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Remote monitoring of gaseous ship emissions using UV/visible solar occultation spectroscopy

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ABSTRACT

The shipping sector will contribute to a substantial fraction of the total European emissions of SO_2 and NO_x in the next decade, according to a recent EU assessment. This has already been recognized by the EU and IMO (International Maritime Organization) and various strategies to reduce these emissions are discussed and partly implemented, such as fuel sulfur capping, new engine nitrogen oxides emission limits, environmentally differentiated fairway dues, and emission trading schemes.

One tool for reducing, controlling and getting a good overview of the distribution of the emissions from the shipping sector, and making it possible to enforce new regulatory schemes, would be the ability to conduct “road side checks” of ships in real traffic, in the same manner as one today conduct such measurements on cars. A feasibility study has therefore been conducted on a new measurement method by which it is possible to remotely monitor the emissions of by-passing ships from another platform, such as a small ship. The remote sensing technique, named the Solar Occultation Flux (SOF) method, is based on measuring UV/visible spectra of the sun. From these spectra the amount of absorbing species (e.g. SO_2 and NO_2) can be derived between the measurement point and the sun. By conducting the observations on a small ship positioned leeward of the by-passing ship to be measured, and simultaneously measure the windspeed, it is possible to derive the emissions from the ship in mass per traveled length unit (i.e. kg S km^{-1}) or mass per time unit (kg S s^{-1}). The anticipated accuracy for the remote measurements is 20-30%.

The aim in this study was to investigate whether one could identify “gross” polluting ships, running on high sulfur fuel and not having NO_x catalysts installed. An additional aim was to investigate the feasibility of using this technique to assess the total emissions from the shipping sector. Measurements of ship emissions in real traffic were therefore made in the inlet channel to Göteborg, Sweden, during a field campaign in June 2001. Emissions of SO_2 (10-100 kg h^{-1}) were detected from about 15 ships during 3 days, and these ships are believed to have used fuel with a sulfur content of 2% and above. For NO_2 no good emission measurements were obtained even though this species was detected in the ship plumes on several occasions. The retrieved NO_2 values had too high variability, which was caused by a combination of problems with the equipment, non-ideal optical design and difficult spectroscopy. Further feasibility studies are therefore needed for NO_2 after having conducted improvements of the hardware and optics.

In addition to the remote measurements, the Swedish Environmental Research Institute conducted measurements on-board a ferry boat (Stena Danica) for intercomparison purposes. This ship was running on fuel with low sulfur content (0.5%) and the emissions were in most cases around 9-13 kg h^{-1} at the locations were the remote measurements were conducted. This was just in the threshold of the present SOF measurement range and in most cases the emissions from this ship were not detected. The few successful SOF measurements of Stena Danica showed values which were consistent with the on-board measurements, however. There was, on the other hand, no problem to detect emissions from the freighter Stena Rail, running on fuel with 2% sulfur content. The emissions from this freighter were about three times higher than those of Stena Danica (2-2.5 kg SO_2 km^{-1}), even though the gross tonnage is about four times lower. The SOF technique thus seems sensitive enough to identify gross polluting ships, running on fuel with high sulfuric content.

The demonstrated measurement range for SO_2, 10-100 kg h^{-1} corresponds to a considerable fraction of the measurement range required to estimate ship emissions from the whole fleet. It

seems feasible, with some optical improvements, to push the lower measurement limit downward in order to use the technique for measuring “clean” ships as well in order to conduct good emission assessments.

The remote measurements of SO_2 in this study indicate that the SOF methodology is quite appropriate for estimating ship emissions but several open questions remain regarding the spectroscopy such as how to better eliminate the solar features in order to improve the measurement sensitivity and accuracy. We believe that the SOF technique could be developed into a useful tool of pinpointing gross polluting ships at sea, concerning the species SO_2. It is, for instance, possible to construct automatic instruments to be put on coast guard vessels.

Sammanfattning

I detta pilotprojekt har en ny mätmetod, kallad SOF, demonstrerats med vilken det är möjligt att mäta svavelutsläpp i kg-per-timme eller kg-per-fartygs-km från fartyg i verklig drift. Detta görs genom att mäta ultravioletta spektra av solen från ett stillastående fartyg vilket är placerat några hundra meter lä om en fartygsfarled. Ur spektra kan mängden av svaveldioxid och kvävedioxid i plymen från förbipasserande fartyg uppskattas. Genom att också mäta vinden är det möjligt att skatta utsläppet i massa per tidsenhet med en noggrannhet på 20-30%.
En mätkampanj genomfördes under 2 veckor under juni 2001 på ett 31 m långt forskningsfartyg, M/S Arne Tiselius, och flera typer av instrument och mätmetodiker testades. Det som fungerade bäst var att utnyttja direkt solmätning i det ultravioletta området för mätning av svaveldioxid (SO_2) i plymen från förbipasserande fartyg. Under projektet genomfördes sådana mätningar under tre dagar och då uppmättes SO_2-emissioner från 15 fartyg vid inloppsrännan till Göteborghamn. Emissionerna låg i intervallet 10 till 100 kg-SO_2-per-timme och troligen gick de uppmätta båtarna på högsvavlig olja (2% eller över). I projektet genomförde även *IVL Svenska Miljöinstitutet* ombordmätning av ett antal komponenter på passagerarfärjan Stena Danica under 5 dagar. Detta gjordes i syfte att validera mätningarna. Stena Danica gick på lågsvavlig olja (0.5%) och det visade sig att dess emissioner (9-13 kg per timme) låg precis vid den undre gränsen för vad SOF metoden klarade av. Detta gjorde att utsläppsplymen från Stena Danica inte kunde mätas så ofta. Ett fåtal mätningar kunde dock göras och dessa indikerar att SOF-metodens värden är konsekventa med ombordmätningarna.

Det visade sig under projektet att optiken i den spektroskopiska utrustningen inte var optimal. Detta gav störningar i mätningar för SO_2 med sämre känslighet som följd. För NO_2 var störningarna ändå större varför några emissionsuppskattningar för detta ämne inte kunde erhållas. Vi tror oss dock veta hur vi skall förbättra optiken och tror att det finns mycket god chans att höja detektionsgränsen för SO_2 betydligt, varför man på ett bra sätt borde kunna mäta även ”renare” fartyg. För NO_2 borde detta också vara möjligt men ytterligare studier behövs för detta ämne.

Resultaten i detta projekt visar att det är möjligt att med SOF-metoden uppskatta huruvida ett fartyg går på hög eller lågsvavlig olja; detta är mycket intressant i samband med att man diskuterar svavelfria zoner till sjöss. För sådan övervakning skulle automatiska system kunna placeras på kustbevakningfartyg eller vid en fast plats nära farleden. Vi tror också, att man med ovannämnda förbättring av detektionsgränsen skulle kunna genomföra bra karteringar av svavelemissioner till sjöss. Man skulle då kunna genomföra mätningar vid t.ex. Öresund och uppskatta emissioner från ett större antal fartyg. Kombinerar man sådana mätningar med en emissionsmodell skulle en mycken bra uppskattning av Östersjöns verkliga svavelemissioner kunna erhållas.

1 INTRODUCTION

In a recent assessment [European Commission, 2002] it has been predicted the NO_x and SO_2 emissions from the shipping sector in European waters will be about the same as from land based sources in Europe in 2010. This is taking into account new EU 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. This should be compared to an average sulfur content of 4.5% for the whole fleet today. In addition to the general maximum level of 1.5%, reduced harbor fees will require even lower sulfuric levels of 0.5% and 1% for ferries and freighters, respectively. The emissions from the shipping sector is thus growing in environmental importance, wherefore the introduction of suitable, cost effective measurements techniques to monitor the emissions is an important tool.

The aim of this project, supported by Vinnova and Sjöfartsverket, was therefore to develop a new spectroscopic approach, named the Solar Occultation Flux method, and to investigate the measurement sensitivity of this technique and it's accuracy and precision, and to develop and optimize the spectroscopy and hardware. The main questions were whether it is possible to identify high emitters of NO_2 and SO_2 remotely from by-passing ships, without on board measurements, but also to investigate whether it is possible to estimate the real emissions.

In the project spectroscopic measurements were conducted from a small research ship in the Göteborg harbor and archipelago. In addition, emission measurements were carried out on-board a ferry boat (Stena Danica) by a research group from the Swedish Environmental research institute.

2 EXPERIMENTAL

A 2 week field-campaign was carried out in the Göteborg harbor and archipelago, between June 9 to June 19, 2001. Several instrumentations were carried aboard a 31 m long research ship, R/V Arne Tiselius, operated by Kristineberg Marine biological Research Laboratory, Fiskebäckskil, Figure 1. The measurements are based on recording the amount of NO_2 and SO_2 in the pathway of the solar light. This is done with a spectrometer by which the fingerprints of the absorbing species are measured in the UV/visible spectral region of the solar light. The solar light is measured either *directly,* by using a solar tracker device or *indirectly,* by-pointing a telescope to the blue sky.

The measurements were conducted both by standing still and letting the wind blow the ship plumes across but also by actively crossing the plumes by passing fairly close behind the by-passing ships. The measurements were conducted in the inlet channel to Göteborg both in the low speed part of the channel (8 knots) south of Arendal, but also further out north of Galterö where the ships were having speeds around 20 knots, Figure 2.

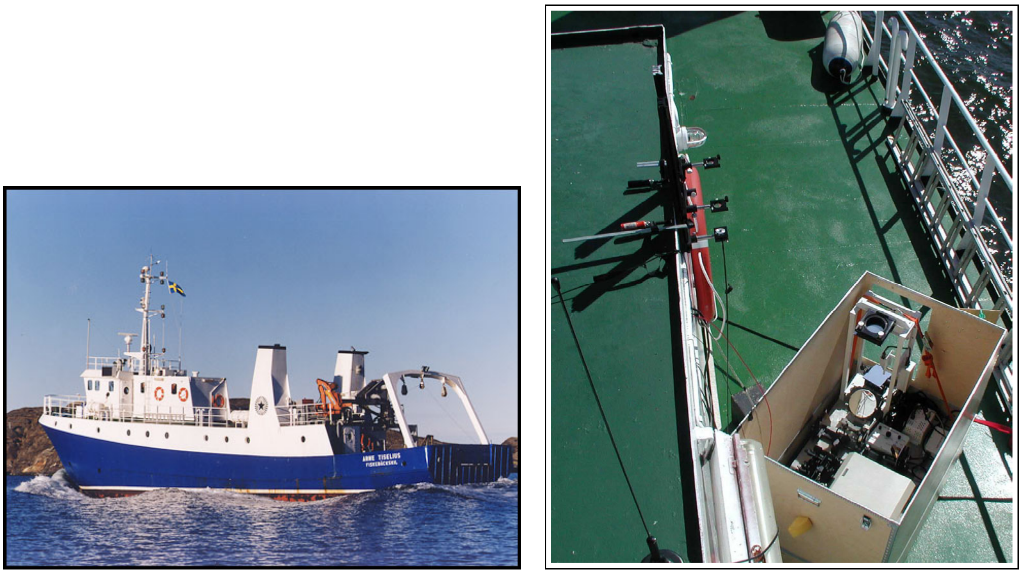

Figure 1. The research ship R/V Arne Tiselius and the solar tracker, zenith sky telescopes and the FTIR. The UV/visible instruments were positioned indoors and connected via optical fibers to the telescope.

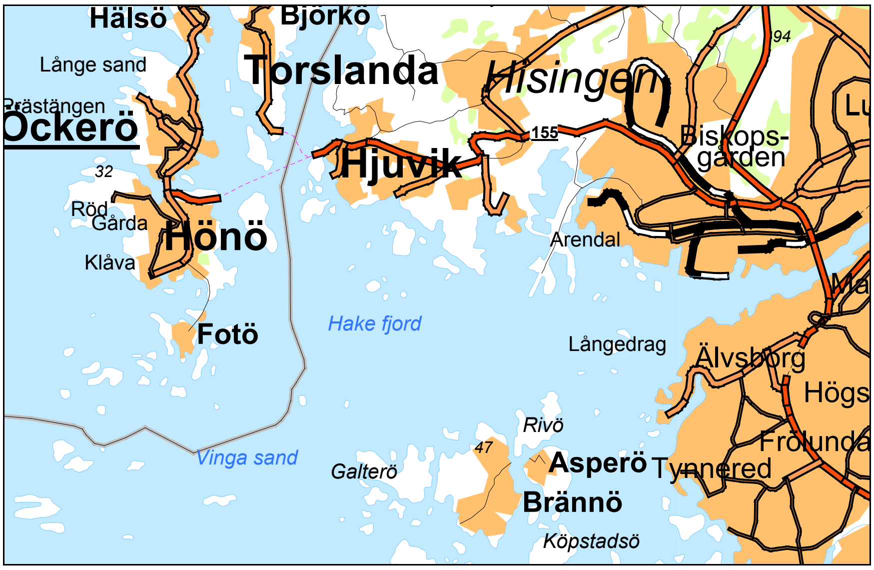

Figure 2. The measurement area in the inlet channel to Göteborg.

2.1 Hardware for the remote measurements

The remote measurements were based on several components which were tested in the project: two UV/visible and one FTIR spectrometer, a solar tracker and a GPS (Global Positioning System). The solar tracker is a device which actively "tracks" the sun and transmits the solar light into the spectrometers independently of the position of the measurement platform. The sun is caught on a primary mirror where some of the light is focused on a quadrupole detector that is connected to two regulators. These regulators control the alignment of the primary mirror in such a way that it always follows the sun and direct the light optically into the spectrometers.

Two UV/visible spectrometers and one infrared one were used to evaluate various technical aspects of the measurements, Table 1. The FTIR was malfunctioning during part of the time and results from this instrument will be presented elsewhere. The spectral resolution of the two UV-systems were fairly similar, around 0.5 nm, but on the spectrometer of the slotted disc system, which has been described in detail elsewhere (Mellqvist, 1996) it was possible to change the wavelength range, in order to retrieve both SO_2 and NO_2. For the Photodiode array (PDA) system only SO_2 could be retrieved.

Focusing lenses of 10 cm focal length were used to collect the solar light from either the solar tracker or the zenith sky, in the former case resulting in a solar image corresponding to 0.9 mm that was imaged onto the optical fibers. This was not ideal since the fiber and the corresponding spectrometer slit then was illuminated only with part of the sun. Since the Fraunhofer lines vary strongly over the surface of the sun, small changes in the solar tracking hence caused residual spectral structures. This seems to have been most critical for the retrieval of NO_2 around 430 nm and less so for SO_2 around 300 nm.

Table 1. Measurement parameters for the two UV/visible spectrometers used in the project.

Detector/ spectrometer	Fiber size	Light mode	Integ. time	Wavelength region/ species measured
1. Slotted disc and PM tube/ Thermo Jarrel-Ash spectrometer	2 mm	Direct sun/ zenith sky	7s	1: 282-352 (SO_2) 2: 412-482 (NO_2)
2. PDA detector/ self-made spectrometer with curved grating	bundle 0.2mm	Direct sun/ zenith sky	10 s	310-410 nm (SO_2)

A wind sensor (Young) was installed in the topmast of the ship (at approx. 15 m height) to measure the wind speed and direction. A Campbell CR10 logger was used to sample the meteorological values every second and these values were then averaged over one minute together with their standard deviations. This simple approach of measuring the wind at only one height at 15 m yields a potential error in the emission calculation for two reasons: firstly, most ship releases occur higher up, around 35-50 m, and secondly, some parts of the plume may get dragged down in the turbulent wake leeward of the ship. This of course depends very much on the design of the ship. The former problem can be estimated from standard formulas of height gradients of the wind at sea, Eq. 1, and the difference between 15 to 50 m corresponds to 25-35% (Ruggles, 1970).

$$U = U^*/k \ln[z/z_0] \qquad \text{(Eq. 1)}$$

here the value of U^**, the friction velocity, somewhat depends upon free wind speed. Ruggles (1970) suggests that, on average,* $U^* = 4\%$ *of the free wind speed at 10m above the surface. The value of* z_0*, the roughness length, is an indicator of the roughness of the surface over which the wind gradient is established i.e. how big and rough the waves are. Ruggles (1970) suggests that a value of* $z_0=0.001$ *to 0.01 reflects a calm sea and light airs (< 1.5 m/s), 0.5 modest ripples and gentle breezes (1.5-5 m/s), 5.0 modest waves and moderate breezes (5.1-8 m/s), and 20 substantial waves and fresh breezes (8.1-13)*

If the plume is dragged into the turbulent wake of the ship the wind of the plume will be considerably lower than the free wind at 15 m since the passing ship will then disturb the wind speed. This has not been studied to any extent in this project.

2.2 Evaluation of spectra

In Figure 3 below an intensity spectrum of the sun is shown from which it is possible to derive the amount of SO_2 (upper) and NO_2 (lower figure) in the ship plume. This is done by dividing the spectra measured inside plume s with spectra measured outside.

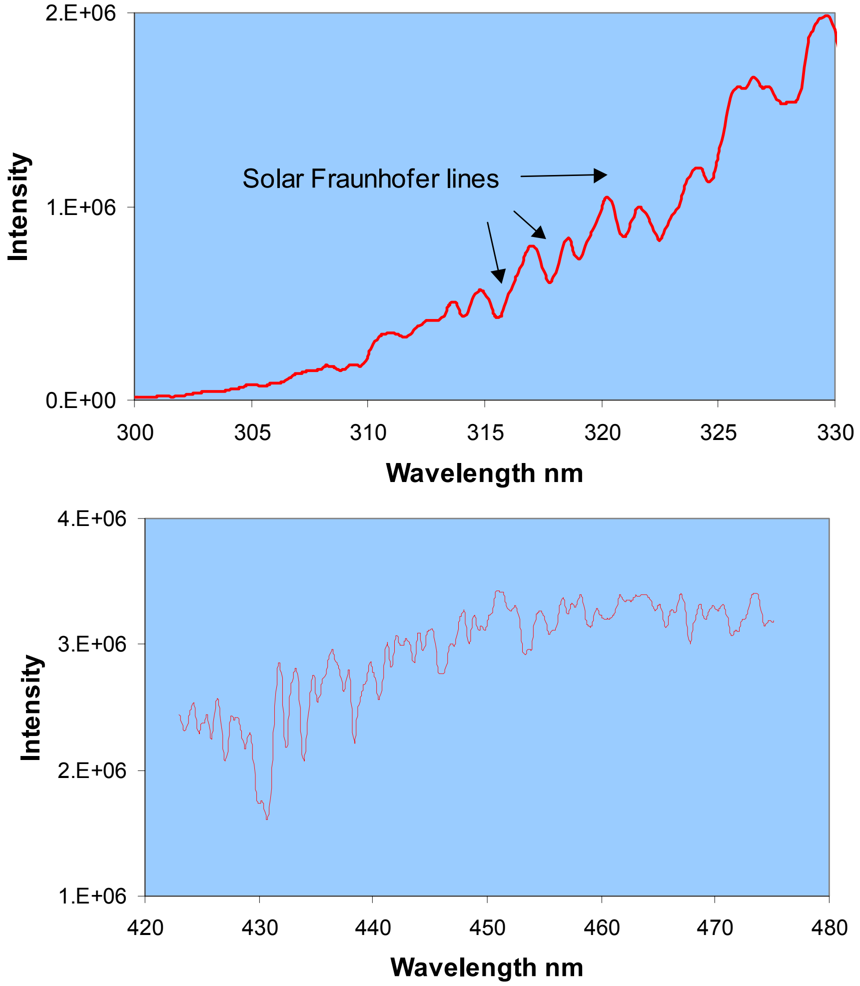

Figure 3. Measured intensity spectra (relative intensity) of the sun in two measured wavelength regions, appropriate for deriving the amount of SO_2 and NO_2, respectively, in the solar light. Some Fraunhofer lines, corresponding to absorption occurring the in the solar atmosphere, are marked.

The NO_2 region has the advantage that there is a lot of available light, but on the other hand there are also more interfering species (water, oxygen dimer), and it is easier to saturate the detector since the light varies considerably in this region (which was also the case we found out). We actually fooled ourselves during the campaign identifying an absorption peak which was thought to be NO_2 in the plume, but this was instead a small saturation of the spectra causing this structure. We therefore had to evaluate the spectra at 430 nm rather 450 nm, and in the former region there are very strong solar lines. One of the amplifiers on the instrument caused "spikes" in some spectra and saturation, not easily seen on first inspection. In addition there was a so-called grating structure around 430 nm in the spectrometer. In the SO_2 region there is considerably less light but on the other hand the disturbance from the Fraunhofer structures of the sun also seems to be much smaller.

The spectra measured in the plume are divided by a reference spectrum recorded outside the plume, so that the atmosphere, the inherent structure of the sun and the instrument function are eliminated. Every spectrum provides information of the molecules that are present between the instrument and the sun. This is called the total column, and is expressed in mg/m^2. The total column of the individual key species are retrieved from every spectrum by high pass filtering the spectra according the algorithms proposed by Platt and Perner [1979], and then fitting reference spectra [Vandaele, 1994] of various species as measured in the laboratory and ring spectra derived from the algorithms by a software package provided by IASB, named winDOAS. The spectral retrieval has been conducted both by using a homemade software [Mellqvist , 1996] and the software DOASIS, developed by University of Heidelberg.

2.3 Methodology for the remote measurements

The solar light is measured either *directly,* by using a solar tracker device or *indirectly,* by pointing a telescope to the blue sky. The measurement system is placed on a boat and then depending whether the by-passing ship is traveling against or across the wind, two measurement modes can be used, i.e. active and passive mode.
In the *passive measurement mode,* the ship is traveling orthogonal to the wind direction. The emissions from the by-passing ship are probed by letting the wind blow the plume across the line-of-sight of the SOF instrument, Figure 4. As can be seen realized from the figure a cross section of the plume will be obtained if the mean amount (column) of the absorbing species is integrated over time. If this cross section is multiplied with the average windspeed of the plume, the emission rate in mass per unit time is obtained according to Eq. 2. Note that in this mode it is not required to know the velocity of the ship in order to obtain useful information since emission per length unit will then be obtained. In the project most measurements have been conducted in this way. The fact that the sun is not in zenith is corrected by a factor corresponding to the Cosine of the solar zenith angle. In cases when the ship is not moving orthogonal to the wind direction, an additional compensation factor corresponding to the Sinus of the difference between the two directions has to be applied. .

$$Emission = \int_{0}^{t'} column(t) \cdot wind_{speed} \cdot velocity_{ship})dt \qquad \text{(Eq. 2)}$$

It should be noted that the anticipated accuracy when conducting this type of measurement is around 20-30%. The main reason for this is that the measurement represents a snapshot of the emissions and that the short term and local variability of the wind will affect the obtained value. This may be difficult to correct for by the wind measurements. Still, the anticpated accuracy is sufficient to identify gross polluting ships but also to conduct statistical measurements to assess the total emissions from a whole fleet. In the latter case the accuracy will be improved since the variability caused by the wind will be averaged out.

In the second measurement mode, the **active** mode, the ship is traveling against the wind, and the emission plume is probed by moving behind the ship (y-direction), across it's travel direction. In this manner the plume of the ship will be traversed and all molecules in the cross section of the plume can be obtained. By multiplying with the wind speed at plume height, the emission rate in kg polluter per meter of travel of the ship will be obtained, as described in Eq. 3. In addition it is also necessary to correct for the fact that the sun is not in zenith and that the plume is not always traversed perpendicularly to the wind direction. By simply multiplying the emission rate with the velocity of the ship the emission in mass unit per unit length will be obtained. Note that it is required to know the speed of the ship in this mode.

$$Emission = \int_0^{y'} column(y) \cdot (wind_{speed} + velocity_{ship}) dy \qquad \text{(Eq. 3)}$$

$$\text{where} \quad column(y) = \int_0^{\infty} c(y,z) \cdot dz \qquad \text{(Eq. 4)}$$

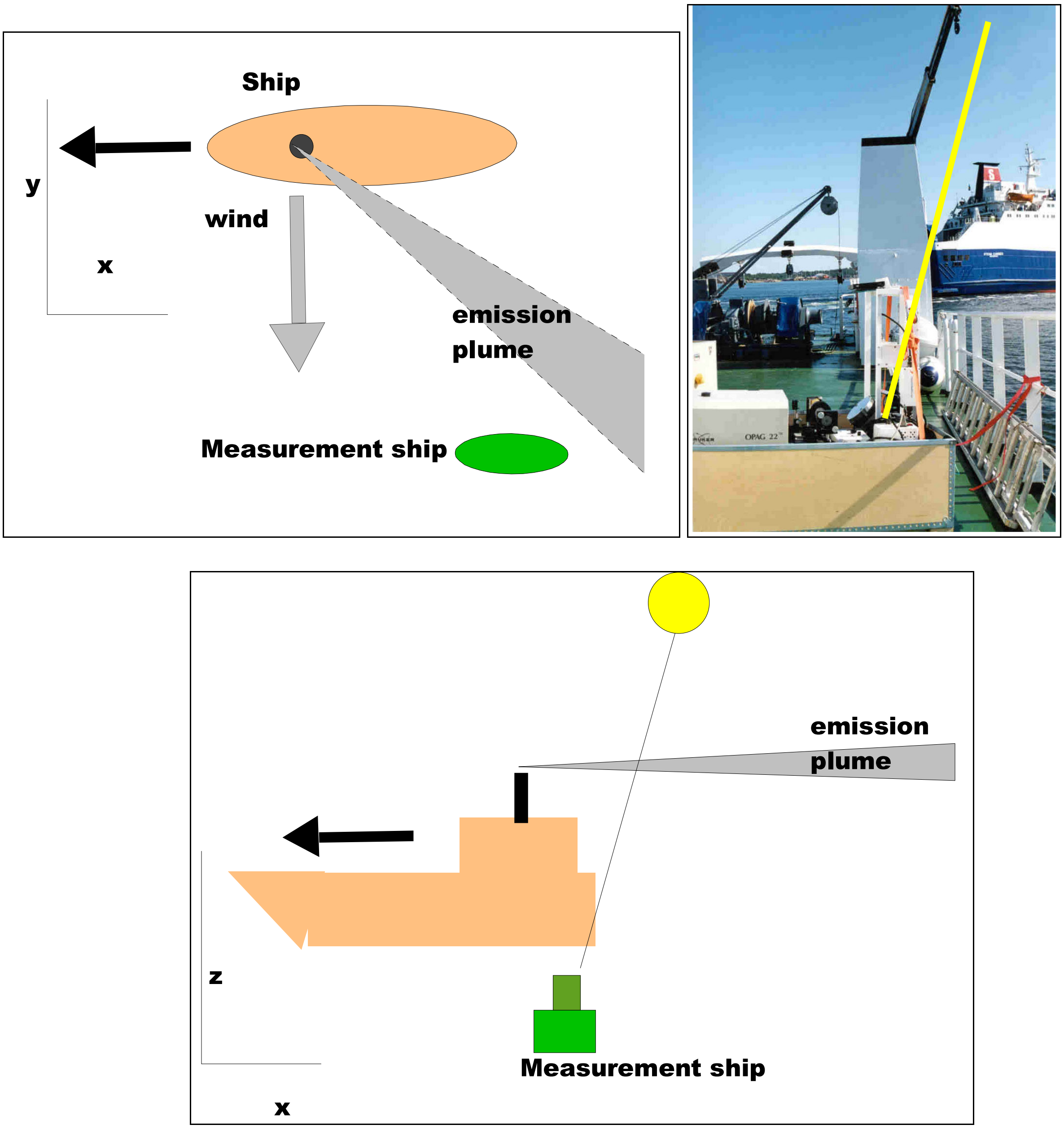

Figure 4. The passive measurement mode seen from above and from the side. The measurement boat lies still, 100-200 m leeward of the harbor channel and the wind brings the plume across the solar light measured by the instrument.

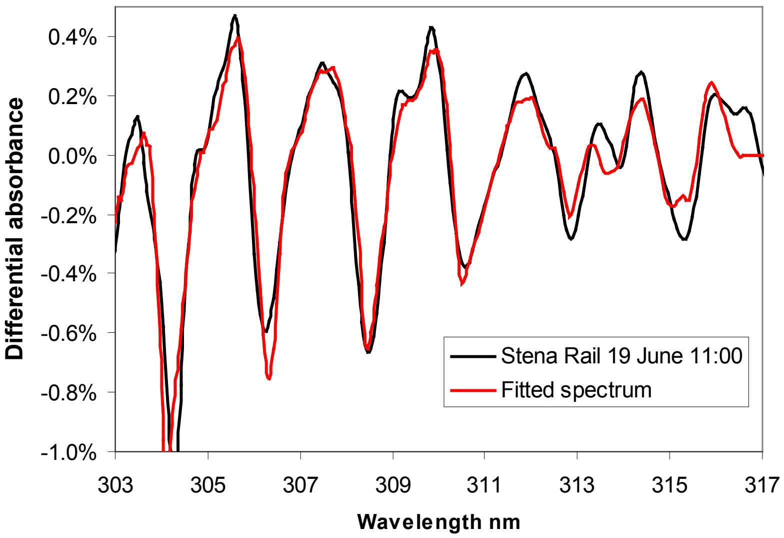

Figure 5. A spectroscopic "finger print" of SO_2 is shown measured in the plume from Stena rail ferry on June 19 2001 when standing still 200 m downwind the inlet channel of Göteborg harbor at Älvsborgsfästning . In addition a fitted reference spectrum of SO_2 is shown which has been obtained by scaling a calibration spectrum from a reference database to the measured spectrum.

2.4 On board in situ instrumentation on Stena Danica

In order to have a handle on the real ship emissions the Swedish Environmental Research Institute conducted conventional on-board measurements on one of the ships to be measured by the remote measurements, Stena Danica. This ferry boat left Göteborg every morning around 9:30 and returned around 17:30. It was running on fuel with 0.5% sulfur content.

In total *Stena Danica* has nine diesel engines and two boilers each with a separate exhaust channel which are housed collectively in an engine casing running up through the ship and exiting as a single emission source plume. Thus to determine the overall emission rates of the plume, individual emission measurements at each operating engine was required and these values then summed. Measurements were made during *Stena Danica's* journeys through Gothenburg's archipelago (two 1 hour periods per day) on the 11th, 12th, 13th and 18th June 2001.

Measurement procedure followed IMO:s Technical NO_x Code and is described in detail elsewhere (Cooper et al., 1996; Cooper and Andréasson, 1999; International Organization of Standardization, 1996; International Maritime Organization, 1997). In addition a Predictive Emission Monitoring System (PEMS) was used to permit measurements at two engines simultaneously (Cooper and Andréasson, 1999). Emissions from all operating diesel engines (4 auxiliary engines and 2, 3 or 4 main engines) were measured continuously or semi-continuously (as 15 second or 30 second averages based on 5 second sampling instances) depending on emission magnitude and emission variation. The small emission contribution from boiler operation was also taken into account in calculating the total emissions.

Relative errors at the 95% confidence limit[1] are calculated as: 19% NO_x, 22% NO_2, 20% CO, 20% CO_2, 14% SO_2 emissions (kg/hr) and 14% exhaust flow (nm^3/hr).

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[1] Based on error calculation used for attainment of accreditation by SWEDAC.

3 RESULTS AND DISCUSSION

3.1 Remote SOF measurements

Some typical results of remote emission measurements of the species SO_2 are shown here, obtained by direct solar measurements in the passive mode, i.e. by standing still leeward of the by-passing ships, letting the wind blow the emission plume across the line-of-sight of the instrument. It was discovered that the use of direct solar light in the remote measurements was considerably better than using solar light scattered in the sky. The direct solar measurements had a noise level in the retrieved columns of 1-2 $mg \cdot m^{-2}$ compared to the zenith sky measurements having corresponding values of 10 $mg \cdot m^{-2}$. The reason for this were probably due to higher light levels in the direct solar case.

For the measurements of NO_2 there were fairly strong residual spectral structures (1%) in the wavelength region used to retrieve this species. These structures were probably caused by solar features, which varied considerably over time due to the way the focusing optics were setup as was described in section 2.2. Hence, for NO_2 further measurements are required in order to assess the possibility of conducting ship measurements remotely.

In Figures 6a-6d results from passive measurements of the SO_2 emissions from M/S Clifford Maersk are shown, conducted a few hundred meters downwind the Göteborg inlet channel at a location named Älvsborgsfästning. This ship is currently one of the world’s largest container vessels along with a series of sister ships and the picture in Figure 6a was taken from the SOF measurement boat just before conducting the measurement. It can be seen that the emission plume ascends quite high and there is therefore little downdraft into the wake of the boat, something that was discussed as a potential problem in section 2.1. In Figure 6b is shown an absorption spectrum of SO_2 measured in the plume from Clifford Maersk. In addition a reference spectrum is shown which has been scaled to the measured one, indicating a total SO_2 column of 44 $mg \cdot m^{-2}$. In Figure 6c the SO_2 columns obtained from two different UV/visible spectrometers are shown when the plume of Clifford Maersk drifted over the line-of-sight of the spectrometers. In addition the integration of the measured columns multiplied by the windspeed according to the Eq. 2 is shown in the figure. It can be seen that the total emission from the freighter was 48 $kg\ h^{-1}$ for the PMT system spectrometer and 8% higher for the PDA spectrometer. We do not understand this discrepancy at this stage, but it may be caused by different sensitivity to the solar lines due to different use of hardware. Nevertheless, this comparison with two entirely different spectroscopic systems gives general credibility to the measurements.

In Figure 6e the influence of the wind field at 15 m height is shown when M/S Clifford Maersk passed. The change in wind direction from southerly to almost westerly, and corresponding decrease in wind speed by a factor of 2 was caused by the passage of the large container ship. In the figures 7-9 the same type of measurements are shown for several ships, and all these data have been summarized in Table 2.

Figure 6a. This picture was taken of M/S Clifford Maersk just before conducting the remote measurements outside Älvsborgsfästning, a couple of hundred meters downwind the inlet channel to the north. The gross tonnage is 91560 tons. There is no information available of the sulfur content in the fuel.

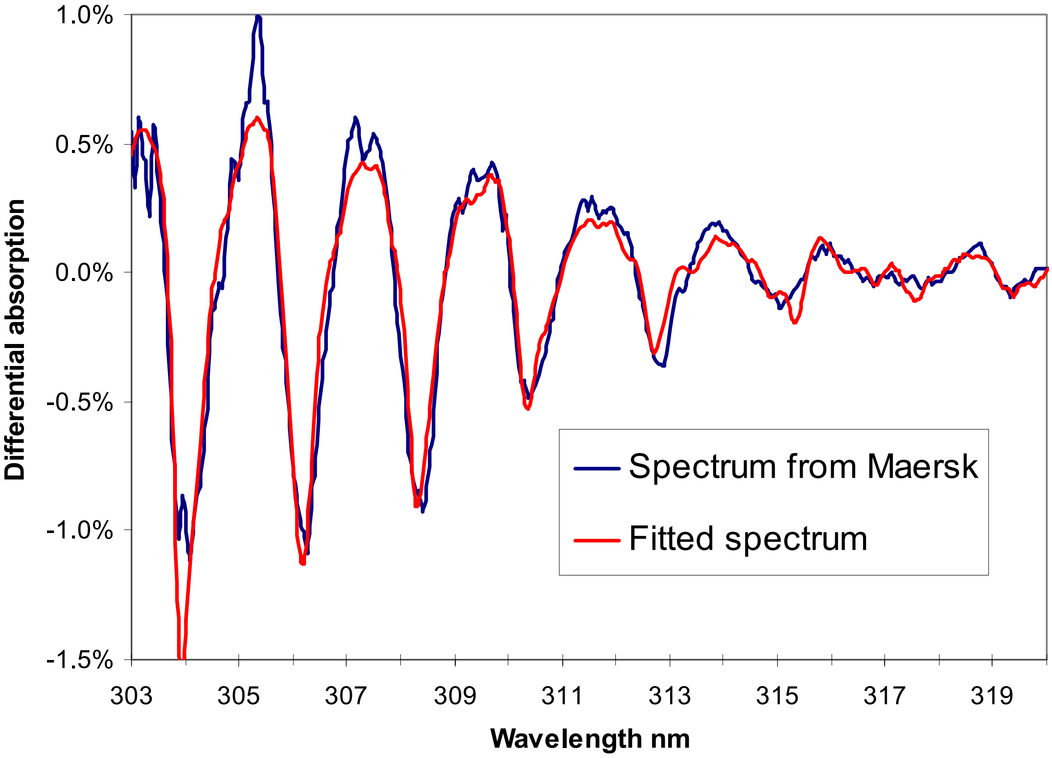

Figure 6b. SO_2 fingerprint and fitted reference spectrum in the downwind plume of M/S Clifford Maersk. The concentration corresponds to 44 mg/m^2.

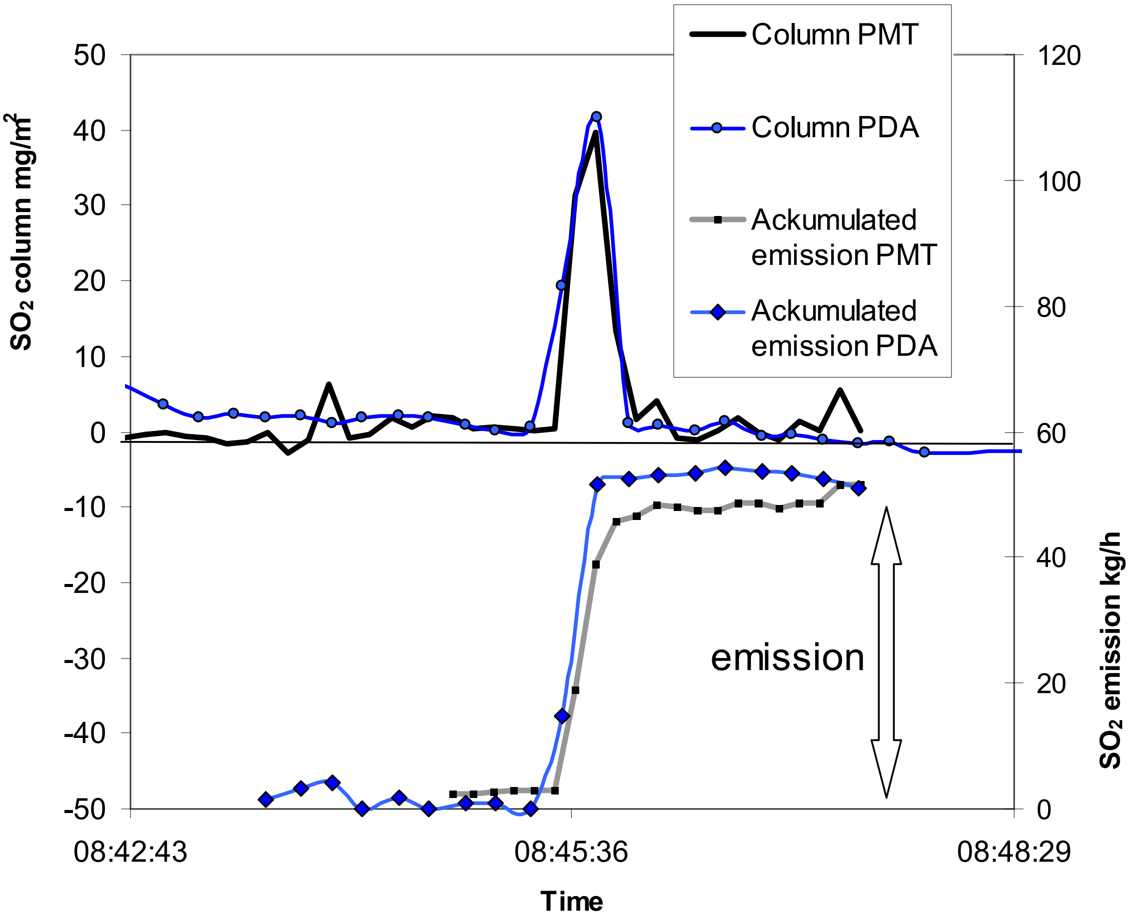

Figure 6c. Measurements of SO_2 columns outside Älvsborgfästning during the passage of M/S Clifford Maersk. Two different spectrometer systems were used : a slotted disc photomultiplier system (PMT) and a Photodiodearray system (PDA). The calculated emission rate of SO_2 is also shown as derived from Eq. 2.

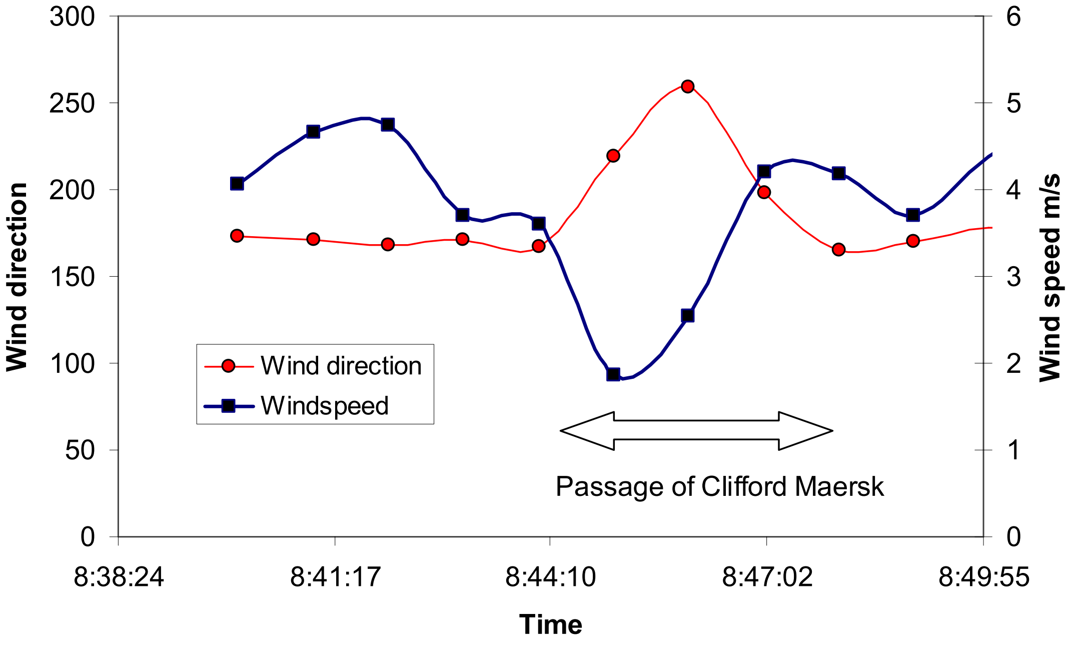

Figure 6d. Influence of the wind field at 15 m height when M/S Clifford Maersk passes. The change in wind direction from southerly to almost westerly, and the corresponding decrease in the wind speed by a factor of 2 is caused by the passage of the large container ship.

Figure 7a. The oil freighter M/S Tärnfors on June 15, 2001. According to the shipping company this ship is running on approx. 2.5% sulfur content in the fuel. The gross tonnage is 5698 tons.

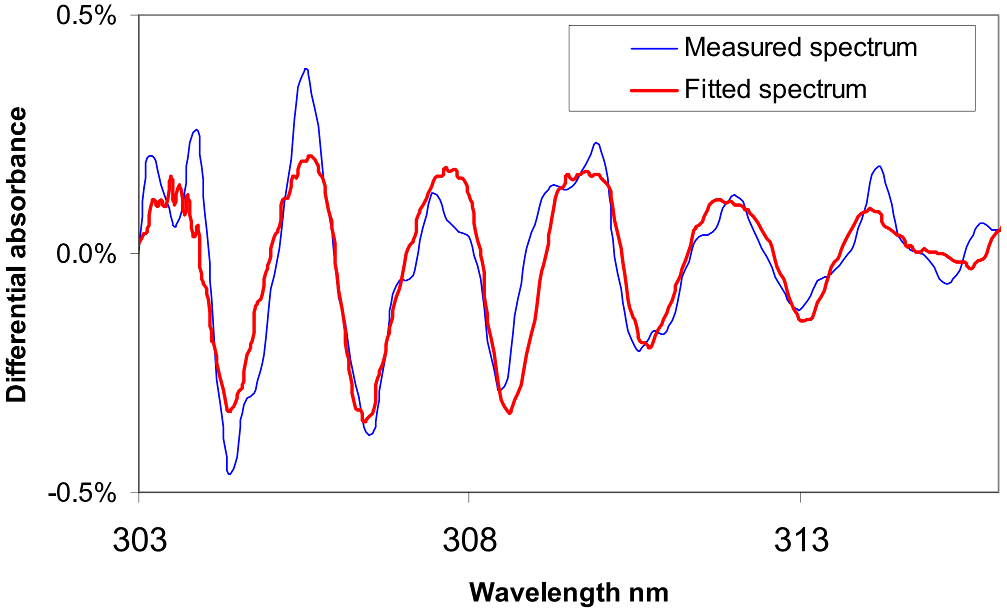

Figure 7b. SO_2 fingerprint and fitted reference spectrum in the plume of M/S Törnfors. The concentration corresponds to 15 mg/m^2 of SO_2.

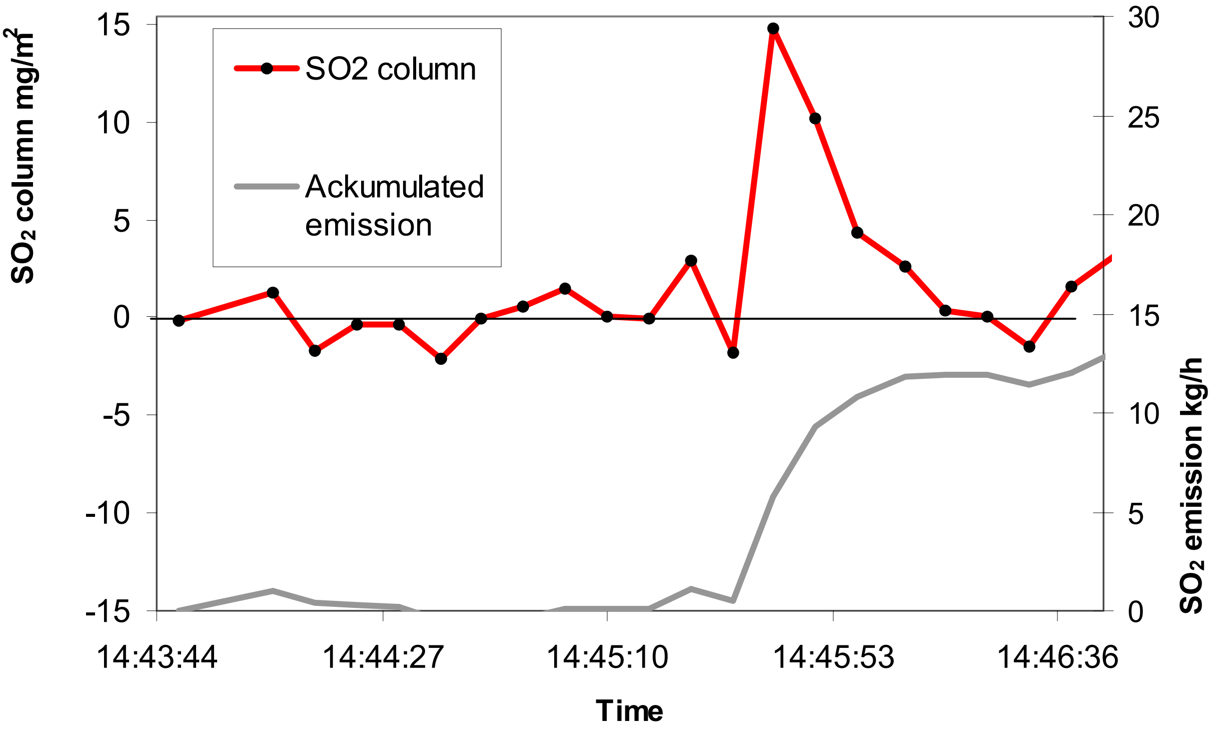

Figure 7c. Measurements of SO_2 columns outside Älvsborgfästning during the passage of M/S Törnfors using a slotted disc photomultiplier (PMT) DOAS system. The calculated emission rate of SO_2 is also shown as derived from Eq. 2.

Figure 8a. M/S Maris on June 15, 2001.

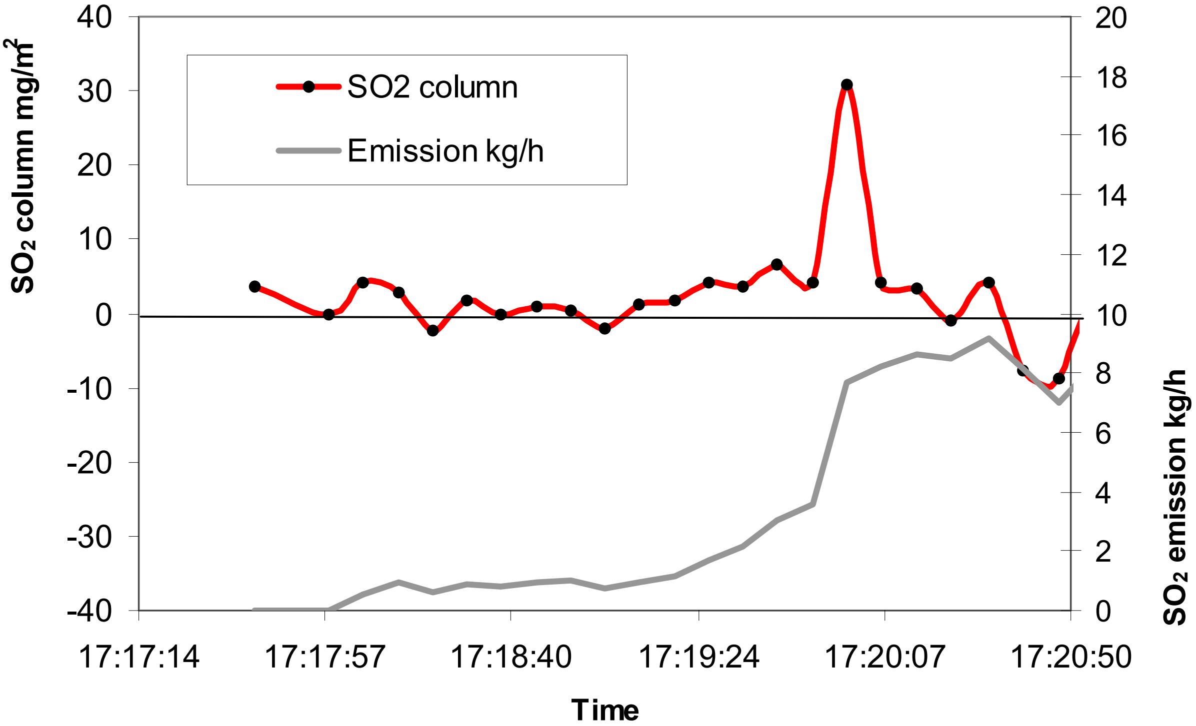

Figure 8b. Measurements of SO_2 columns outside Älvsborgfästning during the passage of M/S Maris using a slotted disc photomultiplier (PMT) DOAS system. The calculated emission rate of SO_2 is also shown as derived from Eq. 2.

Figure 9a. The freighter Stena Scanrail (photo taken on June 15th). This freighter is running on fuel with 2% sulfur content, according to the shipping company. The gross tonnage is 7504 tons.

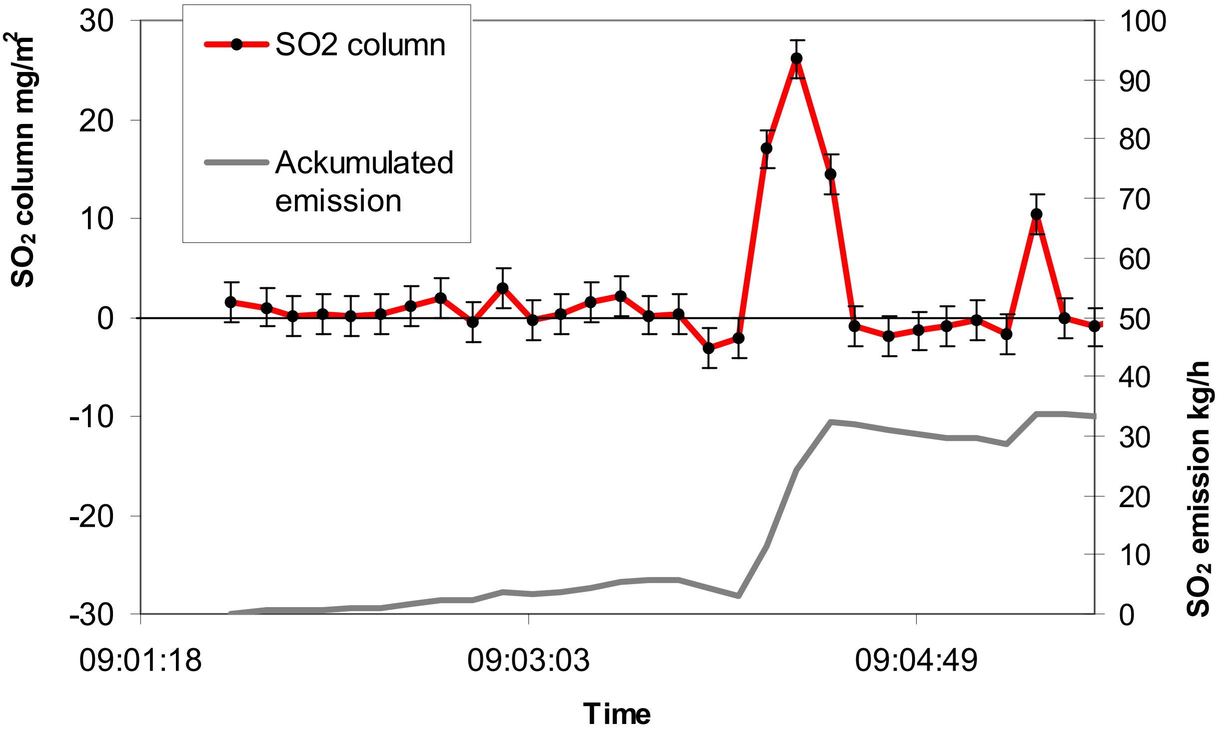

Figure 9b. Measurements of SO_2 columns outside Älvsborgfästning during the passage of M/S Stena Rail using a slotted disc photomultiplier (PMT) DOAS system. The calculated emission rate of SO_2 is also shown as derived from Eq. 2.

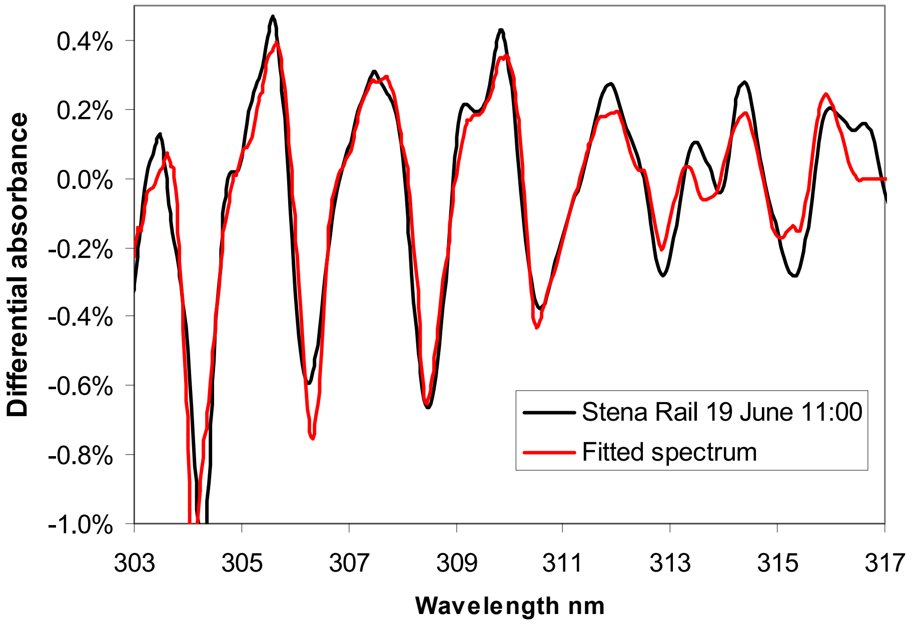

Figure 9c. SO_2 fingerprint and fitted reference spectrum in the plume of M/S Stena rail. The concentration corresponds to 25 mg/m^2 of SO_2.

Table 2. Results from three days of remote SOF measurements in the inlet channel of Göteborg. Most measurements were conducted at locations were the speed limit was 8 knots, with the exception for the measurements at Buttö.

Date/local time	**Ship**	**Location**	**Wind**	**Emission** kg SO2 h^{-1} / kg SO2 km^{-1}	**Comment**
15/6 10:40	Clifford Maersk	Alvsborgsfästning,	S, 5 m/s	49 kg h^{-1} 4.5 kg km^{-1} *53 kg h^{-1}* *4.8 kg km^{-1}*	PMT system *PDA system*
15/6 11:00	Stena Rail	Alvsborgsfästning,	S, 5 m/s	24-35 kg h^{-1} 2.2 kg km^{-1}	2% sulfur content
15/6 15:10	Eimship	Alvsborgsfästning,	S, 5 m/s	118 kg/h 8.2 kg km^{-1}	High emitter
15/6 16:35	Stena Jutlandica	Alvsborgsfästning,	S, 5 m/s	10 kg h^{-1} 0.7 kg km^{-1}	Uncertain,
15/6 16:45	Tärnfors	Alvsborgsfästning,	S, 5 m/s	12 kg h^{-1} 0.8 kg km^{-1}	25 m height 2.5% sulfur content
15/6 17:15	Maris	Alvsborgsfästning,	S, 5 m/s	8 kg h^{-1} 0.6 kg km^{-1}	
15/6 17:16	Stena Danica	Alvsborgsfästning,	S, 5 m/s	10 kg h^{-1} 0.7 kg km^{-1}	Uncertain On-board: 9-14 kg h^{-1}
18/6 17:05	Stena Danica	Buttö	N, 5 m/s	20 kg h^{-1} 0.9 kg km^{-1}	PDA, uncertain 0.5% sulfur On-board: 32 kg h^{-1} Ship speed 20 knots
19/6 09:20	:Stena Carrier	Göteborgsgrund	NV, 4 m/s	9 kg h^{-1} 0.6 kg km^{-1}	Uncertain
19/6 10.00:	Stena Danica	Göteborgsgrund	NV, 4 m/s	6.5 kg h^{-1} 0.5 kg km^{-1}	Uncertain 0.5% sulfur On-board: 9-14 kg h^{-1}
19/6 11:00	Stena Rail	Göteborgsgrund	NV, 4 m/s	30 kg h^{-1} 2.1 kg km^{-1}	2% sulfur

3.2 On board measurements Stena Danica

Calculated continuous profiles of the emissions and exhaust flows for the entire sampling periods are presented elsewhere [Cooper, 2001]. From these results the emission rates when R/V *Arne Tiselius* ("remote sensing ship") traversed the exhaust plume (ca. 1 – 2 minutes) can be obtained. A results summary of the engines operating, ship speed and the emissions noted during these time intervals is presented in Tables 3 and 4 below.

It can be seen that the average emissions varies between 9-14 kg/h of SO_2 and 10-16 kg/h NO_2 when running at around 10 knots, which was the usual situation for most measurements. In general this should considered as rather low emissions.

Table 3. No. of engines operating during the sample periods when *Arne Tiselius* traversed the exhaust plume.

Sample No.	Time / Date	Main engines	Aux. engines	Boilers
1	10:02 11th June	ME2, ME3	AE1, AE2, AE4, AE5	none
2	17:06 11th June	ME1, ME2, ME3, ME4	AE1, AE2, AE4, AE5	none
3	10:10 12th June	ME2, ME3	AE1, AE2, AE3, AE5	none
4	17:05 12th June	ME1, ME2, ME3, ME4	AE1, AE2, AE4, AE5	port
5	10:01 13th June	ME2, ME3	AE1, AE2, AE4, AE5	port
6	17:12 13th June	ME1, ME2, ME3, ME4	AE1, AE2, AE4, AE5	port
7	10:04 18th June	ME2, ME3	AE1, AE2, AE4, AE5	port
8	17:08 18th June	ME1, ME2, ME3	AE1, AE2, AE4, AE5	none

Table 4. Emission rates and ship speed during the sample periods when *Arne Tiselius* traversed the exhaust plume

Sample No.	Time / Date	Speed, Knop	NO_x, Kg/hr	NO_2, Kg/hr	CO, Kg/hr	CO_2, Kg/hr	SO_2, Kg/hr	Exhaust flow, Nm3/hr
1	10:02 11th June	7	93	10	9,9	4 200	9,6	59 000
2	17:06 11th June	21	370	38	18	16 400	46	148 000
3	10:10 12th June	12	140	15	12	5 500	14	63 000
4	17:05 12th June	20	370	41	18	17 000	48	151 000
5	10:01 13th June	8	122	13	9,5	5 200	13	59 000
6	17:12 13th June	20	335	36	17	15 000	42	134 000
7	10:04 18th June	10	144	16	9,7	5 800	14	61 000
8	17:08 18th June	20	275	27	12	11 700	32	102 000

4. DISCUSSION

The aim of the project was to investigate the feasibility of applying SOF measurements for ship emission studies and whether it is possible identify "gross" polluting ships, running on high sulfur oil and not having NO_x catalysts installed. An additional aim was to investigate the feasibility of using this technique to assess the total emission from the shipping sector.

Emissions of SO_2 (10-100 kg h^{-1}) were measured remotely from about 15 ships during 3 days. These ships were probably using fuel with a sulfuric content of 2% or above. The reason for this is that it was difficult to detect emissions from Stena Danica running on 0.5% sulfur content, while among the ships measured several were running on 2-2.5% sulfur content. No good emission measurements were obtained for the species NO_2. This was caused by a combination of problems with the equipment, badly optimized optical design and more difficult spectroscopy due to larger light variability, stronger solar lines and more spectral interference from other species.

The on-board measurements on the ferryboat Stena Danica showed that the emissions were just in the threshold of the present SOF measurement range and in most cases the emissions from this ship were therefore not detected. The few successful SOF measurements of Stena Danica showed values between 6-10 kg h^{-1} in a location were the ships were running at 8 knots and the on-board measurements showed values between 9-13 kg h^{-1}. One measurement was also conducted further out at Buttö and here Stena Danica was running at a speed of approx. 20 knots. The on-board measurements showed 32 kg·h^{-1} while the remote SOF measurements showed only 20 kg·h^{-1}. This measurement was difficult, however, since the high speed of the ships diluted the plume considerably. There was on the other hand no problem to detect emissions from the freighter Stena Rail, running on 2% sulfur content in the fuel. The emissions from this ship were about three times higher than those of Stena Danica (2-2.5 kg SO_2 km^{-1}), even though the gross tonnage is about four times lower.

The SOF technique thus seems sensitive enough to identify the more polluting ships, running for instance on fuel with high sulfuric content (~2%) and the levels of the emissions seems more or less consistent with on-board measurements.

The demonstrated measurement range for SO_2, 10-100 kg h^{-1} covers a good fraction of the emissions of the ship fleet and it seems feasible, with some optical improvements, to push the lower measurement limit downward in order to use the technique for emission assessments. Even though some nice measurements were conducted for SO_2, indicating the appropriateness of the methodology, several open questions remain regarding the spectroscopy such as how to better the eliminate solar features and other spectral features, in order to improve the measurements sensitivity and accuracy. For NO_2 the problems just mentioned were so large that it was not possible to obtain any good emission estimates, even though NO_2 was detected in the plume on some occasions.

Based on the results of this project we believe that SOF technique could be developed into a useful tool of pinpointing gross polluting ships at sea, concerning the species SO_2. For instance, it is possible to construct automatic instruments to be put on coast guard vessels. Optionally a stationary system could be installed on a suitable island near harbor fairway. The measurements can probably be improved to be able to measure emissions from "cleaner" ships", in order to conduct emission inventories. For instance could measurements be conducted in the sound between Denmark and Sweden in order to estimate the ship emissions of the whole Baltic Sea. Regarding NO_2 further feasibility studies are needed, especially after conducting the above mentioned improvements.

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