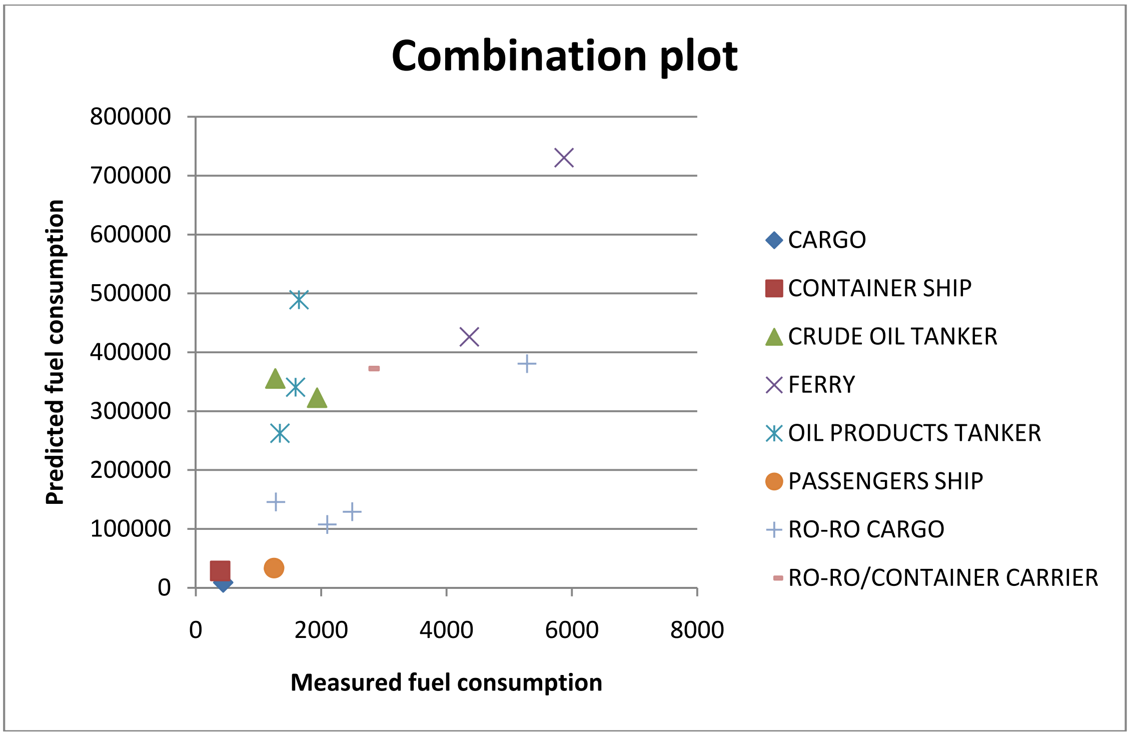

Figure 43. Measured fuel consumption obtained from combined optical and sniffer measurements of SO_2 and CO_2. The data are plotted versus the predicted fuel consumption is given by a proxy corresponding to the cube of the ship speed times the ship weight.

Further work of the measurement uncertainty for the sniffer is needed since such knowledge is crucial for any legal enforcement. Nevertheless, we estimate that the uncertainty for the sulfur content of the sniffer measurement is around 15%, with a negative bias of about 5%. This means that a measurement of 1.8% sulfur in the fuel with certainty is above the 1.5% limit. We believe that the present uncertainty is appropriate for surveillance, especially since the SECA areas now are switching to even lower fuel contents this year. However, the uncertainty can be further reduced by improving the quality assurance and quality control of the measurements. For the NO_x emissions relative to axial power (g NOx/kWh), the error corresponds to 21%, dominated by the uncertainty in ship fuel efficiency. It is uncertain whether the measurement accuracy of the IGPS system is sufficient to check compliance with the Tier II regulation (20% reduction), but whenever it is decided to introduce environmental control areas for NO_x then the Tier 3 limit, with 80% reduction, will be rather easy to control.

The optical system is capable of measuring fluxes from ships both SO_2 and NO_2 for more than half of the ships in summer time conditions. This makes it possible to utilize the optical system as a first indicator of high SO_2 emitters. More work is needed regarding uncertainties, however, especially regarding scattering in the plume and wave reflection errors and at present we are not capable of conducting good error estimation for the optical measurements, although a rough estimate is in the range 30-50%. To improve the optical data one also need to improve the quality of input data such as in the prediction of the apparent wind speed of the wind plumes.

8. Acknowledgements

We thank the Swedish Coastguard for providing the CASA airplanes and their personnel for the cooperation and project support. We also thank the project steering group corresponding to Stefan Lemieszewski, Per Ekberg, Lars Franzen and Alezander Boexhoveden. Dan Ohlsson is acknowledged for building the sniffer system and Mattias Johansson for software support. Financial support is greatly acknowledged from Vinnova, under project 2005-01835, the provincial government of Västra Götaland and the Swedish Maritime Organization. We thank the Swedish National Property Board and the tourist operator Strömma for providing access and transportation to New Älvsborg Fortress. We thank Tom Ryerson at NOAA for technical input into the measurement system and for lending us CO_2 calibration gases. We also want to thank Stena Line for providing their fuel sulfur data.

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Appendix I. Airborne sniffer measurements, around the coast of Sweden, 2007 and 2008

Date	Time	Ship Name	Flag	Ship Type	Year	IMO	MMSI	calibrated value	Measurement unit
2007-08-16	17:14:39	BIRKA EXPRESS	ALAND ISLANDS	RO-RO CARGO	1997	9131993	230,366,000	1.02	% sulfur fuel content
2007-08-16	17:18:48	BIRKA EXPRESS	ALAND ISLANDS	RO-RO CARGO	1997	9131993	230,366,000	1.07	% sulfur fuel content
2007-08-16	17:20:04	BIRKA EXPRESS	ALAND ISLANDS	RO-RO CARGO	1997	9131993	230,366,000	1.24	% sulfur fuel content
2007-08-16	17:22:09	BIRKA EXPRESS	ALAND ISLANDS	RO-RO CARGO	1997	9131993	230,366,000	1.11	% sulfur fuel content
2007-08-16	17:24:26	EMS HIGHWAY	CYPRUS	VEHICLES CARRIER	1999	9195133	212,882,000	1.30	% sulfur fuel content
2007-08-16	17:26:00	EMS HIGHWAY	CYPRUS	VEHICLES CARRIER	1999	9195133	212,882,000	0.99	% sulfur fuel content
2007-08-16	17:35:42	SOUTH MICHELLE	NETHERLANDS ANTILLES	CARGO	1975	7429267	306,729,000	0.85	% sulfur fuel content
2007-08-16	17:49:53	TISTEDAL	GIBRALTAR	CARGO	1996	9113604	236,112,000	0.53	% sulfur fuel content
2007-08-21	13:05:00	EIRINI L.	LIBERIA	BULK CARRIER	1984	8318893	636,008,000	1.21	% sulfur fuel content
2007-08-21	13:27:31	EIRINI L.	LIBERIA	BULK CARRIER	1984	8318893	636,008,000	1.24	% sulfur fuel content
2007-08-21	14:04:01	STENA JUTLANDICA	SWEDEN	RO-RO CARGO	1996	9125944	265,410,000	0.97	% sulfur fuel content
2007-08-21	14:16:07	BAO FU	JAPAN	BULK CARRIER	1987	8608937	431,274,000	1.00	% sulfur fuel content
2007-08-21	15:43:50	SCHIEBORG	NETHERLANDS	RO-RO CARGO	2000	9188233	245,749,000	0.50	% sulfur fuel content
2007-08-21	15:45:30	SCHIEBORG	NETHERLANDS	RO-RO CARGO	2000	9188233	245,749,000	0.67	% sulfur fuel content
2007-08-21	15:59:28	SCHIEBORG	NETHERLANDS	RO-RO CARGO	2000	9188233	245,749,000	0.60	% sulfur fuel content
2007-08-21	16:02:49	SCHIEBORG	NETHERLANDS	RO-RO CARGO	2000	9188233	245,749,000	0.65	% sulfur fuel content
2007-08-21	16:08:36	VLISTBORG	ANTIGUA & BARBUDA	CARGO	1999	9160346	305,479,000	0.77	% sulfur fuel content
2007-08-21	16:12:50	VLISTBORG	ANTIGUA & BARBUDA	CARGO	1999	9160346	305,479,000	0.46	% sulfur fuel content
2007-08-21	17:03:29	AVALON	GIBRALTAR	OIL PRODUCTS TANKER	2005	9327097	236,296,000	1.23	% sulfur fuel content
2007-08-21	17:06:03	AVALON	GIBRALTAR	OIL PRODUCTS TANKER	2005	9327097	236,296,000	1.24	% sulfur fuel content
2007-08-22	10:50:12	EMSBROKER	MADEIRA	CARGO	2002	9247132	255,802,000	1.05	% sulfur fuel content
2007-08-22	10:50:52	EMSBROKER	MADEIRA	CARGO	2002	9247132	255,802,000	0.89	% sulfur fuel content
2007-08-22	10:53:09	EMSBROKER	MADEIRA	CARGO	2002	9247132	255,802,000	1.22	% sulfur fuel content
2007-08-22	14:20:43	KNOCK SHEEN	SINGAPORE	CRUDE OIL TANKER	1998	9172583	565,289,000	1.61	% sulfur fuel content
2007-08-22	14:23:30	KNOCK SHEEN	SINGAPORE	CRUDE OIL TANKER	1998	9172583	565,289,000	1.47	% sulfur fuel content
2007-08-22	14:24:05	KNOCK SHEEN	SINGAPORE	CRUDE OIL TANKER	1998	9172583	565,289,000	1.61	% sulfur fuel content
2007-08-22	14:51:09	VITTA THERESA	Denmark	Chemical and Product Tankers	1991	8918605	219265000	2.95	% sulfur fuel content

2007-08-22	14:51:51	VITTA THERESA	Denmark	Chemical and Product Tankers	1991	8918605	219265000	1.10	% sulfur fuel content
2007-08-22	14:53:00	VITTA THERESA	Denmark	Chemical and Product Tankers	1991	8918605	219265000	1.63	% sulfur fuel content
2007-08-22	14:54:08	VITTA THERESA	Denmark	Chemical and Product Tankers	1991	8918605	219265000	1.86	% sulfur fuel content
2007-08-22	14:55:37	VITTA THERESA	Denmark	Chemical and Product Tankers	1991	8918605	219265000	1.80	% sulfur fuel content
2007-08-22	14:57:24	VITTA THERESA	Denmark	Chemical and Product Tankers	1991	8918605	219265000	1.73	% sulfur fuel content
2007-08-22	14:58:28	VITTA THERESA	Denmark	Chemical and Product Tankers	1991	8918605	219265000	1.71	% sulfur fuel content
2007-08-22	15:07:32	MOEZELBORG	NETHERLANDS	CARGO	1999	9180839	245,315,000	1.51	% sulfur fuel content
2007-08-22	15:08:52	STADIONGRACHT	NETHERLANDS	CARGO	2000	9202508	246,466,000	1.80	% sulfur fuel content
2007-08-22	15:22:10	KNOCK SHEEN	SINGAPORE	CRUDE OIL TANKER	1998	9172583	565,289,000	1.42	% sulfur fuel content
2007-08-22	15:26:54	KNOCK SHEEN	SINGAPORE	CRUDE OIL TANKER	1998	9172583	565,289,000	1.36	% sulfur fuel content
2007-08-22	15:33:12	DEEP BLUE	GREECE	CRUDE OIL TANKER	2005	9299903	240,350,000	1.32	% sulfur fuel content
2007-08-22	15:36:53	DEEP BLUE	GREECE	CRUDE OIL TANKER	2005	9299903	240,350,000	1.44	% sulfur fuel content
2007-08-22	15:49:44	ENGLISH BAY	HONG KONG (CHINA)	BULK CARRIER	2000	9218038	477,101,000	1.57	% sulfur fuel content
2007-08-22	16:05:48	STADIONGRACHT	NETHERLANDS	CARGO	2000	9202508	246,466,000	1.45	% sulfur fuel content
2007-08-22	16:15:28	STENA DANICA	SWEDEN	FERRY	1982	7907245	265,177,000	0.46	% sulfur fuel content
2007-09-18	14:10:10	ENERGIZER	PANAMA	OIL PRODUCTS TANKER	1995	9056571	352,702,000	1.65	% sulfur fuel content
2007-09-18	14:30:54	STENA FORECASTER	SWEDEN	RO-RO CARGO	2003	9214678	266040000	1.56	% sulfur fuel content
2007-09-18	14:31:40	STENA FORECASTER	SWEDEN	RO-RO CARGO	2003	9214678	266040000	1.34	% sulfur fuel content
2007-09-18	14:38:36	SUPERFAST VIII	ESTONIA	FERRY	2001	9198953	276,648,000	1.35	% sulfur fuel content
2007-09-18	14:42:35	SUPERFAST VIII	ESTONIA	FERRY	2001	9198953	276,648,000	1.35	% sulfur fuel content
2007-09-18	14:44:08	SUPERFAST VIII	ESTONIA	FERRY	2001	9198953	276,648,000	1.48	% sulfur fuel content
2007-09-18	14:51:48	SUPERFAST VIII	ESTONIA	FERRY	2001	9198953	276,648,000	1.26	% sulfur fuel content
2007-09-18	14:52:48	SUPERFAST VIII	ESTONIA	FERRY	2001	9198953	276,648,000	1.40	% sulfur fuel content
2007-09-18	14:54:03	SUPERFAST VIII	ESTONIA	FERRY	2001	9198953	276,648,000	1.33	% sulfur fuel content
2007-09-18	14:56:38	FINNLADY	FINLAND	FERRY	2006	9336268	230,987,000	1.42	% sulfur fuel content
2007-09-18	15:36:09	CRYSTAL CROWN	Saint Vincent and the Grenadines	REEFER	1986	8612158	377,386,000	1.82	% sulfur fuel content
2007-09-18	15:37:22	CRYSTAL CROWN	Saint Vincent and the Grenadines	REEFER	1986	8612158	377,386,000	1.67	% sulfur fuel content
2007-09-18	16:09:17	ATLANTIC PROJECT	CYPRUS	RO-RO/CONTAINER CARRIER	1988	8811340	210,359,000	1.20	% sulfur fuel content
2007-09-18	18:31:25	BALTIC FAVOUR	CYPRUS	OIL/CHEMICAL TANKER	2006	9327372	212,055,000	1.12	% sulfur fuel content

2007-09-18	18:34:36	MONTEGO	GREECE	OIL PRODUCTS TANKER	2006	9297553	240,610,000	1.56	% sulfur fuel content
2007-09-18	18:38:22	BALTIC FAVOUR	CYPRUS	OIL/CHEMICAL TANKER	2006	9327372	212,055,000	1.35	% sulfur fuel content
2007-09-18	18:56:03	LIGOVSKY PROSPECT	LIBERIA	OIL PRODUCTS TANKER	2003	9256066	636,012,000	1.37	% sulfur fuel content
2007-09-18	18:57:39	PETIMATA OT RMS	Bulgaria	BULK CARRIER	1979	7813016	207010000	1.31	% sulfur fuel content
2007-09-18	19:09:27	WILSON TYNE	MALTA	BULK CARRIER	1980	7915307	248,245,000	1.35	% sulfur fuel content
2008-08-11	15:42:01	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	7.10	NO/CO_2
2008-08-11	15:43:20	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	7.39	NO/CO_2
2008-08-11	15:43:49	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	8.28	NO/CO_2
2008-08-11	15:46:14	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	16.69	NO/CO_2
2008-08-11	15:51:49	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	12.43	NO/CO_2
2008-08-11	16:15:21	STENA CARISMA	SWEDEN	FERRY	1997	9127760	265,430,000	4.76	NO/CO_2
2008-08-11	16:17:32	STENA DANICA	SWEDEN	FERRY	1982	7907245	265,177,000	16.63	NO/CO_2
2008-08-11	16:18:57	STENA DANICA	SWEDEN	FERRY	1982	7907245	265,177,000	11.99	NO/CO_2
2008-08-11	16:20:16	STENA DANICA	SWEDEN	FERRY	1982	7907245	265,177,000	4.59	NO/CO_2
2008-08-11	17:15:56	STENA JUTLANDICA	SWEDEN	RO-RO CARGO	1996	9125944	265,410,000	7.64	NO/CO_2
2008-08-11	17:17:01	STENA JUTLANDICA	SWEDEN	RO-RO CARGO	1996	9125944	265,410,000	9.69	NO/CO_2
2008-08-11	17:18:10	STENA JUTLANDICA	SWEDEN	RO-RO CARGO	1996	9125944	265,410,000	12.39	NO/CO_2
2008-08-11	17:19:10	STENA JUTLANDICA	SWEDEN	RO-RO CARGO	1996	9125944	265,410,000	12.92	NO/CO_2
2008-08-11	17:20:33	STENA JUTLANDICA	SWEDEN	RO-RO CARGO	1996	9125944	265,410,000	14.43	NO/CO_2
2008-08-11	17:21:37	STENA JUTLANDICA	SWEDEN	RO-RO CARGO	1996	9125944	265,410,000	10.83	NO/CO_2
2008-08-11	15:07:46	PAVEL KORCHAGIN	RUSSIA	CARGO	1980	7832775	273,118,000	45.39	gNO_x/kg fuel
2008-08-11	15:08:42	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	49.71	gNO_x/kg fuel
2008-08-11	15:10:46	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	67.19	gNO_x/kg fuel
2008-08-11	15:12:32	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	71.75	gNO_x/kg fuel
2008-08-11	15:14:39	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	83.15	gNO_x/kg fuel

2008-08-11	15:16:18	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	82.71	gNO_x/kg fuel
2008-08-11	15:16:50	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	59.15	gNO_x/kg fuel
2008-08-11	15:17:46	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	75.01	gNO_x/kg fuel
2008-08-11	15:54:51	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	74.34	gNO_x/kg fuel
2008-08-11	15:55:24	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	56.52	gNO_x/kg fuel
2008-08-11	15:57:58	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	53.07	gNO_x/kg fuel
2008-08-11	15:59:30	HELENE	FAEROE ISLANDS	CARGO	1980	8007183	231,337,000	56.23	gNO_x/kg fuel
2008-08-11	16:06:26	STENA CARISMA	SWEDEN	FERRY	1997	9127760	265,430,000	26.92	gNO_x/kg fuel
2008-08-11	16:07:28	STENA CARISMA	SWEDEN	FERRY	1997	9127760	265,430,000	25.60	gNO_x/kg fuel
2008-08-11	16:08:52	STENA CARISMA	SWEDEN	FERRY	1997	9127760	265,430,000	24.65	gNO_x/kg fuel
2008-08-11	16:09:37	STENA CARISMA	SWEDEN	FERRY	1997	9127760	265,430,000	24.21	gNO_x/kg fuel
2008-08-11	16:23:18	STENA DANICA	SWEDEN	FERRY	1982	7907245	265,177,000	61.01	gNO_x/kg fuel
2008-08-11	16:26:51	STENA DANICA	SWEDEN	FERRY	1982	7907245	265,177,000	65.97	gNO_x/kg fuel
2008-08-11	17:09:07	STENA JUTLANDICA	SWEDEN	RO-RO CARGO	1996	9125944	265,410,000	63.32	gNO_x/kg fuel
2008-08-11	17:10:32	STENA JUTLANDICA	SWEDEN	RO-RO CARGO	1996	9125944	265,410,000	55.01	gNO_x/kg fuel
2008-08-11	17:11:46	STENA JUTLANDICA	SWEDEN	RO-RO CARGO	1996	9125944	265,410,000	61.42	gNO_x/kg fuel
2008-08-11	17:26:26	STENA JUTLANDICA	SWEDEN	RO-RO CARGO	1996	9125944	265,410,000	70.31	gNO_x/kg fuel
2008-08-11	17:27:13	STENA JUTLANDICA	SWEDEN	RO-RO CARGO	1996	9125944	265,410,000	61.98	gNO_x/kg fuel
2008-08-11	17:28:21	STENA JUTLANDICA	SWEDEN	RO-RO CARGO	1996	9125944	265,410,000	61.37	gNO_x/kg fuel
2008-08-11	17:29:50	STENA JUTLANDICA	SWEDEN	RO-RO CARGO	1996	9125944	265,410,000	56.90	gNO_x/kg fuel
2008-08-11	17:31:11	STENA JUTLANDICA	SWEDEN	RO-RO CARGO	1996	9125944	265,410,000	61.64	gNO_x/kg fuel
2008-08-12	15:53:58	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	3.45	NO/CO_2
2008-08-12	15:55:19	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	7.16	NO/CO_2
2008-08-12	15:56:34	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	9.21	NO/CO_2

2008-08-12	15:57:42	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	11.60	NO/CO_2
2008-08-12	16:10:43	SLINGEBORG	NETHERLANDS	RO-RO CARGO	2000	9188245	245,745,000	10.08	NO/CO_2
2008-08-12	16:10:54	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	4.68	NO/CO_2
2008-08-12	16:11:37	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	9.95	NO/CO_2
2008-08-12	16:11:49	SLINGEBORG	NETHERLANDS	RO-RO CARGO	2000	9188245	245,745,000	13.99	NO/CO_2
2008-08-12	16:12:54	SLINGEBORG	NETHERLANDS	RO-RO CARGO	2000	9188245	245,745,000	17.86	NO/CO_2
2008-08-12	16:13:12	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	14.14	NO/CO_2
2008-08-12	16:14:12	SLINGEBORG	NETHERLANDS	RO-RO CARGO	2000	9188245	245,745,000	18.27	NO/CO_2
2008-08-12	16:30:32	MAERSK SEMARANG	LIBERIA	CONTAINER SHIP	2007	9330070	636,091,000	10.29	NO/CO_2
2008-08-12	16:31:57	MAERSK SEMARANG	LIBERIA	CONTAINER SHIP	2007	9330070	636,091,000	13.47	NO/CO_2
2008-08-12	16:32:45	MAERSK SEMARANG	LIBERIA	CONTAINER SHIP	2007	9330070	636,091,000	11.50	NO/CO_2
2008-08-12	16:34:31	MAERSK SEMARANG	LIBERIA	CONTAINER SHIP	2007	9330070	636,091,000	8.82	NO/CO_2
2008-08-12	16:35:29	MAERSK SEMARANG	LIBERIA	CONTAINER SHIP	2007	9330070	636,091,000	3.14	NO/CO_2
2008-08-12	10:29:42	DISCOVERY	BERMUDA	PASSENGERS SHIP	1972	7108514	310,382,000	43.02	gNO_x/kg fuel
2008-08-12	10:29:54	FINNSTRAUM	NORWAY INTERNATIONAL REGISTER	OIL/CHEMICAL TANKER	1999	9172222	257,409,000	87.68	gNO_x/kg fuel
2008-08-12	10:54:17	HANS LEHMANN	ANTIGUA & BARBUDA	CARGO	2007	9406702	305,278,000	80.86	gNO_x/kg fuel
2008-08-12	11:24:42	KALKVIK	NORWAY INTERNATIONAL REGISTER	CARGO	2006	9341172	258,909,000	54.94	gNO_x/kg fuel
2008-08-12	11:41:03	THAMES HIGHWAY	BAHAMAS	RO-RO CARGO	2005	9316294	311,996,000	62.76	gNO_x/kg fuel
2008-08-12	12:16:38	URANUS	ANTIGUA & BARBUDA	CONTAINER SHIP	1992	9053919	304011000	77.10	gNO_x/kg fuel
2008-08-12	12:17:47	URANUS	ANTIGUA & BARBUDA	CONTAINER SHIP	1992	9053919	304011000	87.27	gNO_x/kg fuel
2008-08-12	15:36:24	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	38.84	gNO_x/kg fuel
2008-08-12	15:37:54	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	39.44	gNO_x/kg fuel
2008-08-12	15:39:08	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	57.03	gNO_x/kg fuel
2008-08-12	15:40:25	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	63.85	gNO_x/kg fuel

2008-08-12	15:41:29	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	66.31	gNO_x/kg fuel
2008-08-12	15:42:12	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	66.99	gNO_x/kg fuel
2008-08-12	15:47:18	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	39.58	gNO_x/kg fuel
2008-08-12	15:48:43	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	44.53	gNO_x/kg fuel
2008-08-12	15:50:24	GERD KNUTSEN	ISLE OF MAN (UK)	OIL PRODUCTS TANKER	1996	9041057	235,807,000	51.01	gNO_x/kg fuel
2008-08-12	16:03:13	SLINGEBORG	NETHERLANDS	RO-RO CARGO	2000	9188245	245,745,000	64.63	gNO_x/kg fuel
2008-08-12	16:19:41	MAERSK SEMARANG	LIBERIA	CONTAINER SHIP	2007	9330070	636,091,000	64.26	gNO_x/kg fuel
2008-08-12	16:20:57	MAERSK SEMARANG	LIBERIA	CONTAINER SHIP	2007	9330070	636,091,000	73.59	gNO_x/kg fuel
2008-08-12	16:22:02	MAERSK SEMARANG	LIBERIA	CONTAINER SHIP	2007	9330070	636,091,000	76.46	gNO_x/kg fuel
2008-08-12	16:22:19	MAERSK SEMARANG	LIBERIA	CONTAINER SHIP	2007	9330070	636,091,000	36.92	gNO_x/kg fuel
2008-08-12	16:23:09	MAERSK SEMARANG	LIBERIA	CONTAINER SHIP	2007	9330070	636,091,000	80.89	gNO_x/kg fuel
2008-08-12	16:24:19	MAERSK SEMARANG	LIBERIA	CONTAINER SHIP	2007	9330070	636,091,000	81.50	gNO_x/kg fuel
2008-08-12	16:24:39	MAERSK SEMARANG	LIBERIA	CONTAINER SHIP	2007	9330070	636,091,000	57.04	gNO_x/kg fuel
2008-08-12	16:25:33	MAERSK SEMARANG	LIBERIA	CONTAINER SHIP	2007	9330070	636,091,000	89.23	gNO_x/kg fuel
2008-08-12	16:26:41	MAERSK SEMARANG	LIBERIA	CONTAINER SHIP	2007	9330070	636,091,000	49.78	gNO_x/kg fuel
2008-08-12	17:06:06	FROSTA	MALTA	OIL/CHEMICAL TANKER	2006	9334296	248,114,000	45.27	gNO_x/kg fuel
2008-08-12	17:07:02	FROSTA	MALTA	OIL/CHEMICAL TANKER	2006	9334296	248,114,000	18.94	gNO_x/kg fuel
2008-08-12	17:08:08	FROSTA	MALTA	OIL/CHEMICAL TANKER	2006	9334296	248,114,000	6.78	gNO_x/kg fuel
2008-08-13	09:52:36	NAN	Hong Kong	BULK CARRIER	1981	7433490	477521000	0.68	% sulfur fuel content
2008-08-13	09:53:43	NAN	Hong Kong	BULK CARRIER	1981	7433490	477521000	0.98	% sulfur fuel content
2008-08-13	09:54:40	NAN	Hong Kong	BULK CARRIER	1981	7433490	477521000	0.95	% sulfur fuel content
2008-08-13	10:26:09	STENA NAUTICA	SWEDEN	RO-RO/PASSENGER SHIP	1986	8317954	265,859,000	0.71	% sulfur fuel content
2008-08-13	10:27:05	STENA NAUTICA	SWEDEN	RO-RO/PASSENGER SHIP	1986	8317954	265,859,000	0.38	% sulfur fuel content
2008-08-13	10:27:59	STENA NAUTICA	SWEDEN	RO-RO/PASSENGER SHIP	1986	8317954	265,859,000	0.61	% sulfur fuel content
2008-08-13	10:47:47	BIRKA TRANSPORTER	ALAND ISLANDS	RO-RO CARGO	1991	8820858	230,189,000	1.42	% sulfur fuel content

2008-08-13	10:48:46	BIRKA TRANSPORTER	ALAND ISLANDS	RO-RO CARGO	1991	8820858	230,189,000	1.13	% sulfur fuel content
2008-08-13	10:50:11	BIRKA TRANSPORTER	ALAND ISLANDS	RO-RO CARGO	1991	8820858	230,189,000	1.70	% sulfur fuel content
2008-08-13	14:16:57	SCF YENISEI	LIBERIA	OIL PRODUCTS TANKER	2007	9333412	636,013,000	1.32	% sulfur fuel content
2008-08-13	14:18:01	SCF YENISEI	LIBERIA	OIL PRODUCTS TANKER	2007	9333412	636,013,000	1.39	% sulfur fuel content
2008-08-13	14:19:11	SCF YENISEI	LIBERIA	OIL PRODUCTS TANKER	2007	9333412	636,013,000	1.01	% sulfur fuel content
2008-08-13	14:20:10	SCF YENISEI	LIBERIA	OIL PRODUCTS TANKER	2007	9333412	636,013,000	1.05	% sulfur fuel content
2008-08-13	14:21:24	SCF YENISEI	LIBERIA	OIL PRODUCTS TANKER	2007	9333412	636,013,000	1.37	% sulfur fuel content
2008-08-13	14:39:30	SUPERFAST VII	ESTONIA	FERRY	2001	9198941	276,647,000	1.20	% sulfur fuel content
2008-08-13	14:40:31	SUPERFAST VII	ESTONIA	FERRY	2001	9198941	276,647,000	1.08	% sulfur fuel content
2008-08-13	14:41:36	SUPERFAST VII	ESTONIA	FERRY	2001	9198941	276,647,000	1.20	% sulfur fuel content
2008-08-13	14:42:36	SUPERFAST VII	ESTONIA	FERRY	2001	9198941	276,647,000	1.12	% sulfur fuel content
2008-08-13	14:43:25	SUPERFAST VII	ESTONIA	FERRY	2001	9198941	276,647,000	1.19	% sulfur fuel content
2008-08-13	14:44:28	SUPERFAST VII	ESTONIA	FERRY	2001	9198941	276,647,000	1.19	% sulfur fuel content
2008-08-13	15:11:48	TRANSREEL	SWEDEN	RO-RO CARGO	1987	8515893	265,150,000	0.78	% sulfur fuel content
2008-08-13	15:12:22	TRANSREEL	SWEDEN	RO-RO CARGO	1987	8515893	265,150,000	0.87	% sulfur fuel content
2008-08-13	15:13:08	TRANSREEL	SWEDEN	RO-RO CARGO	1987	8515893	265,150,000	0.78	% sulfur fuel content
2008-08-13	15:14:10	TRANSREEL	SWEDEN	RO-RO CARGO	1987	8515893	265,150,000	0.75	% sulfur fuel content
2008-08-13	15:47:18	LITEYNY PROSPECT	LIBERIA	OIL PRODUCTS TANKER	2003	9256078	636,012,000	1.22	% sulfur fuel content
2008-08-13	15:48:05	LITEYNY PROSPECT	LIBERIA	OIL PRODUCTS TANKER	2003	9256078	636,012,000	1.12	% sulfur fuel content
2008-08-13	15:48:54	LITEYNY PROSPECT	LIBERIA	OIL PRODUCTS TANKER	2003	9256078	636,012,000	1.47	% sulfur fuel content
2008-08-13	15:49:45	LITEYNY PROSPECT	LIBERIA	OIL PRODUCTS TANKER	2003	9256078	636,012,000	1.48	% sulfur fuel content
2008-08-13	15:50:40	LITEYNY PROSPECT	LIBERIA	OIL PRODUCTS TANKER	2003	9256078	636,012,000	1.54	% sulfur fuel content
2008-08-13	15:54:22	MOSCOW KREMLIN	LIBERIA	CRUDE OIL TANKER	1998	9166390	636,011,000	1.31	% sulfur fuel content
2008-08-13	15:55:25	MOSCOW KREMLIN	LIBERIA	CRUDE OIL TANKER	1998	9166390	636,011,000	1.49	% sulfur fuel content
2008-08-13	15:57:14	MOSCOW KREMLIN	LIBERIA	CRUDE OIL TANKER	1998	9166390	636,011,000	1.22	% sulfur fuel content
2008-08-13	15:58:17	MOSCOW KREMLIN	LIBERIA	CRUDE OIL TANKER	1998	9166390	636,011,000	1.17	% sulfur fuel content
2008-08-13	16:00:20	LITEYNY PROSPECT	LIBERIA	OIL PRODUCTS TANKER	2003	9256078	636,012,000	1.19	% sulfur fuel content
2008-08-13	16:01:05	ANTARES	NORWAY INTERNATIONAL REGISTER	RO-RO CARGO	1988	8500680	257,689,000	1.04	% sulfur fuel content
2008-08-13	16:02:10	BALTIC EAGER	PANAMA	RO-RO CARGO	1979	7804065	356,277,000	1.33	% sulfur fuel content

2008-08-13	16:06:46	FINNPULP	SWEDEN	RO-RO CARGO	2002	9212644	266,295,000	1.14	% sulfur fuel content
2008-08-13	16:13:10	CARL OLDENDORFF	LIBERIA	CARGO	2002	9249025	636,091,000	1.25	% sulfur fuel content
2008-08-13	16:15:06	CRYSTAL DIAMOND	LUXEMBOURG	CHEMICAL TANKER	2006	9327059	253,281,000	1.24	% sulfur fuel content
2008-08-13	16:15:29	TRANSREEL	SWEDEN	RO-RO CARGO	1987	8515893	265,150,000	0.95	% sulfur fuel content
2008-08-13	16:16:18	TRANSREEL	SWEDEN	RO-RO CARGO	1987	8515893	265,150,000	0.79	% sulfur fuel content
2008-08-13	16:17:47	WILSON REEF	MALTA	BULK CARRIER	1975	7382665	248,200,000	1.42	% sulfur fuel content
2008-08-13	16:23:19	ISABELLA	MALTA	OIL PRODUCTS TANKER	2004	9255672	215,545,000	1.37	% sulfur fuel content
2008-08-14	08:40:42	VIA	SWEDEN	CARGO	1967	6705298	265,260,000	1.24	% sulfur fuel content
2008-08-14	08:41:06	FREDERIK	MALTA	CONTAINER SHIP	2005	9328637	256,022,000	0.97	% sulfur fuel content
2008-08-14	08:42:13	FREDERIK	MALTA	CONTAINER SHIP	2005	9328637	256,022,000	0.89	% sulfur fuel content
2008-08-14	08:43:14	FREDERIK	MALTA	CONTAINER SHIP	2005	9328637	256,022,000	1.03	% sulfur fuel content
2008-08-14	08:48:02	APATURA	GIBRALTAR	CHEMICAL TANKER	2004	9258624	236,260,000	0.79	% sulfur fuel content
2008-08-14	08:48:55	APATURA	GIBRALTAR	CHEMICAL TANKER	2004	9258624	236,260,000	1.10	% sulfur fuel content
2008-08-14	08:49:45	APATURA	GIBRALTAR	CHEMICAL TANKER	2004	9258624	236,260,000	1.06	% sulfur fuel content
2008-08-14	08:51:42	APATURA	GIBRALTAR	CHEMICAL TANKER	2004	9258624	236,260,000	1.24	% sulfur fuel content
2008-08-14	09:08:51	AUTOSUN	MADEIRA	VEHICLES CARRIER	2000	9227053	255,801,000	0.83	% sulfur fuel content
2008-08-14	09:09:39	AUTOSUN	MADEIRA	VEHICLES CARRIER	2000	9227053	255,801,000	1.02	% sulfur fuel content
2008-08-14	09:10:41	AUTOSUN	MADEIRA	VEHICLES CARRIER	2000	9227053	255,801,000	1.12	% sulfur fuel content
2008-08-14	09:11:38	AUTOSUN	MADEIRA	VEHICLES CARRIER	2000	9227053	255,801,000	0.67	% sulfur fuel content
2008-08-14	09:14:46	MARJA	NETHERLANDS	CONTAINER SHIP	1995	9113721	245,451,000	1.25	% sulfur fuel content
2008-08-14	09:15:24	OSTANHAV	SWEDEN	CARGO	1983	8129395	265,073,000	0.79	% sulfur fuel content
2008-08-14	09:19:11	PULPCA	NETHERLANDS	RO-RO CARGO	2008	9345386	245,097,000	1.21	% sulfur fuel content
2008-08-14	09:19:55	PULPCA	NETHERLANDS	RO-RO CARGO	2008	9345386	245,097,000	1.12	% sulfur fuel content
2008-08-14	09:20:33	PULPCA	NETHERLANDS	RO-RO CARGO	2008	9345386	245,097,000	0.90	% sulfur fuel content
2008-08-14	09:21:13	PULPCA	NETHERLANDS	RO-RO CARGO	2008	9345386	245,097,000	0.95	% sulfur fuel content
2008-08-14	10:05:04	FINNMAID	FINLAND	FERRY	2006	9319466	230,982,000	1.12	% sulfur fuel content
2008-08-14	10:05:03	FINNMAID	FINLAND	FERRY	2006	9319466	230,982,000	1.04	% sulfur fuel content
2008-08-14	10:05:37	FINNMAID	FINLAND	FERRY	2006	9319466	230,982,000	1.12	% sulfur fuel content
2008-08-14	10:06:52	FINNMAID	FINLAND	FERRY	2006	9319466	230,982,000	1.08	% sulfur fuel content

2008-08-14	10:07:38	MERCHANT	GERMANY	RO-RO CARGO	1982	8020604	218,252,000	1.23	% sulfur fuel content
2008-08-14	10:08:25	MERCHANT	GERMANY	RO-RO CARGO	1982	8020604	218,252,000	1.57	% sulfur fuel content
2008-08-14	10:09:53	MERCHANT	GERMANY	RO-RO CARGO	1982	8020604	218,252,000	1.55	% sulfur fuel content
2008-08-14	10:10:45	FINNMAID	FINLAND	FERRY	2006	9319466	230,982,000	1.30	% sulfur fuel content
2008-08-21	11:44:58	TIMCA	NETHERLANDS	RO-RO/CONTAINER CARRIER	2006	9307358	246,521,000	1.31	% sulfur fuel content
2008-08-21	11:45:56	TIMCA	NETHERLANDS	RO-RO/CONTAINER CARRIER	2006	9307358	246,521,000	1.19	% sulfur fuel content
2008-08-21	11:46:45	TIMCA	NETHERLANDS	RO-RO/CONTAINER CARRIER	2006	9307358	246,521,000	1.42	% sulfur fuel content
2008-08-21	11:47:26	TIMCA	NETHERLANDS	RO-RO/CONTAINER CARRIER	2006	9307358	246,521,000	1.31	% sulfur fuel content
2008-08-21	11:48:10	TIMCA	NETHERLANDS	RO-RO/CONTAINER CARRIER	2006	9307358	246,521,000	1.36	% sulfur fuel content
2008-08-21	11:48:55	TIMCA	NETHERLANDS	RO-RO/CONTAINER CARRIER	2006	9307358	246,521,000	1.80	% sulfur fuel content
2008-08-21	12:20:06	CARTAGENA	ANTIGUA & BARBUDA	CONTAINER SHIP	1995	9123817	304,753,000	1.11	% sulfur fuel content
2008-08-21	12:20:49	CARTAGENA	ANTIGUA & BARBUDA	CONTAINER SHIP	1995	9123817	304,753,000	1.03	% sulfur fuel content
2008-08-21	12:21:29	CARTAGENA	ANTIGUA & BARBUDA	CONTAINER SHIP	1995	9123817	304,753,000	1.01	% sulfur fuel content
2008-08-21	12:38:13	RUSICH 5	RUSSIA	CARGO	2005	9353046	273,317,000	1.07	% sulfur fuel content
2008-08-21	12:38:51	RUSICH 5	RUSSIA	CARGO	2005	9353046	273,317,000	1.26	% sulfur fuel content
2008-08-21	12:50:20	BALTIC BREEZE	SINGAPORE	VEHICLES CARRIER	1983	8312590	563,374,000	1.70	% sulfur fuel content
2008-08-21	12:53:52	BALTIC BREEZE	SINGAPORE	VEHICLES CARRIER	1983	8312590	563,374,000	1.39	% sulfur fuel content
2008-08-21	17:14:14	MINERVA ASTRA	GREECE	CRUDE OIL TANKER	2001	9230098	237,841,000	1.46	% sulfur fuel content
2008-08-21	17:15:00	MINERVA ASTRA	GREECE	CRUDE OIL TANKER	2001	9230098	237,841,000	1.61	% sulfur fuel content
2008-08-21	17:15:36	MINERVA ASTRA	GREECE	CRUDE OIL TANKER	2001	9230098	237,841,000	1.20	% sulfur fuel content
2008-08-21	17:19:08	EAGLE TURIN	SINGAPORE	CRUDE OIL TANKER	2008	9360465	565,770,000	1.33	% sulfur fuel content
2008-08-21	17:19:44	EAGLE TURIN	SINGAPORE	CRUDE OIL TANKER	2008	9360465	565,770,000	1.40	% sulfur fuel content
2008-08-21	17:35:42	PIONEER ATLANTIC	PANAMA	BULK CARRIER	1998	9057458	353,269,000	1.48	% sulfur fuel content
2008-08-21	17:36:16	PIONEER ATLANTIC	PANAMA	BULK CARRIER	1998	9057458	353,269,000	1.11	% sulfur fuel content
2008-08-21	17:36:57	PIONEER ATLANTIC	PANAMA	BULK CARRIER	1998	9057458	353,269,000	1.05	% sulfur fuel content
2008-08-21	17:38:13	PIONEER ATLANTIC	PANAMA	BULK CARRIER	1998	9057458	353,269,000	1.52	% sulfur fuel content
2008-08-21	17:56:44	TONGAN	GERMANY	CARGO	2007	9371402	218,106,000	1.42	% sulfur fuel content
2008-08-21	18:03:41	TONGAN	GERMANY	CARGO	2007	9371402	218,106,000	1.63	% sulfur fuel content

2008-08-22	14:23:00	TRANSREEL	SWEDEN	RO-RO CARGO	1987	8515893	265,150,000	10.77	NO/CO_2
2008-08-22	14:25:36	TRANSREEL	SWEDEN	RO-RO CARGO	1987	8515893	265,150,000	11.59	NO/CO_2
2008-08-22	14:52:27	AURORA	GERMANY	RO-RO CARGO	1982	8020599	211,622,000	8.26	NO/CO_2
2008-08-22	14:53:07	AURORA	GERMANY	RO-RO CARGO	1982	8020599	211,622,000	10.08	NO/CO_2
2008-08-22	14:53:41	AURORA	GERMANY	RO-RO CARGO	1982	8020599	211,622,000	12.00	NO/CO_2
2008-08-22	14:54:11	AURORA	GERMANY	RO-RO CARGO	1982	8020599	211,622,000	11.54	NO/CO_2
2008-08-22	14:54:44	AURORA	GERMANY	RO-RO CARGO	1982	8020599	211,622,000	12.58	NO/CO_2
2008-08-22	15:20:29	FINNMAID	FINLAND	FERRY	2006	9319466	230,982,000	19.96	NO/CO_2
2008-08-22	15:24:39	FINNMAID	FINLAND	FERRY	2006	9319466	230,982,000	23.76	NO/CO_2
2008-08-22	15:26:06	FINNMAID	FINLAND	FERRY	2006	9319466	230,982,000	18.95	NO/CO_2
2008-08-22	15:27:10	FINNMAID	FINLAND	FERRY	2006	9319466	230,982,000	20.84	NO/CO_2
2008-08-22	14:13:56	TRANSREEL	SWEDEN	RO-RO CARGO	1987	8515893	265,150,000	44.92	gNO_x/kg fuel
2008-08-22	14:14:37	TRANSREEL	SWEDEN	RO-RO CARGO	1987	8515893	265,150,000	52.12	gNO_x/kg fuel
2008-08-22	14:16:30	TRANSREEL	SWEDEN	RO-RO CARGO	1987	8515893	265,150,000	48.66	gNO_x/kg fuel
2008-08-22	14:18:32	TRANSREEL	SWEDEN	RO-RO CARGO	1987	8515893	265,150,000	44.30	gNO_x/kg fuel
2008-08-22	14:44:05	AURORA	GERMANY	RO-RO CARGO	1982	8020599	211,622,000	67.55	gNO_x/kg fuel
2008-08-22	14:44:53	AURORA	GERMANY	RO-RO CARGO	1982	8020599	211,622,000	64.36	gNO_x/kg fuel
2008-08-22	14:45:30	AURORA	GERMANY	RO-RO CARGO	1982	8020599	211,622,000	60.22	gNO_x/kg fuel
2008-08-22	14:46:13	AURORA	GERMANY	RO-RO CARGO	1982	8020599	211,622,000	61.21	gNO_x/kg fuel
2008-08-22	14:46:46	AURORA	GERMANY	RO-RO CARGO	1982	8020599	211,622,000	61.59	gNO_x/kg fuel
2008-08-22	14:47:17	AURORA	GERMANY	RO-RO CARGO	1982	8020599	211,622,000	82.59	gNO_x/kg fuel
2008-08-22	15:09:01	FINNMAID	FINLAND	FERRY	2006	9319466	230,982,000	89.12	gNO_x/kg fuel
2008-08-22	15:14:03	FINNMAID	FINLAND	FERRY	2006	9319466	230,982,000	106.89	gNO_x/kg fuel
2008-08-22	15:13:48	FINNMAID	FINLAND	FERRY	2006	9319466	230,982,000	40.32	gNO_x/kg fuel

2008-08-22	15:16:00	FINNMAID	FINLAND	FERRY	2006	9319466	230,982,000	68.38	gNO_x/kg fuel
2008-08-22	15:17:02	FINNMAID	FINLAND	FERRY	2006	9319466	230,982,000	79.52	gNO_x/kg fuel
2008-08-23	13:30:08	TRANSEUROPA	GERMANY	RO-RO CARGO	1995	9010175	211,687,000	19.46	NO/CO_2
2008-08-23	13:33:09	TRANSEUROPA	GERMANY	RO-RO CARGO	1995	9010175	211,687,000	21.64	NO/CO_2
2008-08-23	13:57:07	SUN EMERALD	SAINT VINCENT & GRENADINES	REEFER	1983	8012310	377,435,000	8.51	NO/CO_2
2008-08-23	13:57:53	SUN EMERALD	SAINT VINCENT & GRENADINES	REEFER	1983	8012310	377,435,000	13.72	NO/CO_2
2008-08-23	13:58:39	SUN EMERALD	SAINT VINCENT & GRENADINES	REEFER	1983	8012310	377,435,000	14.57	NO/CO_2
2008-08-23	16:20:31	FINLANDIA	GERMANY	RO-RO CARGO	1981	8002640	218,033,000	14.73	NO/CO_2
2008-08-23	16:25:44	FINLANDIA	GERMANY	RO-RO CARGO	1981	8002640	218,033,000	11.89	NO/CO_2
2008-08-23	16:42:13	MARE ACTION	MARSHALL ISLANDS	OIL/CHEMICAL TANKER	2005	9295335	538,090,000	21.18	NO/CO_2
2008-08-23	16:44:39	MARE ACTION	MARSHALL ISLANDS	OIL/CHEMICAL TANKER	2005	9295335	538,090,000	16.22	NO/CO_2
2008-08-23	17:06:11	KANG HONG	HONG KONG (CHINA)	BULK CARRIER	2005	9323558	477,995,000	4.46	NO/CO_2
2008-08-23	17:06:54	KANG HONG	HONG KONG (CHINA)	BULK CARRIER	2005	9323558	477,995,000	5.98	NO/CO_2
2008-08-23	17:07:37	KANG HONG	HONG KONG (CHINA)	BULK CARRIER	2005	9323558	477,995,000	11.88	NO/CO_2
2008-08-23	17:08:12	KANG HONG	HONG KONG (CHINA)	BULK CARRIER	2005	9323558	477,995,000	16.39	NO/CO_2
2008-08-23	17:08:40	KANG HONG	HONG KONG (CHINA)	BULK CARRIER	2005	9323558	477,995,000	18.34	NO/CO_2
2008-08-23	12:58:21	BALTIC SEA I	CYPRUS	OIL/CHEMICAL TANKER	2003	9261396	212,100,000	77.42	gNO_x/kg fuel
2008-08-23	13:00:43	BALTIC SEA I	CYPRUS	OIL/CHEMICAL TANKER	2003	9261396	212,100,000	73.47	gNO_x/kg fuel
2008-08-23	13:01:29	BALTIC SEA I	CYPRUS	OIL/CHEMICAL TANKER	2003	9261396	212,100,000	67.53	gNO_x/kg fuel
2008-08-23	13:03:25	BALTIC SEA I	CYPRUS	OIL/CHEMICAL TANKER	2003	9261396	212,100,000	47.91	gNO_x/kg fuel
2008-08-23	13:20:50	TRANSEUROPA	GERMANY	RO-RO CARGO	1995	9010175	211,687,000	79.00	gNO_x/kg fuel
2008-08-23	13:22:39	TRANSEUROPA	GERMANY	RO-RO CARGO	1995	9010175	211,687,000	73.07	gNO_x/kg fuel
2008-08-23	13:25:16	TRANSEUROPA	GERMANY	RO-RO CARGO	1995	9010175	211,687,000	88.21	gNO_x/kg fuel
2008-08-23	13:27:18	TRANSEUROPA	GERMANY	RO-RO CARGO	1995	9010175	211,687,000	74.37	gNO_x/kg fuel

2008-08-23	13:52:15	SUN EMERALD	SAINT VINCENT & GRENADINES	REEFER	1983	8012310	377,435,000	81.10	gNO_x/kg fuel
2008-08-23	13:53:08	SUN EMERALD	SAINT VINCENT & GRENADINES	REEFER	1983	8012310	377,435,000	77.47	gNO_x/kg fuel
2008-08-23	13:53:53	SUN EMERALD	SAINT VINCENT & GRENADINES	REEFER	1983	8012310	377,435,000	54.08	gNO_x/kg fuel
2008-08-23	14:15:36	GRIGORIY ALEKSANDROV	RUSSIA	BULK CARRIER	1986	8610215	273,141,000	51.04	gNO_x/kg fuel
2008-08-23	14:16:27	GRIGORIY ALEKSANDROV	RUSSIA	BULK CARRIER	1986	8610215	273,141,000	88.31	gNO_x/kg fuel
2008-08-23	14:17:20	GRIGORIY ALEKSANDROV	RUSSIA	BULK CARRIER	1986	8610215	273,141,000	72.55	gNO_x/kg fuel
2008-08-23	14:19:03	GRIGORIY ALEKSANDROV	RUSSIA	BULK CARRIER	1986	8610215	273,141,000	83.00	gNO_x/kg fuel
2008-08-23	14:20:15	GRIGORIY ALEKSANDROV	RUSSIA	BULK CARRIER	1986	8610215	273,141,000	81.33	gNO_x/kg fuel
2008-08-23	16:11:23	FINLANDIA	GERMANY	RO-RO CARGO	1981	8002640	218,033,000	57.56	gNO_x/kg fuel
2008-08-23	16:14:04	FINLANDIA	GERMANY	RO-RO CARGO	1981	8002640	218,033,000	43.66	gNO_x/kg fuel
2008-08-23	16:27:27	FINLANDIA	GERMANY	RO-RO CARGO	1981	8002640	218,033,000	44.66	gNO_x/kg fuel
2008-08-23	16:27:40	FINLANDIA	GERMANY	RO-RO CARGO	1981	8002640	218,033,000	40.21	gNO_x/kg fuel
2008-08-23	16:36:23	MARE ACTION	MARSHALL ISLANDS	OIL/CHEMICAL TANKER	2005	9295335	538,090,000	95.07	gNO_x/kg fuel
2008-08-23	16:39:01	MARE ACTION	MARSHALL ISLANDS	OIL/CHEMICAL TANKER	2005	9295335	538,090,000	106.03	gNO_x/kg fuel
2008-08-23	16:51:44	TAIPAN	GERMANY	CARGO	2007	9349174	218,053,000	70.65	gNO_x/kg fuel
2008-08-23	17:11:44	KANG HONG	HONG KONG (CHINA)	BULK CARRIER	2005	9323558	477,995,000	91.84	gNO_x/kg fuel
2008-08-23	17:12:20	KANG HONG	HONG KONG (CHINA)	BULK CARRIER	2005	9323558	477,995,000	93.77	gNO_x/kg fuel
2008-08-23	17:28:01	MAERSK NAIRN	MALTA	OIL/CHEMICAL TANKER	2006	9312080	249231000	71.47	gNO_x/kg fuel
2008-08-23	17:29:03	MAERSK NAIRN	MALTA	OIL/CHEMICAL TANKER	2006	9312080	249231000	53.61	gNO_x/kg fuel
2008-08-24	13:33:39	WEC MAJORELLE	CYPRUS	CONTAINER SHIP	1995	9108063	210,716,000	1.56	% sulfur fuel content
2008-08-24	13:36:39	WEC MAJORELLE	CYPRUS	CONTAINER SHIP	1995	9108063	210,716,000	1.77	% sulfur fuel content
2008-08-24	13:38:44	AMUR 2514	RUSSIA	CARGO	1986	8721404	273,319,000	1.65	% sulfur fuel content
2008-08-24	13:40:44	SEABOURN PRIDE	BAHAMAS	PASSENGERS SHIP	1988	8707343	311,084,000	1.98	% sulfur fuel content
2008-08-24	13:42:54	ICELAND CEMENT	BAHAMAS	CEMENT CARRIER	1978	7638349	311,738,000	2.28	% sulfur fuel content
2008-08-24	13:47:55	SEABOURN PRIDE	BAHAMAS	PASSENGERS SHIP	1988	8707343	311,084,000	1.39	% sulfur fuel content

2008-08-24	14:01:17	MASTERA	FINLAND	CRUDE OIL TANKER	2003	9235892	230,945,000	1.62	% sulfur fuel content
2008-08-24	14:04:19	MASTERA	FINLAND	CRUDE OIL TANKER	2003	9235892	230,945,000	1.60	% sulfur fuel content
2008-08-24	14:06:12	MASTERA	FINLAND	CRUDE OIL TANKER	2003	9235892	230,945,000	1.64	% sulfur fuel content
2008-08-24	14:08:26	TORM FOX	DENMARK INTERNATIONAL REGISTER	OIL/CHEMICAL TANKER	2005	9302114	220,568,000	1.05	% sulfur fuel content
2008-08-24	14:09:49	TORM FOX	DENMARK INTERNATIONAL REGISTER	OIL/CHEMICAL TANKER	2005	9302114	220,568,000	1.34	% sulfur fuel content
2008-08-24	14:12:57	TORM FOX	DENMARK INTERNATIONAL REGISTER	OIL/CHEMICAL TANKER	2005	9302114	220,568,000	1.89	% sulfur fuel content
2008-08-24	14:37:22	SIRRAH	NETHERLANDS	CONTAINER SHIP	2002	9255402	244,371,000	1.47	% sulfur fuel content
2008-08-24	14:45:00	PETERSBURG	LIBERIA	RO-RO CARGO	1986	8311883	636,091,000	1.75	% sulfur fuel content
2008-08-24	14:45:43	PETERSBURG	LIBERIA	RO-RO CARGO	1986	8311883	636,091,000	1.66	% sulfur fuel content
2008-08-24	14:48:52	PETERSBURG	LIBERIA	RO-RO CARGO	1986	8311883	636,091,000	1.18	% sulfur fuel content
2008-08-24	15:22:02	BETIS	HONG KONG (CHINA)	BULK CARRIER	2004	9288514	477,701,000	1.88	% sulfur fuel content
2008-08-24	15:23:19	BETIS	HONG KONG (CHINA)	BULK CARRIER	2004	9288514	477,701,000	2.05	% sulfur fuel content
2008-08-24	15:24:09	BETIS	HONG KONG (CHINA)	BULK CARRIER	2004	9288514	477,701,000	2.02	% sulfur fuel content
2008-08-24	09:42:25	BEACHY HEAD	U.K.	RO-RO CARGO	2003	9234094	235,573,000	4.40	NO/CO_2
2008-08-24	09:44:11	SCOTTISH STAR	BAHAMAS	REEFER	1985	8315994	309,053,000	16.94	NO/CO_2
2008-08-24	09:31:44	BEACHY HEAD	U.K.	RO-RO CARGO	2003	9234094	235,573,000	65.74	gNO_x/kg fuel
2008-08-24	09:32:21	SCOTTISH STAR	BAHAMAS	REEFER	1985	8315994	309,053,000	43.65	gNO_x/kg fuel
2008-08-24	09:32:50	JORK	CYPRUS	CONTAINER SHIP	2001	9234991	209,715,000	67.01	gNO_x/kg fuel
2008-08-24	09:34:10	JORK	CYPRUS	CONTAINER SHIP	2001	9234991	209,715,000	61.22	gNO_x/kg fuel
2008-08-24	09:34:31	SCOTTISH STAR	BAHAMAS	REEFER	1985	8315994	309,053,000	87.14	gNO_x/kg fuel
2008-08-24	09:35:03	BEACHY HEAD	U.K.	RO-RO CARGO	2003	9234094	235,573,000	61.12	gNO_x/kg fuel
2008-08-24	09:36:20	BEACHY HEAD	U.K.	RO-RO CARGO	2003	9234094	235,573,000	77.98	gNO_x/kg fuel
2008-08-24	09:37:02	SCOTTISH STAR	BAHAMAS	REEFER	1985	8315994	309,053,000	79.41	gNO_x/kg fuel
2008-08-24	09:37:28	JORK	CYPRUS	CONTAINER SHIP	2001	9234991	209,715,000	104.45	gNO_x/kg fuel
2008-08-24	09:57:06	SNOW LAND	Cook Islands	REEFER	1972	7203223	518173000	85.87	gNO_x/kg fuel
2008-08-24	09:58:45	SNOW LAND	Cook Islands	REEFER	1972	7203223	518173000	76.02	gNO_x/kg fuel

2008-08-24	10:04:01	SNOW LAND	Cook Islands	REEFER	1972	7203223	518173000	69.17	gNO_x/kg fuel
2008-08-24	10:18:22	BEACHY HEAD	U.K.	RO-RO CARGO	2003	9234094	235,573,000	80.32	gNO_x/kg fuel
2008-08-24	10:32:03	MASTERA	FINLAND	CRUDE OIL TANKER	2003	9235892	230,945,000	65.12	gNO_x/kg fuel
2008-08-24	10:34:30	MASTERA	FINLAND	CRUDE OIL TANKER	2003	9235892	230,945,000	74.08	gNO_x/kg fuel

Appendix II Stationary sniffer measurements Älvsborgsfästning.

Time	IMO	% Sulfur fuel content
2007-06-11 16:03	209840000	1.56
2007-06-29 22:00	210987000	0.43
2007-06-15 09:06	211237900	1.26
2007-06-11 17:59	211278920	1.40
2007-06-12 09:34	219359000	2.53
2007-05-25 19:01	219851000	0.75
2007-06-05 14:51	219961000	1.14
2007-06-29 02:58	220223000	0.95
2007-07-13 19:39	220223000	1.35
2007-06-13 15:42	220253000	1.33
2007-06-24 10:02	220253000	1.18
2007-05-24 16:08	220253000	1.28
2007-06-16 18:26	220464000	0.60
2007-06-14 00:14	230965000	0.94
2007-07-02 11:50	233150000	0.07
2007-06-07 20:34	234648000	1.02
2007-06-16 18:15	234648000	0.58
2007-06-30 18:00	234648000	1.25
2007-06-15 07:58	235054390	1.49
2007-06-08 08:20	235506000	0.53
2007-06-08 03:11	235613000	1.09
2007-06-08 11:50	235613000	1.19
2007-07-04 12:26	235613000	1.11
2007-05-25 12:54	235613000	1.11
2007-05-26 08:30	244063000	0.76
2007-06-29 06:50	244180000	0.85
2007-06-29 06:57	244180000	0.78
2007-06-08 09:42	244268000	1.17
2007-05-25 11:33	244268000	1.05
2007-07-02 06:38	244735000	0.87
2007-06-06 00:04	245452000	0.67
2007-06-29 12:41	245452000	0.68
2007-06-11 23:51	245745000	0.51
2007-06-24 17:40	245745000	0.32
2007-05-26 06:18	245745000	0.29
2007-06-30 05:09	245749000	0.75
2007-06-30 14:02	245749000	0.81
2007-05-24 20:04	245749000	0.27
2007-05-25 01:49	245749000	0.56

2007-05-25 09:54	246497000	0.68
2007-05-26 02:07	246497000	0.38
2007-05-25 20:41	246549000	0.73
2007-06-25 14:55	246550000	1.16
2007-05-25 07:13	255623000	0.89
2007-05-25 07:12	255623000	0.76
2007-06-06 08:48	256200000	1.13
2007-06-15 07:46	256200000	0.99
2007-05-24 20:11	256200000	0.91
2007-06-30 06:13	257363000	1.13
2007-05-23 20:16	257433000	0.92
2007-06-13 18:38	265025000	0.65
2007-05-14 14:19	265025000	0.37
2007-06-23 10:00	265092000	0.45
2007-06-08 09:57	265177000	0.34
2007-06-12 10:09	265177000	0.38
2007-06-12 19:21	265177000	0.41
2007-06-20 10:00	265177000	0.36
2007-06-21 09:55	265177000	0.32
2007-06-23 10:04	265177000	0.35
2007-06-26 10:04	265177000	0.26
2007-06-24 19:09	265177000	0.32
2007-06-25 01:42	265177000	0.24
2007-06-29 09:48	265177000	0.37
2007-06-29 17:14	265177000	0.28
2007-06-30 09:53	265177000	0.41
2007-06-30 16:14	265177000	0.47
2007-07-01 09:46	265177000	0.43
2007-05-23 19:19	265177000	0.33
2007-05-25 10:12	265177000	0.32
2007-05-25 19:18	265177000	0.32
2007-05-26 01:43	265177000	0.24
2007-05-26 09:57	265177000	0.30
2007-06-13 19:51	265200000	0.33
2007-06-13 19:55	265200000	1.07
2007-06-15 19:48	265200000	0.38
2007-06-29 19:45	265200000	0.32
2007-07-01 08:21	265200000	0.34
2007-05-23 19:47	265200000	0.44
2007-06-14 00:13	265223000	0.90
2007-06-15 06:58	265223000	1.10

2007-06-29 09:35	265223000	0.04
2007-06-15 09:18	265246000	1.12
2007-06-07 13:39	265285000	1.02
2007-06-08 10:52	265285000	0.72
2007-06-09 13:43	265285000	0.99
2007-06-13 13:43	265285000	0.93
2007-06-13 23:07	265285000	0.75
2007-06-24 13:24	265285000	0.82
2007-06-24 21:06	265285000	0.87
2007-06-24 22:48	265285000	0.99
2007-06-29 11:05	265285000	0.91
2007-06-29 13:27	265285000	0.71
2007-06-29 20:49	265285000	0.81
2007-07-04 13:33	265285000	1.07
2007-05-14 11:00	265285000	0.71
2007-05-14 11:00	265285000	0.70
2007-05-24 21:03	265285000	1.03
2007-05-24 23:04	265285000	0.66
2007-05-25 13:36	265285000	0.65
2007-05-25 23:09	265285000	0.86
2007-06-08 08:28	265292000	0.40
2007-06-16 19:42	265292000	0.11
2007-06-24 10:24	265292000	0.46
2007-06-22 19:52	265292000	0.39
2007-06-22 19:52	265292000	0.39
2007-06-24 16:32	265292000	0.45
2007-06-24 19:44	265292000	0.35
2007-06-30 11:20	265292000	0.39
2007-05-24 19:48	265292000	0.39
2007-05-26 08:27	265292000	0.27
2007-05-26 01:20	265408000	0.75
2007-06-08 08:24	265410000	0.42
2007-06-12 00:39	265410000	0.43
2007-06-24 22:34	265410000	0.46
2007-06-25 00:10	265410000	0.41
2007-06-29 08:20	265410000	0.41
2007-06-29 16:27	265410000	0.41
2007-06-29 22:32	265410000	0.39
2007-06-30 16:14	265410000	0.47
2007-07-01 08:12	265410000	0.42
2007-05-23 16:37	265410000	0.37

2007-05-25 00:31	265410000	0.39
2007-05-25 08:45	265410000	0.36
2007-05-25 13:30	265410000	0.39
2007-05-25 16:31	265410000	0.31
2007-05-26 00:33	265410000	0.39
2007-05-26 06:37	265410000	0.36
2007-05-26 08:25	265410000	0.34
2007-05-25 19:33	265427000	0.57
2007-06-09 13:07	265430000	0.05
2007-06-24 13:10	265430000	0.05
2007-06-24 13:10	265430000	0.05
2007-06-24 17:04	265430000	0.07
2007-06-24 18:23	265430000	0.06
2007-06-29 18:18	265430000	0.06
2007-06-29 22:04	265430000	0.10
2007-07-02 11:55	265430000	1.17
2007-05-14 11:33	265430000	0.08
2007-05-14 11:33	265430000	0.08
2007-05-25 07:58	265430000	0.04
2007-05-26 07:54	265430000	0.06
2007-05-25 11:46	265430000	0.07
2007-05-26 13:09	265430000	0.04
2007-07-02 07:37	265478000	1.52
2007-05-23 20:11	265478000	1.40
2007-06-29 09:38	265541460	0.10
2007-06-04 13:26	265548440	0.36
2007-06-08 07:36	265550210	0.17
2007-06-29 09:42	265565010	0.07
2007-06-30 08:25	265585140	0.44
2007-05-26 09:11	265882000	1.44
2007-07-01 09:13	265883000	0.56
2007-07-01 19:19	265883000	0.91
2007-05-25 19:25	265883000	0.50
2007-06-16 17:33	265884000	0.51
2007-06-16 17:33	265884000	0.53
2007-06-16 17:33	265884000	0.53
2007-06-08 09:58	266039000	0.42
2007-06-12 19:15	266039000	0.46
2007-06-16 17:09	266039000	0.36
2007-06-24 15:10	266039000	0.37
2007-05-26 09:27	266039000	0.34

2007-06-19 19:31	266105000	0.50
2007-06-29 19:10	266105000	0.33
2007-05-23 19:13	266105000	0.32
2007-05-25 19:15	266105000	0.28
2007-05-26 05:56	266110000	0.74
2007-06-29 14:20	266120000	0.90
2007-06-06 06:41	266122000	1.08
2007-06-18 06:49	266122000	0.88
2007-06-24 15:30	266122000	1.01
2007-06-29 20:56	266122000	0.76
2007-07-02 06:34	266122000	1.14
2007-05-26 06:42	266122000	0.60
2007-06-27 09:39	266132000	1.46
2007-06-24 22:22	266132000	0.81
2007-06-30 17:32	266132000	1.39
2007-06-30 17:46	266132000	0.43
2007-05-25 21:19	266132000	1.07
2007-05-25 21:34	266132000	0.92
2007-06-24 22:51	266212000	0.04
2007-06-12 06:37	266240000	1.16
2007-06-12 23:14	266240000	1.20
2007-06-30 08:04	266240000	1.40
2007-05-23 23:34	266240000	1.24
2007-06-25 00:38	266243000	0.62
2007-05-25 23:04	266248000	0.73
2007-06-09 13:20	304010800	0.95
2007-06-29 08:54	304158000	1.38
2007-05-26 09:11	304159000	1.48
2007-06-11 16:52	304265000	0.21
2007-05-10 12:25	304753000	1.26
2007-05-25 15:00	304753000	0.98
2007-05-11 00:09	304874000	0.74
2007-06-29 06:37	305041000	1.07
2007-06-29 06:38	305041000	1.05
2007-06-07 12:54	305050000	1.94
2007-06-15 06:56	308124000	1.27
2007-07-01 16:25	308374000	1.24
2007-06-29 15:32	311332000	0.99
2007-06-11 15:58	376626000	0.78
2007-05-25 15:35	376626000	0.44
2007-05-26 04:15	538002180	0.31