National Institute for Public Health
and the Environment
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Sulphur dioxide emissions

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RIVM Report 609021119/2012

Colophon

A.J.C. Berkhout
D.P.J. Swart
G.R. van der Hoff
J.B. Bergwerff

Contact:
M. Mooij
Advisory Service for the Inspectorate, Environment and Health
martje.mooij@rivm.nl

This investigation has been performed by order and for the account of VROM-Inspectie, within the framework of M/690021/09-LI-Lidar.

Abstract

Sulphur dioxide emissions of oceangoing vessels measured remotely with Lidar

RIVM developed a shore-based instrument to measure the sulphur dioxide emissions of passing seagoing vessels. This instrument applies the Lidar (*Light Detection And Ranging*) technique by scanning the exhaust plume of a passing ship with a laser beam and, after analysis of the return signals, determining the emissions. This whole procedure occurs unnoticed by the passing ship. The instrument was used between 2006 and 2008 to measure sulphur dioxide emissions from a large number of ships sailing on the Western Scheldt estuary and North Sea Canal. The highest measured emission of sulphur dioxide was 37 grammes per second.

The total amount of sulphur dioxide emissions in the Netherlands has been declining for many years. Since 2006, emissions from oceangoing shipping vessels have been declining as well, but not as fast as those from other sources. Consequently, the contribution from oceangoing shipping vessels has become a proportionally more important source of sulphur dioxide emissions. In 2010, 55 percent of the Dutch sulphur dioxide emissions originated with seagoing vessels; in 1990, this was 21 percent.

Seagoing ships are not allowed to use sulphur-rich fuel in Dutch territorial waters and on the North Sea. However, this relatively cheap fuel may be on board for use elsewhere at sea. To what extent ship owners comply with this ban is not known. Traditional measurement methods, such as taking fuel samples on board, require a ship to be boarded. Therefore, a team of inspectors can check only a few ships per day using such control measures.

Lidar systems have not yet been recognised as a law enforcement instrument; consequently, no fines can be imposed based on Lidar measurements only. However, data collected by the Lidar instrument may be used to identify possible offenders, leading to the subsequent boarding of the ship in question by a law enforcement official to ascertain whether the law was breached. When this integral approach is implemented, the use of the Lidar instrument is cost-effective despite current legal restrictions due to its capability to scan the emissions of almost all passing ships. The deployment of patrol vessels, with their high running costs, then only becomes necessary to monitor those ships which, based on Lidar data, are the most likely offenders. Moreover, the use of the Lidar instrument greatly increases the chance of identifying and catching offenders. It can therefore be expected that fewer ships will breach the ban on the use of sulphur-rich fuel.

Keywords:
sulphur dioxide, SO_2, emission, ocean shipping, Lidar, remote sensing

Rapport in het kort

Zwaveldioxide-uitstoot van zeeschepen op afstand gemeten met Lidar

Het RIVM heeft een instrument ontwikkeld om vanaf de wal de zwaveldioxide-uitstoot van voorbijvarende zeeschepen te meten. Dit instrument maakt gebruik van de zogeheten Lidar-techniek (*Light Detection And Ranging*). Het instrument scant met een laserbundel de rookpluim van een passerend schip en stelt zo onopgemerkt de uitstoot vast. Hiermee is tussen 2006 en 2008 bij een groot aantal schepen op de Westerschelde en op het Noordzeekanaal de uitstoot van zwaveldioxide gemeten. De hoogst gemeten uitstoot bedroeg 37 gram per seconde.

De totale uitstoot van zwaveldioxide neemt in Nederland al jaren af. Sinds 2006 daalt ook de uitstoot door de zeescheepvaart, maar minder hard dan de uitstoot door andere bronnen. Daardoor is de zeescheepvaart een steeds belangrijker bron van deze emissie geworden. In 2010 was 55 procent van de Nederlandse uitstoot van zwaveldioxide afkomstig van de zeescheepvaart. In 1990 was dit nog 21 procent.

Zeeschepen mogen binnen de territoriale wateren en op de Noordzee niet op zwavelrijke brandstof varen. Deze relatief goedkope brandstof mag echter wel aan boord zijn voor gebruik elders op zee. Het is onbekend in hoeverre reders zich aan het verbod houden. Bij de traditionele meetmethoden worden brandstofmonsters aan boord genomen. Dit vereist dat iemand aan boord gaat, waardoor een controleteam slechts enkele schepen per dag kan controleren.

De Lidar is nog geen wettelijk erkend instrument, waardoor op dit moment op grond van alleen Lidar-metingen geen boetes gegeven kunnen worden. De Lidar kan wel gebruikt worden om vermoedelijke overtreders te identificeren, waarna een wetshandhaver per patrouilleboot aan boord kan gaan om de overtreding vast te stellen. Inzet op deze wijze blijkt op dit moment al wel kosteneffectief. Dit komt doordat hiermee vrijwel alle passerende schepen kunnen worden gemeten en dure scheepspatrouilles uitsluitend hoeven worden ingezet voor vermoedelijke overtreders. Bovendien wordt de pakkans zo sterk vergroot. Daardoor mag verwacht worden dat het aantal overtredingen zal afnemen als de Lidar wordt ingezet.

Trefwoorden:
zwaveldioxide, SO_2, emissie, zeescheepvaart, Lidar, remote sensing

Contents

Summary

This report describes the use of a new measurement method for determining the sulphur dioxide emissions of oceangoing vessels. The measurements were made from an inspection vehicle on shore using a scanning laser beam. This technology is known as LIDAR, *Light Detection And Ranging*. As part of the study described in this report, the mobile Lidar instrument that was previously developed by RIVM was modified for detecting sulphur dioxide and for measuring the smoke plumes of passing ships. These developments were successfully completed and have resulted in an operational instrument.

This method can be used for inspection purposes when monitoring the sulphur content of fuels used by passing ships, both as an independent instrument and in combination with other methods. An important advantage is that the ship's crew is unaware that measurements are being conducted. Another advantage over traditional methods is its efficiency: the emissions of virtually every passing ship can be measured. When the Lidar technology is combined with other methods, the Lidar measurements can be used to determine which ships should be boarded for additional inspection with the other methods. In this case, the Lidar is used as a surveillance and detection instrument.

In 2006, a pilot study was conducted on the Western Scheldt estuary. On five measurement days, the emissions of 24 ships were determined. The highest measured emission was 37 g per second.

Based on this pilot study, a lower limit of quantification of 0.1 g per second was established. Most of the measured ships were well above this limit. A typical emission measurement has a measurement uncertainty of approximately 20%.

The use of the instrument depends partly on the weather. There must be sufficient wind, and the wind must blow from a suitable direction for the measurement location. The weather must also be dry. If these conditions are met on a measurement day, then there is a very high probability that a large number of ships can be successfully measured.

In 2007 and 2008, the instrument was used again, on the North Sea Canal and again on the Western Scheldt estuary. This time, the VROM Inspectorate simultaneously collected fuel samples on board the ships as the RIVM collected samples of flue gasses. Only a small number of ships were measured both by Lidar and by taking samples on board; as a result the intended comparison was not possible. However, this new study once again showed that Lidar itself was highly useable.

When used as a screening method, the measurement instrument is highly cost-effective. The Lidar can identify potential violators; as a result, patrol ships can be deployed much more efficiently than is now the case. Because the probability of catching violators is greatly increased, the number of violations is expected to decrease.

Sulphur dioxide emissions in the Netherlands have been decreasing for many years. Since 2006, emissions from ocean shipping have also declined, but less quickly than those from other sources. As a result, ocean shipping has become an increasingly important source of sulphur dioxide emissions. In 2010, for

example, 55% of the sulphur dioxide emissions in the Netherlands originated from ocean shipping.

1 Introduction

1.1 Sulphur dioxide emissions in the Netherlands

Sulphur dioxide emissions in the Netherlands have been decreasing for many years. This is illustrated in Figure 1-1. Emissions from sources on land (terrestrial) have declined from 192 kt in 1990 to 33 kt in 2010, a decline of nearly 83%. This decline can be attributed to the Decree on Emission Requirements for Combustion Plants (*Besluit Emissie-Eisen Stookinstallaties* - BEES) for the energy sector, refineries and industry, as well as the Acidification Covenant (*verzuringsconvenant*) with the energy sector. Concrete measures that have reduced emissions include the introduction of flue gas purification at refineries, in industry and the energy sector; the transition from oil to gas at refineries and in the chemical industry; and the use of low-sulphur coal in coal-fired power plants. In addition, the sulphur content of the fuels used in transport have been reduced, causing the emissions from traffic and transport to decline (CBS et al., 2011a).

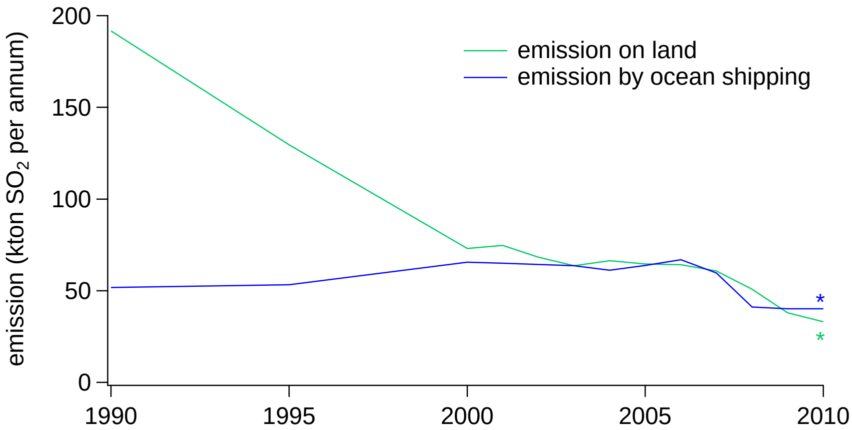

Figure 1-1. The development of sulphur dioxide emissions between 1990 and 2010
Source: CBS, 2011a
**: preliminary data*

The emissions from ocean shipping show a different picture (Figure 1-1). The blue line in this figure shows the emissions of sulphur dioxide from oceangoing ships within the Netherlands – in harbours, on waterways and on the continental shelf. Until 2006, emissions increased by 29%, from 52 kt in 1990 to 67 kt in 2006. This was followed by a sharp decline – of almost 40% – to 40 kt in 2009. The net decline between 1990 and 2009 amounted to 22%. The decline of the emissions from before 2006 can be attributed to two causes. First, in recent years, ships have begun to sail more slowly, thus reducing fuel consumption. In addition, during this period the maximum allowable sulphur content of the fuel was reduced to 1.5%[1] for ships sailing on the North Sea[2] (CBS et al., 2011b). The largest proportion (more than 77% in 2009, CBS et al., 2011b) of the

[1] Mass percentage, amounting to 15 g of sulphur per kg of fuel.
[2] On 1 July 2010, the maximum sulphur content on the North Sea was reduced still further, to 1%.

emissions from ocean shipping took place on the Dutch portion of the continental shelf, with the rest in harbours and inland waterways.

Because emissions of sulphur dioxide from ocean shipping declined much less rapidly than emissions from other sources, the relative contribution of ocean shipping rose sharply. For example, in 1990 approximately 21% of emissions originated from ocean shipping, while in 2010 the relative contribution rose to 55%.

1.2 Norms for the sulphur fraction of fuels

Various standards apply to marine fuel, depending on the type of fuel and the location where it is used. These standards emerged from the MARPOL convention (International Convention for the Prevention of Pollution from Ships), an agreement made within the framework of the IMO (International Maritime Organization). Within this convention, the norms are periodically tightened.

Since 2005, a maximum of 4.5% sulphur has applied to fuel used on the open sea. Beginning on 1 January 2012, the standard will be tightened further to 3.5%, and on 1 January 2020 to 0.5% (IMO)[3]. On the North Sea, stricter standards apply. On 21 November 2006, an amendment to Annex VI of the MARPOL convention came into force which classified the North Sea as an *SO_x Emission Control Area* (SECA). At that time, the maximum permissible sulphur content in a SECA was 1.5%. On 1 July 2010, this maximum was reduced to 1%, and on 1 January 2015 it will be reduced even further to 0.1% (IMO). A maximum of 0.1% already applies to oceangoing vessels while moored in harbours in the Netherlands (based on Directive 1999/32/EC). In comparison, the maximum allowable sulphur content of diesel fuel, both for ships on inland waterways and road vehicles, is 0.001% (Directive 98/70/EC).

1.3 Problem definition

High-sulphur fuels are significantly cheaper than low-sulphur ones. According to the legislation, such high-sulphur fuels can be carried on board ships, but they cannot be used in harbours and on the North Sea. However, enforcing this rule is difficult if monitoring can only be done on board. In the Netherlands, the VROM Inspectorate has conducted periodic inspections into the sulphur content of the fuels on board oceangoing ships. During these inspections, violations were regularly ascertained. For example, in 2003 approximately 40% of the oceangoing ships that were inspected were issued a summons for using fuels with an excessively high sulphur content (VROM-Inspectie, 2004)[4]. However, these inspections covered only a small fraction of the total oceangoing shipping in the Netherlands[5]. A suitable enforcement instrument, one which can detect the fuel being used on larger numbers of ships, is lacking. As a result, it is conceivable that ships on the North Sea and on waterways such as the Western Scheldt estuary use fuels containing more sulphur than is permitted at those locations. In that case, the actual emissions would be much higher than those shown in Figure 1-1.

[3] The implementation on this date of the reduction to 0.5% depends on the results of a feasibility study. This study will take the availability of low sulphur fuel, among other aspects, into account. It is possible that a decision will be made to delay the reduction until 1 January 2025 (IMO).
[4] Supplementary data from the VROM Inspectorate shows that in recent years the number of violations has declined; between 2004 and 2009, a violation was ascertained for 25% of the fuel samples taken.
[5] In 2004 the VROM Inspectorate took 71 fuel samples on oceangoing ships (VROM-Inspectie, 2005). In that same year, the customs service registered 88,724 ship arrivals or departures in the harbours in the Netherlands (CBS, 2011b).

1.4 Aim of the project

The aim of the project is to investigate whether, and to what extent, the above problem can be solved by using Lidar technology, and whether an accurate picture can be obtained of the sulphur dioxide emissions of oceangoing vessels on the major shipping routes in the Netherlands.

This technology has the important advantage that the measurements can be conducted remotely, and therefore go unnoticed. The instrument works with a laser beam and can be described as a type of radar for detecting sulphur dioxide. It has a range of approximately 2.5 km. With this Lidar method, the emissions of oceangoing ships underway can be measured.

The RIVM developed and built this Lidar system in cooperation with a number of external parties, including the VROM Inspection and Investigation Service and the National Police Services Agency. It is a mobile instrument with the specific purpose of measuring emissions remotely to benefit surveillance and enforcement. The instrument is mounted on an inspection vehicle that provides all necessary infrastructure and can operate autonomously. At present, this mobile Lidar is capable of determining concentrations and emissions of three trace gases: sulphur dioxide, nitrogen oxide and ammonia. The instrument has been designed in such a way that the list of detectable gases can be expanded relatively easily, for example with nitric oxide and/or benzene.

In 2005, the instrument was first used operationally to evaluate satellite measurements of nitrogen oxide. It was used for this purpose again in 2006 and 2009. In 2006 and 2007, on behalf of the VROM Directorate on Climate Change and Industry, successful operational emission measurements of ammonia were performed, first on an artificial source, and after that on fertilised fields and pastures. Extensive reports on these activities were published (Berkhout et al., 2008, Brinksma et al., 2008, Volten et al., 2009).

In 2006, 2007 and 2008, on behalf of the VROM Inspectorate, measurements were conducted of the sulphur dioxide emissions of passing oceangoing ships. A report on the 2006 measurements was published previously (Swart et al., 2007). The present report is a revision and extension of that report. The measurements on passing oceangoing ships were continued in 2009, this time under the auspices of the Joint Research Centre (JRC) of the European Commission in Ispra, Italy. The reporting on these activities is now in the final stages.

Figure 1-2 shows the exterior and interior of the inspection vehicle.

Figure 1-2. The inspection vehicle: exterior and interior

1.5 Research question and realisation

The research described in this report can be divided into three components, which were all realised completely or partially.

(1) Making the Lidar suitable for measuring the SO_2 emissions of oceangoing ships while underway

Important technical challenges in this part of the research were scanning the smoke plume with the laser beam and analysing the measurements with a very short integration time. Both modifications were necessary because the ships were in motion, so there was not much time to conduct the measurements. The technology is described in Chapter 2.

(2) Conducting a pilot study, where the emissions of ships were measured while they were underway

In the pilot study, performed in 2006, measurements were conducted on the Western Scheldt during five days in total. We attempted to measure the emissions of 42 passing ships. These attempts were successful in 24 cases. The results are presented in Chapter 3.

(3) The comparison of the results of the Lidar measurements with the results of measurements conducted on board the ships

For this purpose, in 2007 and 2008, measurements were again conducted on the North Sea Canal and the Western Scheldt estuary. These activities were coordinated with the Advisory Service for the Inspectorate, Environment and Health (IMG) of RIVM, which conducted the measurements on board the ships. The Lidar measurements were only conducted on days when IMG also conducted measurements on board ships. The aim was, where possible, to measure the emissions of ships on which IMG had also conducted a measurement or planned to do so. However, it turned out that only a small number of ships were actually measured by both teams. The results of the Lidar measurements are presented in Chapter 3.

In Chapter 4, the results are discussed along with a number of characteristics of the measurement technology that are important with respect to enforcement, such as precision and selectivity. A number of conclusions and recommendations are presented.

2 Materials and methods

2.1 The Lidar technology

The acronym Lidar stands for *Light Detection And Ranging*. This technology has many similarities with radar. A brief pulse of light is emitted. Some of the light is reflected by molecules and aerosols in the air. This reflected light is received with a telescope, detected and analysed. By measuring the time lapse between sending and receiving the light, the distance to the reflecting particles can be derived.

The Lidar system used in the present study sends out two differently coloured pulses of light in rapid sequence. The colours are chosen in such a way that the first colour is more strongly absorbed by the target gas (in this case SO_2) than the second colour. If SO_2 is present, the reflected light from the first light pulse will be more strongly attenuated than the light from the second pulse. The SO_2 concentration at the location from which the light is reflected can be derived from the degree of attenuation. Because molecules that reflect light are present everywhere along the route of the light beam, it is theoretically possible to also determine the concentration along the entire route. In practice, with the Lidar system used in this study, a value can be determined every 100 to 200 m, at a distance ranging from about 350 m to about 2500 m from the instrument. The instrument is described in greater detail elsewhere (Berkhout et al., 2008, Volten et al., 2009).

By making such a concentration measurement in the same horizontal direction, but by varying the vertical direction, the concentration distribution of SO_2 can be determined in a vertical plane. This is shown schematically in Figure 2-1.

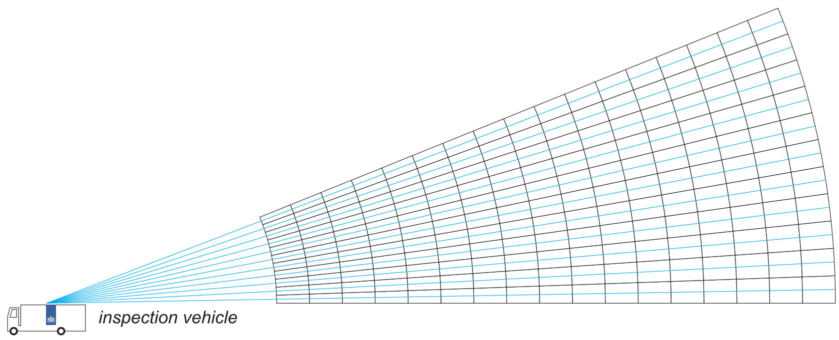

Figure 2-1. Schematic overview of the determination of the SO_2 concentration in a vertical plane
The measurement directions are shown in blue, the black cells indicate segments for which a concentration is determined.

For the emission measurements of the oceangoing vessels, a vertical plane is used that is composed of nine or more directions. The maximum distance is approximately 2.5 km, the maximum elevation about 300 m. Measuring all directions in a scanning plane takes about 45 seconds, after which the light beam is returned to the initial position and the scanning plane is again measured. In principle, such a cycle can be repeated an unlimited number of times.

2.2 Determining the emission

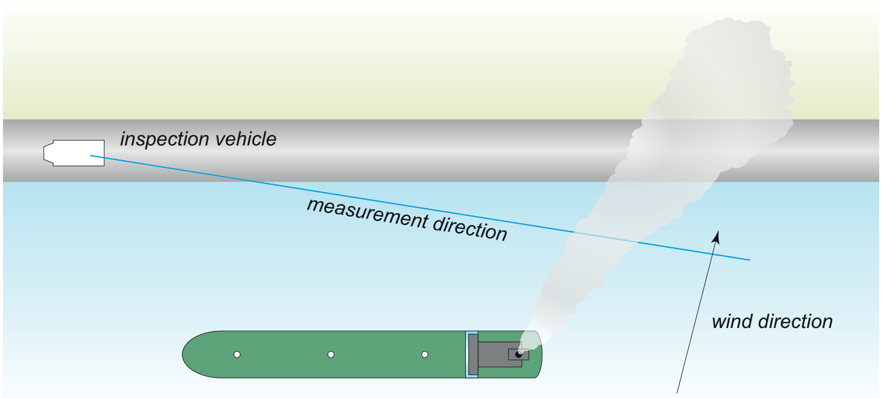

Figure 2-2. View from above of the situation during an emission measurement

Figure 2-2 is a schematic representation of how the emission is measured. The Lidar is set up on shore. The vertical scanning surface is positioned as much as possible at right angles to the wind direction and parallel to the direction the ships are travelling. The instrument is turned on and begins to measure SO_2 concentrations continuously. If a ship passes, the smoke plume is driven by the wind through the scanning plane (Figure 2-3).

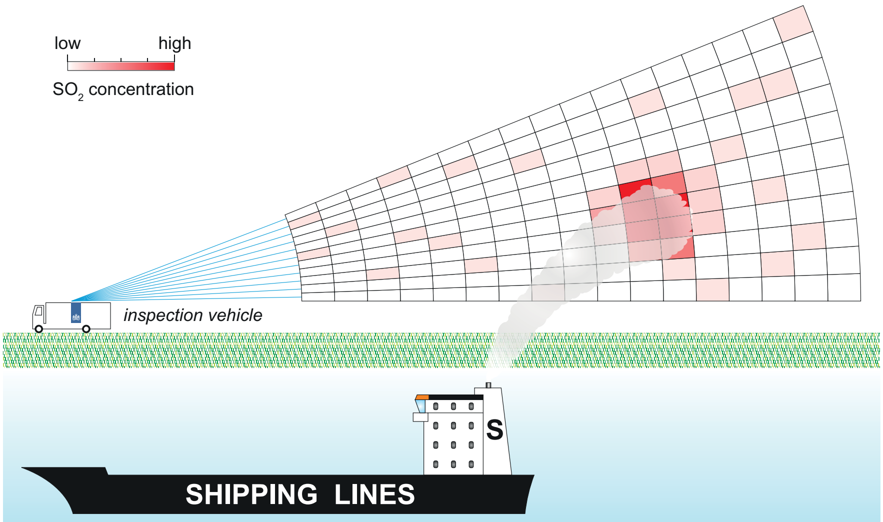

Figure 2-3. Side view of the situation during an emission measurement

In the Lidar signal, the soot and other particulate matter in the smoke plume can be seen. In this way, it can be determined where the plume passes through the scanning plane. At the same location, the SO_2 concentration is determined. The area of the section through the plume can also be derived from this information. Finally, to determine the emission value, the concentration and area are multiplied by the wind speed, while taking account of the wind direction.

2.3 Measurement locations

Most of the measurements discussed in this report were conducted on oceangoing vessels on the Western Scheldt. The initial choice for a measurement location was the mouth of the Canal through South Beveland near Hansweert. This was chosen because the sea lane runs near the coast, and because – with the prevalent wind – the scanning plane could be placed both parallel to the sea lane and perpendicular to the wind direction. See Figure 2-4 for an overview of the measurement locations. Ultimately, the inspection vehicle was stationed at three distinct locations around the mouth of the Canal, depending on the suitability of the locations. In Figure 2-4 they are marked with 1, 2 and 3. See Figure 2-5 for a photograph of the inspection vehicle at location 1.

Figure 2-4. The measurement locations at Hansweert and Walsoorden
The locations at Hansweert are marked with ❶, ❷ and ❸, and the measurement location at Walsoorden is marked with ❹. For locations 1 and 4, the measurement directions are shown. Anemometer: measurement mast of Rijkswaterstaat where wind speed, wind direction and water level are measured.

These locations were satisfactory if the wind came from the south and the west. However, if the wind came from the east, measurements could not be taken because it was impossible to position the scanning plane downwind from the sea lane. Therefore, in 2007 and 2008, a fourth location was used: on the dike near the harbour of Walsoorden, which is marked with 4 in Figure 2-4.

Figure 2-5. The inspection vehicle at location 1 (see also Figure 2-4)

In addition to the measurements on the Western Scheldt, measurements were also conducted during two days on the North Sea Canal (Figure 2-6). The first measurement location on the canal was at the Velserterminal on the north bank; this location is marked with 5 on the figure. The second location, marked with 6, was on the south bank of the canal, near the Houtrakgemaal.

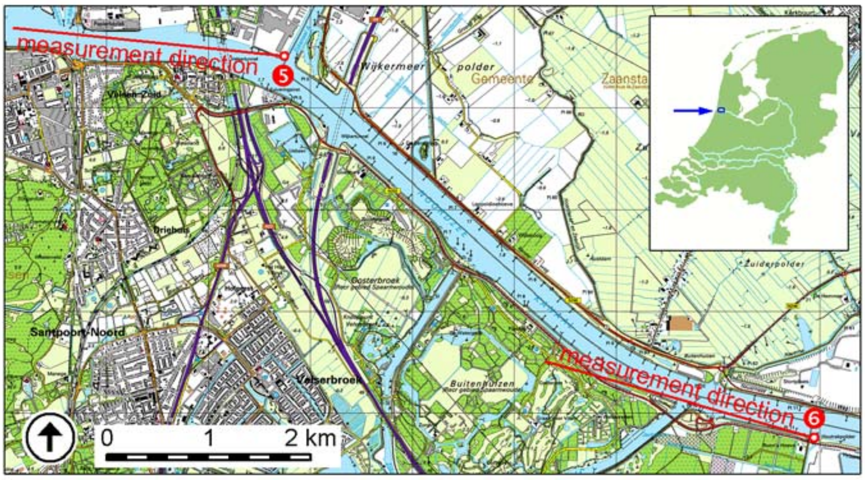

Figure 2-6. Measurement locations at the Velserterminal and at the Houtrakgemaal
The Velserterminal location is marked with ❺, and the Houtrakgemaal location is marked with ❻

2.4 Wind measurement

An automatic anemometer, part of the ZEGE measurement network (*Zeeuwse getijdenwateren*), is situated near the Hansweert measurement locations (see Figure 2-4). This measurement network is maintained by the Hydro Meteo Centrum Zeeland (HMCZ), a subdepartment of the Rijkswaterstaat Zeeland Directorate. The wind and tidal data are published on the Internet (via www.hmcz.nl). To calculate the emission values in this report, these data were used with the measurements taken at Hansweert and Walsoorden. The wind speed was calculated at the elevation at which the Lidar measurement indicated that the smoke plume was present; this was based on a logarithmic wind profile (Stull, 1988), the measured wind speed and the measured water height.

For the locations on the North Sea Canal (Velserterminal and Houtrakgemaal, (Figure 2-6), a permanent wind measurement facility was not available. Therefore an extendable 5.5 m wind mast was used, which had three anemometers to measure wind speed and wind direction (Figure 2-7). This wind measurement procedure is described more extensively elsewhere (Berkhout et al., 2008, p. 24). It was unnecessary to measure the water level at these locations because the North Sea Canal, unlike the Western Scheldt, is not tidal.

Figure 2-7. The inspection vehicle on the dike near the Houtrakgemaal (location 6)
The wind mast is located to the left of the wind turbine.

2.5 Measurement procedure

On a measurement day, the following procedure was used: upon arrival at the location, the inspection vehicle was first stabilised and levelled. The orientation of the vehicle with respect to the north was then determined. After this, based on the dominant wind direction on that day, a measurement direction was chosen. The laser and the telescope were then calibrated to each other for every angle of inclination. At this point, the system was ready to take measurements of a passing ship.

For every passing ship, the following procedure was used: the instrument began taking measurements when the ship approached, but was not yet within measurement range. From this point on, complete scans of the vertical plane were made continuously. At a certain point, the wind blew the smoke plume of the ship through the measurement plane, which could be seen from the measurement signals. The smoke plumes were visible in a sequence of scanning plane measurements. Measurements continued until the smoke plume of the ship could no longer be seen in the measurement signals.

The measurements were processed by determining the concentration at various locations in the plume, and then multiplying this concentration with the corresponding plume area and the wind speed at that elevation. After this, all partial contributions were added up across the entire plume surface. In this way, an emission value was determined for every scanning plane measurement. Because the smoke plumes of all ships were visible in a sequence of scanning plane measurements, more than one emission value could be determined for all ships. In this way it could be determined how the emission developed during the period of approximately five minutes when the plumes of most ships were visible.

2.6 Determining an emission value from a measurement

Figure 2-8. The HMS Rotterdam, shortly before it sailed past the inspection vehicle

To show how the emission value was determined, the measurements conducted on the HMS Rotterdam (Figure 2-8) are used as an example. This ship passed through the Western Scheldt on 9 October 2006. On that day, the Lidar was positioned at measurement location 1 (Figure 2-4). Due to the wind direction, the Lidar was aimed towards the southeast in order to take the most accurate measurements of the plumes. At approximately 10:30 hours UTC[6], the smoke plume of this ship entered the scanning plane of the Lidar. The SO_2 concentrations that were measured at that time are shown in Figure **2-9**. In this figure, the horizontal axis shows the distance to the Lidar and the vertical axis shows the elevation above the water surface. Note that the vertical axis is extended with respect to the horizontal axis; in reality the scanning plane is much more elongated than shown in the figure. The colour of the plane indicates the concentration of SO_2.

[6]All times in this report are given in UTC (*Coordinated Universal Time*).UTC is one hour behind Central European Time (CET) and two hours behind Central European Summer Time (CEST), both of which are used in the Netherlands; 10:30 hours UTC is therefore 11:30 hours CET and 12:30 hours CEST.

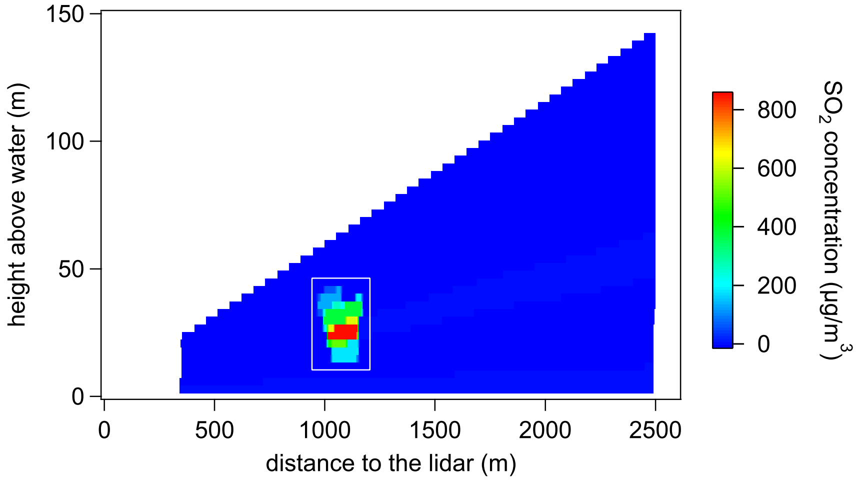

Figure 2-9. Cross section through the smoke plume of the HMS Rotterdam The colour indicates the concentration of SO_2 in the air. The white rectangle shows the plume as it was used in the further analysis.

To derive an emission value from these data, in Figure **2-9** the plume has been selected (the white rectangle in Figure **2-9**; this selected area is shown in Figure 2-10 B). For every elevation, the total quantity of SO_2 at that elevation is determined. This results in a gas load curve (also shown in Figure 2-10 B). The emission value can be derived by multiplying this value by the wind profile (Figure 2-10 A), corrected for the angle between the wind direction and the scanning plane, and then adding up all values. For this ship at that time, the emission value was 7.1 g per second.

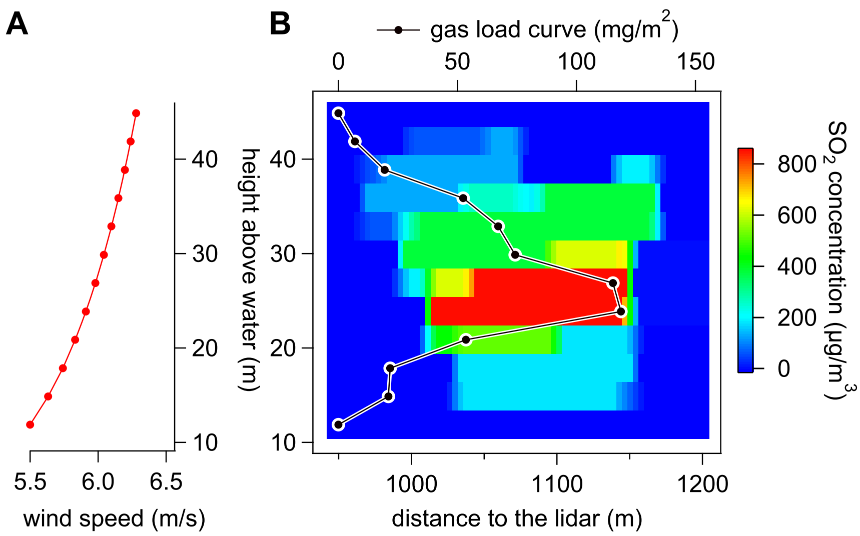

Figure 2-10 ***A****: logarithmic wind profile;* ***B****: cross-section from Figure 2-9 of the smoke plume of the HMS Rotterdam, and the corresponding gas load curve*

As stated in Section 2.3, when processing the measurements taken on the Western Scheldt, the wind speed was used which was measured at the nearby measurement mast of Rijkswaterstaat. Every 10 minutes, this measurement mast provides data such as wind speed and wind direction. It also measures the water level. The wind speed used for the calculations is the velocity measured at the mast reduced to the velocity at 10 m above sea level. The logarithmic wind profile is calculated from the wind speed and the water level (Figure 2-10 A). Figure **2-11** shows the wind and water data as measured by Rijkswaterstaat on 9 October 2006, with all ships measured on that day. From these data, wind speed, wind direction and water level can be determined for every ship at the time it passed the measurement location. Because a passage takes less than 10 minutes (a ship remains within range of the Lidar for no more than 5 minutes), a single emission value for each passage is sufficient, even though multiple emission values per ship were determined for each passage.

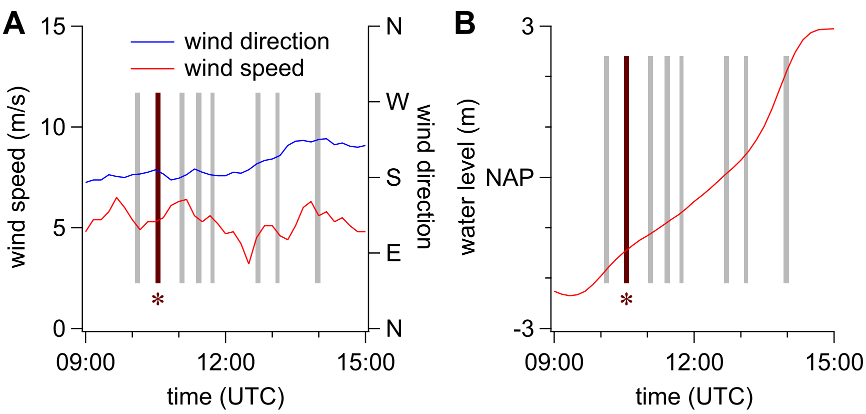

Figure 2-11. Wind and water data at Hansweert, measured by Rijkswaterstaat, on 9 October 2006
*The ships measured on this date are shown with grey bars. The ship discussed in this example, the HMS Rotterdam, has been marked with an *.*
***A**: wind speed, reduced to 10 m elevation, and wind direction; **B**: water level*

In Figure **2-9**, the plume can be clearly distinguished from the background. It is also clear that the entire plume is in the picture. However, during the measurement days there were situations where this was not the case. For example, the plume was sometimes located so close to the beginning of the scanning plane that part of the plume was not yet in the picture. In those cases, however, the entire plume was usually in the picture during the previous or subsequent scanning plane measurement, so that an emission value could still be determined. It also happened that two ships passed each other just as their smoke plumes came into the picture. In that case, the smoke plumes could not be distinguished from each other and no emission value could be determined.

2.7 Deriving the sulphur content of the fuel from an emission value

The Lidar measures an emission value in grammes of sulphur dioxide per second. Although the legislation on shipping has no provisions that apply directly to these emissions, it does impose limits on the sulphur content of the fuel that is used. To determine the percentage of sulphur in the fuel that is being used at that moment from an emission value, the fuel consumption at that time must also be known. Therefore, this aspect was determined for a number of ships during the measurement campaign. The average fuel consumption of these ships is known, so the sulphur content of the fuel can be calculated using the following formula:

$$\text{sulphur content} = \frac{\text{emissions} \cdot \dfrac{M_S}{M_{SO_2}}}{\text{consumption}} \cdot 100\%$$

Where:

sulphur content:	the sulphur content in the fuel, in percent by mass;
emissions:	the emissions measured by Lidar, in grammes of SO_2 per second;
M_S:	the atomic mass of sulphur (g per mol);
M_{SO_2}:	the molecular mass of SO_2 (g per mol);
consumption:	the fuel consumption, in grammes of fuel per second.

This formula assumes that all sulphur in the fuel is converted into sulphur dioxide. If this is not the case, and the sulphur is also emitted in the form of other compounds, this leads to an underestimation of the sulphur content because the Lidar does not measure these other compounds. In addition, the fuel consumption of the ships is not known exactly; only estimates are available. Therefore, the percentages of sulphur given in this report are estimates.

2.8 Comparison with other measurement methods

After determining the sulphur content in the fuel, the data from the Lidar can be compared with the results of other measurement methods that yield the sulphur content directly. In the measurement campaign described in this report, an attempt was made to compare the Lidar data with the direct measurements of sulphur content in fuel samples that were taken on board. For this purpose, people went on board passing ships to take the samples. This study was conducted by the Advisory Service for the Inspectorate, Environment and Health (IMG) of RIVM and the VROM Inspectorate. To ensure the greatest possible overlap between these Lidar measurements and the samples, during the second part of the measurement campaign described here, all Lidar measurements were conducted on days when samples were also taken. The IMG measurements have been described in a separate report (Mooij et al., 2010).

2.9 Design of the measurement campaign

This report describes the results that were obtained in 2006, 2007 and 2008. During the first year, 2006, the emphasis was primarily on demonstrating that sulphur dioxide emissions of oceangoing ships could be measured with this Lidar instrument. During this first year, measurements were conducted on days when conditions were optimal for a good Lidar measurement. These results have been described in a separate report (Swart et al., 2008).

In 2007 and 2008 the attention shifted to the comparison with the direct determination of the sulphur content in samples that were taken while on board. During those years, an attempt was made to measure the emissions of all ships from which fuel samples were also taken. To this end, the use of the Lidar instrument was coordinated with IMG and the VROM Inspectorate, which took samples. To go on board the ships, IMG and the VROM Inspectorate used a police boat. This boat had to be reserved long in advance. Consequently, it was difficult to plan for the optimal use of the Lidar, because there were unavoidably days on which the weather conditions were suboptimal for Lidar measurements.

3 Results

In Section 3.1 the emission values are reported for each measurement day for all ships measured on that day. Section 3.2 discusses the results of a determination of the lower limit of quantification. Finally, the results are summarised in Section 3.3.

3.1 Measurement results per measurement day

3.1.1 Measurement results on 16 May 2006

On this day, the inspection vehicle was positioned in Hansweert at location 3 (Figure 2-4). Measurements were conducted on the smoke plumes of seven ships. Two or more emission values could be allocated to five of the ships. The results are shown in Table 3-1.

Table 3-1. Results of emission measurements on 16 May 2006

name of ship	in/out[a]	time (UTC)[b]	emission (g/s)
MSC Jade	in	11:48-11:50	10
			9.8
			21
Probo Emu	in	12:00-12:02	23
			48
			33
Blexen	out	12:36-12:41	1.8
			1.5
			3.5
			2.8
			2.6
			2.6
Arklow Rainbow	out	13:13-13:16	4.9
			2.3
			1.1
			2.9
			0.91
Chopin	out	13:23-13:26	1.7
			2.8
JA Sunrise	out	13:26-13:35	plume too close to plume of Stolt Inspiration; analysis impossible
Stolt Inspiration	in	13:26-13:35	plume too close to plume of JA Sunrise; analysis impossible

[a] *In: sailing towards Antwerp; Out: sailing towards Vlissingen*
[b] *The time interval that the plume was visible on Lidar. Times are given in UTC (see note 6, page 20).*

3.1.2 Measurement results on 21 June 2006

On this day, the inspection vehicle was positioned in Hansweert at location 1. Measurements were conducted on the smoke plumes of five ships. Two or more emission values could be allocated to all these ships. The results are shown in Table 3-2.

Table 3-2. Results of emission measurements on 21 June 2006

name of ship	in/out	time (UTC)	emission (g/s)
Margareta B	out	11:49-11:51	0.64
			6.1
Maersk Malacca	out	12:04-12:08	30
			33
			45
Tai Shan	in	12:10-12:14	17
			20
			16
			19
			19
Izmir Express	out	12:46-12:49	7.9
			27
Ek-River	out	12:54-12:57	5.3
			5.4
			4.6

3.1.3 *Measurement results on 23 June 2006*

On this day, the inspection vehicle was positioned in Hansweert at location 1. Measurements were conducted on the smoke plumes of 11 ships. Two or more emission values could be allocated to three of these ships. Emission values could not be determined for the other eight ships due to the lack of wind. The smoke plume of these ships was either not blown through the scanning plane at all, or this took so long that the plume could no longer be recognised as such in the Lidar signal. The results are shown in Table 3-3.

Table 3-3. Results of emission measurements on 23 June 2006

name of ship	in/out	time (UTC)	emission (g/s)
Bastiaan Broere	out	10:06-10:08	0.22
			9.5
Kristin Knudsen	in	10:08-10:10	plume did not go through scanning plane
Sichem Marbella	out	12:21-10:45	plume did not go through scanning plane
Trout	out	10:21-10:45	plume did not go through scanning plane
Vijitra Naree	in	11:45-11:50	2.9
			5.4
			7.4
			8.3
			5.5
			2.1
			1.7
Swalinge	in	11:55-12:03	plume did not go through scanning plane
MSC Eyra	in	12:08-12:10	plume did not go through scanning plane
MSC Mee May	out	12:17-12:20	3.1
			2.7
			3.1
			2.9
			3.6

name of ship	in/out	time (UTC)	emission (g/s)
Betsy S	in	12:20-12:22	plume did not go through scanning plane
Rhonestern	in	12:29-12:42	plume did not go through scanning plane
Atlantic Cartier	out	12:46-12:50	plume did not go through scanning plane

3.1.4 *Measurement results on 9 October 2006*

On this day, the inspection vehicle was positioned in Hansweert at location 1. Measurements were conducted on the smoke plumes of 12 ships. Three or more emission values could be allocated to ten of these ships. The results are shown in Table 3-4.

Table 3-4. Results of emission measurements on 9 October 2006

name of ship	in/out	time (UTC)	emission (g/s)
MSC London	in	10:04-10:10	25
			31
			21
			26
			15
HMS Rotterdam	out	10:30-10:36	12
			14
			7.2
			7.1
			7.9
			2.4
Altair	in	10:39-10:46	plume did not go through scanning plane
MSC Maureen	out	11:01-11:07	64
			26
			23
Betsy S	out	11:22-11:29	16
			6.6
			3.5
			3.7
			1.4
			1.3
NCC Hijaz	in	11:41-11:46	15
			13
			8.6
			13
			20
Happy Girl	out	12:39-12:45	4.5
			6.7
			5.9
			5.0
Neera Naree	in	12:45-12:49	plume did not go through scanning plane
CS AV Rio Rapel	in	13:01-13:04	27
			30
			13
			18

name of ship	in/out	time (UTC)	emission (g/s)
Neveska Lady	out	13:05-13:12	26
			13
			18
			10
			16
Manzanillo II[7]	out	13:55-13:58	1.6
			1.4
			1.1
Jilihu	in	13:58-14:02	1.6
			7.8
			0.44
			1.6

3.1.5 *Measurement results on 10 October 2006*

On this day, the inspection vehicle was positioned in Hansweert at location 1. Measurements were conducted on the smoke plumes of seven ships. To only one of these ships three emission values could be allocated. The fact that emission values could not be determined for the other ships was, similar to the measurements on 23 June, due to the lack of wind. The smoke plume of these ships was either not blown through the scanning plane at all, or this took so long that the plume could no longer be recognised as such in the Lidar signal. The results are shown in Table 3-5.

Table 3-5. Results of emission measurements on 10 October 2006

name of ship	in/out	time (UTC)	emission (g/s)
Southern Juice	in	11:05-11:13	plume did not go through scanning plane
Manzanillo II	out	11:21-11:27	plume did not go through scanning plane
Sloman Challenger	in	11:27-11:33	plume did not go through scanning plane
MSC Marta	in	14:07-14:13	plume did not go through scanning plane
Al-Sabahia	in	14:23-14:31	plume did not go through scanning plane
Seaturbot	out	14:30-14:35	plume did not go through scanning plane
Stena Forecaster	out	14:41-14:44	2.8
			1.9
			2.0

3.1.6 *Measurement results on 16 October 2007*

On this day, the inspection vehicle was positioned at the Velserterminal at location 5. Measurements were conducted on the smoke plumes of 11 ships. One of these ships, the Geopotes 14, was a trailing suction hopper dredger, which sailed past three times. Consequently, there were 14 ship passages in total. One or more emission values could be allocated to five of these ships. the results are shown in Table 3-6.

[7] Utility ship; after passing the measurement location, it worked on the buoys marking the sea lane.

Table 3-6. Results of emission measurements on 16 October 2007

name of ship	direction of travel [a]	time (UTC)	emission (g/s)
Narcea	E	8:13-8:19	2.5
Water Lelie *with crane*	E	8:34-8:40	-
Rio	W	9:01-9:04	0.14
			0.30
Westerschelde	W	9:04-9:06	-
small tug	W	9:14-9:15	-
Jedset	E	9:15-9:16	-
Explorer	W	9:16-9:17	-
Geopotes 14	W	9:23-9:26	4.5
			4.0
			3.3
P42	W	11:08-11:13	-
Geopotes 14	E	11:52-11:55	8.1
			9.9
Scelveringhe	W	12:28-12:35	-
Stolt Hikawa	W	12:57-13:07	-
Geopotes 14	W	13:08-13:12	7.5
			6.1
			4.2

[a] *Direction of travel. W: sailing to the west; E: sailing to the east*

3.1.7 *Measurement results on 1 November 2007*

On this day, the inspection vehicle was positioned in Hansweert at location 2. Measurements were conducted on the smoke plumes of 21 ships. One or more emission values could be allocated to 19 of these ships. The results are shown in Table 3-7.

Table 3-7. Results of emission measurements on 1 November 2007

name of ship	in/out	time (UTC)	emission (g/s)
Crigee	out	9:08-9:09	-
Ginga Puma	in	9:25-9:28	1.2
			0.74
			0.69
			0.49
Marble Highway	out	9:37-9:39	0.10
			0.61
			0.12
Oper Casablanca	out	9:50-9:51	0.13
			0.44
MSC Mathilde	in	9:53-9:56	1.9
			2.8
			2.5
Okapy	out	10:27-10:33	-
Leda Maersk	out	10:36-10:39	29
			21
			22
			13
Hilda Knutsen	in	10:41-10:44	3.9
			4.1
			11

name of ship	in/out	time (UTC)	emission (g/s)
			4.9
Buxsailor	out	11:20-11:23	9.7
			8.6
			9.1
			11
			5.9
Nibe Maersk	out	11:28-11:30	5.2
			5.9
			5.0
Birka Transporter	out	11:41-11:44	2.0
			4.4
			2.7
			2.5
Philipp Essberger	in	12:00-12:02	6.1
Shipholbrock Sun	in	12:05-12:07	5.9
			14
Oland	in	13:09-13:11	3.1
Ottawa Express	in	13:13-13:15	6.9
			9.7
			17
Baco-liner 2	in	13:26-13:29	14
			6.0
			6.8
Atlantis Alvarado	out	13:39-13:42	1.0
			0.89
			0.37
			0.79
			0.51
Grande America	in	14:18-14:21	16
			28
			26
Helene S	in	14:24-14:26	29
			12
MSC Bremen	in	14:42-14:44	18
			29
Cap Arnauti	in	14:48-14:49	23

3.1.8 *Measurement results on 2 November 2007*

On this day, the inspection vehicle was positioned in Hansweert at location 2. Measurements were conducted on the smoke plumes of ten ships. Emission values could not be allocated to any of these ships. The results are shown in Table 3-8.

Table 3-8. Results of emission measurements on 2 November 2007

name of ship	in/out	time (UTC)	emission (g/s)
Ocean Light	in	8:51-8:57	-
Tarnvik	in	8:57-9:03	-
MCT Alioth	in	9:03-9:09	-
Alessandra Bottiglieri	in	9:17-9:26	-
Geest Trader	in	9:39-9:48	-
Stella Polaris	out	9:39-9:48	-
Njatasja Theresa	out	9:48-10:03	-
Gerd Sibum	in	10:03-10:14	-
Margaretha	out	10:14-10:21	-
Horn Cap	in	10:27-10:31	-

3.1.9 *Measurement results on 9 November 2007*

On this day, the inspection vehicle was positioned at the Houtrakgemaal at location 6. Measurements were conducted on the smoke plumes of seven passing ships, and on the ferry. The latter vessel was measured twice. Consequently, there were nine ship passages. Emission values were allocated to two of these ships. The results are shown in Table 3-9.

Table 3-9. Results of emission measurements on 9 November 2007

name of ship	direction of travel [a]	time (UTC)	emission (g/s)
Rijkspont 8 Buitenhuizen *ferry*	N	13:32-13:39	-
Sophia	W	13:32-13:39	-
Karla *hydrofoil*	E	13:37-13:38	0.35
Rijkspont 8 Buitenhuizen *ferry*	S	13:44-13:46	-
Condor	W	13:53-13:55	-
Nitrico II	W	14:27-14:37	-
Catharina Amalia *hydrofoil*	E	14:37-14:38	0.09
Argus	W	14:39-14:44	-
Orisant	W	15:10-15:15	-

[a] *Direction of travel. N: crossing the canal from south to north; S: crossing from north to south; W: sailing to the west; E: sailing to the east*

3.1.10 *Measurement results on 14 November 2007*

On this day, the inspection vehicle was positioned in Walsoorden at location 4. Measurements were conducted on the smoke plumes of 20 ships. One or more emission values could be allocated to 15 of these ships. Note that the MSC Grace and the Alpha Agas passed simultaneously. However, it was possible to differentiate their smoke plumes. The results are shown in Table 3-10.

Table 3-10. Results of emission measurements on 14 November 2007

name of ship	in/out	time (UTC)	emission (g/s)
Bow Sirius	in	9:27-9:30	2.9
			4.6
Dion	in	9:33-9:36	1.1
			2.2
			3.5
			1.7
			0.83
MSC Grace	in	9:51-9:56	2.0
			5.1
			4.9
			3.3
Alpha Agas	in	9:52-9:58	0.72
			2.7
			1.4
			1.7
			3.1
			2.6
			0.52
Dutch Faith	in	10:13-10:17	1.3
			1.4
			1.4
Dole Europa	out	10:19-10:21	3.2
			6.3
Ostra	in	10:27-10:31	0.55
			0.47
			0.52
			0.35
			0.22
Stability	out	10:32-10:50	-
Tone	in	10:47-10:47	0.97
			0.52
			0.45
Ever Result	in	10:59-11:04	19
			9.0
			11
Stolt Guillemot	out	11:05-11:10	-
Grendon	in	11:49-11:51	0.23
Nora	in	12:15-12:18	4.0
			1.7
Delmas Annemone	in	12:25-12:30	2.0
			1.3
			0.22
			0.02
Coral Nettuno	out	12:30-12:39	-
General Dabrowski	in	12:39-12:42	1.2
			0.55
Lexa Maersk	in	13:32-13:35	7.2
			8.3
			2.3
Clipper Sira	in	13:47-13:48	0.11
Alpine Girl	in	14:44-14:53	-
MSC Monica	out	14:59-15:00	-

3.1.11 *Measurement results on 15 November 2007*

On this day, the inspection vehicle was positioned in Walsoorden at location 4. Measurements were conducted on the smoke plumes of 18 ships. One or more emission values could be allocated to nine of these ships. The results are shown in Table 3-11.

Table 3-11. Results of emission measurements on 15 November 2007

name of ship	in/out	time (UTC)	emission (g/s)
Alcedo	in	10:12-10:13	1.1
Pinta	in	10:38-10:47	-
Itajai Express	in	11:07-11:10	5.9
			3.7
Deltagas	out	11:39-11:46	-
Granato	in	11:59-12:02	4.1
			3.4
			2.3
Valparaiso Express	in	12:06-12:08	7.6
			1.9
Cerambycida	in	12:45-12:47	-
Clipper Inge	out	12:47-12:52	-
Pakri Victory	in	12:52-12:54	5.1
			6.7
Irbe Venta	in	12:56-13:00	0.51
			1.1
Orisant	in	13:06-13:14	-
Georg Essberger	in	13:14-13:16	-
Pinta	in	13:30-13:33	0.70
			0.71
Southern Juice + MSC Japan	out	14:02-14:07	smoke plumes were mixed, therefore no emission value
Pine Arrow	out	14:22-14:25	1.3
			0.79
MSC Baleares	in	14:41-14:44	2.1
			1.5
Bluarrow	out	14:49-15:04	-

3.1.12 *Measurement results on 16 November 2007*

On this day, the inspection vehicle was positioned in Hansweert at location 2. Measurements were conducted on the smoke plumes of two ships. Three emission values could be allocated to one these ships. The results are shown in Table 3-12.

Table 3-12. Results of emission measurements on 16 November 2007

name of ship	in/out	time (UTC)	emission (g/s)
Sigas Centurion	in	11:28-11:43	-
Atlantic Cartier	out	12:44-12:47	14
			18
			20

3.1.13 *Measurement results on 15 May 2008*

On this day, the inspection vehicle was positioned in Walsoorden at location 4. Measurements were conducted on the smoke plumes of 12 ships. An emission value was allocated to one of these ships. The results are shown in Table 3-13.

Table 3-13. Results of emission measurements on 15 May 2008

name of ship	in/out	time (UTC)	emission (g/s)
Gerd Sibum	in	8:41-8:55	-
Nord Bell	in	9:03-9:16	-
Stolt Avocet	in	9:19-9:28	-
Alana	in	9:19-9:28	-
Knud Lauritzen	in	9:57-9:59	2.9
MSC Sindy	out	10:03-10:09	-
Doerte	out	12:42-13:03	-
Gent	in	12:42-13:03	-
Jaeger Arrow	out	12:42-13:03	-
Poplar Arrow	in	13:30-13:42	-
Shipolbrock Luban	in	13:49-13:58	-
Gwenn	in	14:05-14:14	-

3.1.14 *Measurement results on 16 May 2008*

On this day, the inspection vehicle was positioned in Hansweert at location 2. Measurements were conducted on the smoke plumes of 11 ships. One or more emission values could be allocated to two of these ships. The results are shown in Table 3-14.

Table 3-14. Results of emission measurements on 16 May 2008

name of ship	in/out	time (UTC)	emission (g/s)
OOCL Tokyo	in	8:00-8:11	-
MSC Malin	in	8:13-8:26	-
Arco Dijk	out	8:39-8:45	-
Grande America	in	8:48-8:55	-
Al Bahia	in	9:24-9:25	33
Russian ship	in	9:33-9:40	-
Fry Stream	in	9:57-10:06	-
MSC Lauren	in	11:00-11:08	-
Sigas Earl	out	11:25-11:34	-
Nord Bell	out	11:38-12:41	2.0
			5.5
			3.2
Tinsdal	out	11:59-12:03	-

3.1.15 *Measurement results on 9 October 2008*

On this day, the inspection vehicle was positioned in Hansweert at location 2. Measurements were conducted on the smoke plumes of 17 ships. One or more emission values could be allocated to four of these ships. The results are shown in Table 3-15.

Table 3-15. Results of emission measurements on 9 October 2008

name of ship	in/out	time (UTC)	emission (g/s)
Saint Roch + Clipper Nadja	out	8:06-8:10	smoke plumes were mixed, therefore no emission value
Atlantic Companion	in	9:42-9:43	10
Birka Express	in	10:37-10:51	-
Atlantic Concert	out	12:04-12:06	27 13
Emotion	in	12:08-12:15	-
Zim Rio Grande	out	12:58-13:05	-
Grande Francia	out	13:05-13:09	26 32 12
Nakskov Maersk	in	13:12-13:24	-
San Fernanado	in	13:44-13:46	-
Ym Utopia	out	13:47-13:49	29 15
Frisia Lissabon	in	13:55-14:04	-
Free Impala	out	13:55-14:04	-
Mejana	out	13:55-14:04	-
Xim Pu Dong	in	14:20-14:38	-
Toronto Express	in	14:20-14:38	-
Cmacgm Cortess	in	14:40-14:46	-

3.1.16 *Measurement results on 10 October 2008*

On this day, the inspection vehicle was positioned in Hansweert at location 2. Measurements were conducted on the smoke plumes of 22 ships. One or more emission values could be allocated to 13 of these ships. The results are shown in Table 3-16.

Table 3-16. Results of emission measurements on 10 October 2008

name of ship	in/out	time (UTC)	emission (g/s)
Kraftca	in	7:42-7:36	8.3 18 11
Emotion + Stolt Jade	out	7:48-7:55	smoke plumes were mixed, therefore no emission value
Sigas Earl	out	7:56-7:58	5.5 7.1
Mary Bonsild	out	8:03-8:09	-
John Mitchell	out	8:27-8:30	7.1 6.6 4.9
APL London	out	8:51-8:54	37 22
Reinbek WG Huggin	out	9:02-9:05	20 26 17
Manzanillo II	out	9:10-9:12	8.4 4.2
Stolt Tern	out	9:16-9:24	-
MSC Togo	out	9:31-9:34	18 35 12
Cmacgm Quetzal	in	9:34-9:39	-
MSC France	in	9:46-9:48	16 33
Cool Water	in	9:52-9:56	-
MSC Sweden	out	10:19-10:21	25 17
Ruth Borghard	in	10:21-10:25	-
KLPD P41	out	11:34-11:35	0.27
Frisia Lissabon	out	11:34-11:37	24 18 17
Mar Patricia	in	12:20-12:21	0.10
Manzanillo II	out	12:46-12:53	-
Tempest	out	13:01-13:08	-
Xin Pu Dong	out	13:19-13:23	40 36 27 16

3.1.17 *Measurement results on 17 November 2008*

On this day, the inspection vehicle was positioned in Hansweert at location 2. Measurements were conducted on the smoke plumes of 13 ships. Two or more emission values could be allocated to six of these ships. The results are shown in Table 3-17.

Table 3-17. Results of emission measurements on 17 November 2008

name of ship	in/out	time (UTC)	emission (g/s)
Happy Falcon	in	9:26-9:36	-
JRS Capella	in	9:48-9:50	8.0
			20
Petrohue + Lisa	in	10:08-10:13	smoke plumes were mixed, therefore no emission value
Hibiyapark	out	10:34-10:39	20
			11
			5.7
			4.9
Beautrophy	out	11:02-11:10	-
MSC Bremen	in	11:38-11:42	17
			42
			25
			36
Bro Distributor	in	12:45-12:53	-
Amsteldijk	out	14:14-14:18	9.0
			10
			7.7
Ionian Princess	in	14:26-14:35	-
Mary Wonsild	out	14:50-14:52	0.55
			0.22
Selandia Swan	out	15:11-15:13	7.3
			12
Skier Star	out	15:28-15:30	-

3.1.18 *Measurement results on 18 November 2008*

On this day, the inspection vehicle was positioned in Hansweert at location 2. Measurements were conducted on the smoke plume of one ship. Three emission values were allocated to this ship. The results are shown in Table 3-18.

Table 3-18. Results of emission measurements on 18 November 2008

name of ship	in/out	time (UTC)	emission (g/s)
Bertina	out	10:43-10:47	9.7
			8.1
			6.5

3.2 Determining the lower limit of quantification

The limit of quantification of the measurements was based on the measurement results in situations where no smoke plumes were present from ships sailing past. These measurements were used to determine an emission value; this was done in the same way (see section 2.6) as for the measurements where ships were present. This determination was carried out for six scanning plane measurements, all of which were performed on 9 October 2006. The emission values are shown in Table 3-19. The average of these six emission values provides an estimate of the lower limit of quantification: 0.1 g SO_2 per second.

Table 3-19. Results of emission measurements without smoke plumes, 9 October 2006

time (UTC)	emission (g/s)
11:24-11:26	0.11
12:44-12:45	0.06
10:30-10:31	0.14
11:01-11:02	0.22
11:45-11:45	0.07
13:05-13:05	0.09
Average	0.1 ± 0.1

3.3 Summary of all measurement results

During the first measurement campaign in 2006, measurements were conducted on 42 ships on five measurement days. An emission value could be determined for 24 ships. A summary of the measurement days is shown in Table 3-20.

Table 3-20. Summary of the measurement days in 2006

date	ships measured[a]	ships with an emission value [b]	wind speed (m/s)[c]	wind direction (°)[d]
16-05-2006	7	5	3.3	220-279
21-06-2006	5	5	9.8	209-213
23-06-2006	11	3	1.4	151-219
09-10-2006	12	10	5.2	177-226
10-10-2006	7	1	3.0	73-136
all days	42	24		

[a] *Measurements were conducted on the smoke plumes of this number of ships.*
[b] *An emission value could be determined for this number of ships.*
[c] *The average wind speed on this day*
[d] *The two extremes of wind direction on this day, shown in degrees east of north. A wind direction of 270° is therefore a westerly wind.*

There were three very successful measurement days – 16 May, 21 June and 9 October – during which an emission value could be determined for 20 of the 24 measured ships. On the other two measurement days, 23 June and 10 October, emission values could be determined for only 4 of the 16 ships measured. In Chapter 4, the factors that determine whether or not the emissions of a passing ship can be measured are discussed.

An overview of the total number of ships measured in all years is shown in Table 3-21.

Table 3-21. Overview of measured ships

Year	ships measured[a]	ships with an emission value [b]	success[c]
2006	42	24	57%
2007	93	51	55%
2008	76	27	36%
all years	211	102	48%

[a] *Measurements were conducted on the smoke plumes of this number of ships.*
[b] *An emission value could be determined for this number of ships.*
[c] *Percentage of ships for which an emission value could be determined*

In Table 3-22, an average emission value is shown for each measured ship. This is the average of the one to seven emission values as listed in Table 3-1 through Table 3-18. If more than one emission value has been determined, then the standard deviation is also given. This is an indication of the variation in the individual emission values. The number of emission values is also listed.

Table 3-22. Results of emission measurements

name of ship	measurement location	date	number of emission values	average emission (g/s)
MSC Jade	Hansweert	16-05-2006	3	14 ± 6
Probo Emu			3	35 ± 12
Blexen			6	2.5 ± 0.7
Arklow Rainbow			5	2.4 ± 1.6
Chopin			2	2.2 ± 0.8
Margareta B	Hansweert	21-06-2006	2	3.4 ± 3.9
Maersk Malacca			3	36 ± 8
Tai Shan			5	18 ± 1
Izmir Express			2	17 ± 13
Ek-River			3	5.1 ± 0.4
Bastiaan Broere	Hansweert	23-06-2006	2	4.9 ± 6.6
Vijitra Naree			7	4.8 ± 2.6
MSC Mee May			5	3.1 ± 0.3
MSC London	Hansweert	09-10-2006	5	24 ± 6
HMS Rotterdam			6	8.4 ± 4.2
MSC Maureen			3	37 ± 23
Betsy S			6	5.5 ± 5.7
NCC Hijaz			5	14 ± 4
Happy Girl			4	5.5 ± 1.0
CS AV Rio Rapel			4	21 ± 7
Neveska Lady			5	17 ± 6
Manzanillo II			3	1.4 ± 0.3
Jilihu			4	2.9 ± 3.3
Stena Forecaster	Hansweert	10-10-2006	3	2.2 ± 0.5
Narcea	Velser-terminal	16-10-2007	1	2.5
Rio			2	0.2 ± 0.1
Geopotes 14[8]			3	3.9 ± 0.6

[8] Trailing suction hopper dredger, which sailed past three times on this day.

name of ship	measure-ment location	date	number of emission values	average emission (g/s)
Geopotes 14			2	9.0 ± 1.3
Geopotes 14			3	5.9 ± 1.6
Ginga Puma	Hansweert	01-11-2007	4	0.8 ± 0.3
Marble Highway			3	0.3 ± 0.3
Oper Casablanca			2	0.3 ± 0.2
MSC Mathilde			3	2.4 ± 0.5
Leda Maersk			3	24 ± 4.5
Hilda Knutsen			4	6.0 ± 3.4
Buxsailor			4	9.5 ± 0.9
Nibe Maersk			3	5.3 ± 0.5
Birka Transporter			4	2.9 ± 1.0
Philipp Essberger			1	6.1
Shipholbrock Sun			2	9.7 ± 5.5
Oland			1	3.1
Ottawa Express			3	11 ± 5.1
Baco-liner 2			3	8.9 ± 4.3
Atlantis Alvarado			5	0.7 ± 0.3
Grande America			3	23 ± 6.4
Helene S			3	20 ± 12
MSC Bremen			2	24 ± 7.9
Cap Arnauti			1	23
Karla	Houtrak-gemaal	09-11-2007	1	0.4
Catharina Amalia			1	0.1
Bow Sirius	Wals-oorden	14-11-2007	2	3.7 ± 1.2
Dion			5	1.9 ± 1.0
MSC Grace			4	3.8 ± 1.5
Alpha Agas			7	1.8 ± 1.0
Dutch Faith			2	1.4 ± 0.1
Dole Europa			2	4.8 ± 2.2
Ostra			5	0.4 ± 0.1
Tone			3	0.6 ± 0.3
Ever Result			3	13 ± 5.4
Grendon			2	0.2 ± 0.04
Nora			2	2.9 ± 1.6
Delmas Annemone			4	0.9 ± 0.9
General Dabrowski			2	0.9 ± 0.5
Lexa Maersk			3	5.9 ± 3.2
Clipper Sira			1	0.1
Alcedo	Wals-oorden	15-11-2007	1	1.1
Itajai Express			2	4.8 ± 1.5

name of ship	measure-ment location	date	number of emission values	average emission (g/s)
Granato			3	3.3 ± 0.9
Valparaiso Express			2	4.7 ± 4.0
Pakri Victory			2	5.9 ± 1.1
Irbe Venta			2	0.8 ± 0.4
Pinta			2	0.7 ± 0.00
Pine Arrow			2	1.0 ± 0.4
MSC Baleares			2	1.8 ± 0.4
Atlantic Cartier	Hansweert	16-11-2007	3	17 ± 2.8
Knud Lauritzen	Wals-oorden	15-05-2008	1	2.9
Al Bahia	Hansweert	16-05-2008	1	33
Nord Bell			3	3.6 ± 1.8
Atlantic Companion	Hansweert	09-10-2008	1	10
Atlantic Concert			2	20 ± 9.5
Grande Francia			3	23 ± 10
Ym Utopia			2	22 ± 10
Kraftca	Hansweert	10-10-2008	3	12 ± 4.7
Sigas Earl			2	6.3 ± 1.1
John Mitchell			3	6.2 ± 1.1
APL London			2	29 ± 11
Reinbek WG Huggin			3	21 ± 4.8
Manzanillo II			2	6.3 ± 3.0
MSC Togo			3	21 ± 12
MSC France			2	24 ± 12
MSC Sweden			2	21 ± 5.2
KLPD P41			1	0.3
Frisia Lissabon			3	20 ± 4.1
Mar Patricia			1	0.1
Xin Pu Dong			4	30 ± 10
JRS Capella	Hansweert	17-11-2008	2	14 ± 8.7
Hibiyapark			4	10 ± 7.0
MSC Bremen			4	30 ± 11
Amsteldijk			3	9.1 ± 1.3
Mary Wonsild			2	0.4 ± 0.2
Selandia Swan			2	9.6 ± 3.3
Bertina	Hansweert	18-11-2008	3	8.1 ± 1.6

3.4 Determining the percentage of sulphur in the fuel

As described in Section 2.7, to determine the percentage of sulphur in the fuel, the fuel consumption of the ship at the time the Lidar measurement was conducted must be known. These data were supplied by the VROM Inspectorate, but were available only for a limited number of ships. Based on these data and using the formula shown in Section 2.7, the percentage of sulphur in the fuel could be determined for seven ships. These percentages are shown in Table 3-23.

Table 3-23. Determining percentages of sulphur

name of ship	date	fuel consumption (tonnes/day)[a]	emission (g/s)[b]	percentage of sulphur (percentage by weight)
Narcea	16-10-2007	9	2.5	1.2
Geopotes 14	16-10-2007	30	3.9	0.56
Geopotes 14	16-10-2007	30	9	1.3
Knud Lauritzen	15-05-2008	47	2.9	0.27
Mar Patricia	10-10-2008	17	0.1	0.025
JRS Capella	17-11-2008	26	14.1	2.3
Selandia Swan	17-11-2008	23	9.6	1.8

[a] *The fuel consumption of this ship, based on a power setting of 75% of the main motor capacity*
[b] *The average measured emission for this ship; also refer to Table 3-22*

Three of these ships were also sampled by IMG and the VROM Inspectorate. These directly measured percentages of sulphur could be compared with the percentages of sulphur derived from the Lidar measurement; the results are shown in Table 3-24.

Table 3-24. Comparison of percentages of sulphur

name of ship	date	percentage of sulphur derived from Lidar (w/w)[a]	percentage of sulphur measured on board (w/w)[b]
Mar Patricia	10-10-2008	0.025	1.330
JRS Capella	17-11-2008	2.3	1.380
Selandia Swan	17-11-2008	1.8	1.340

[a] *The percentage of sulphur in the fuel as derived from the Lidar measurement taken from a distance*
[b] *The percentage of sulphur in the fuel as measured directly on board*

The emission of the Mar Patricia as measured by Lidar was extremely low; this resulted in a low percentage of sulphur, much lower than the percentage that was measured directly on board. The percentages of sulphur derived from the Lidar measurements of the JRS Capella and the Selandia Swan corresponded more closely with the measurements taken directly on board. However, three ships are not enough to reliably ascertain whether the measurement methods yield the same results; more simultaneous measurements are required for this purpose.

If the nominal fuel consumption of a ship is known, along with its speed, the instantaneous fuel consumption can be modelled. Then it becomes possible to estimate the sulphur content in the fuel for almost every ship. This is discussed in greater detail in Section 4.3.

3.5 Historical development of emissions

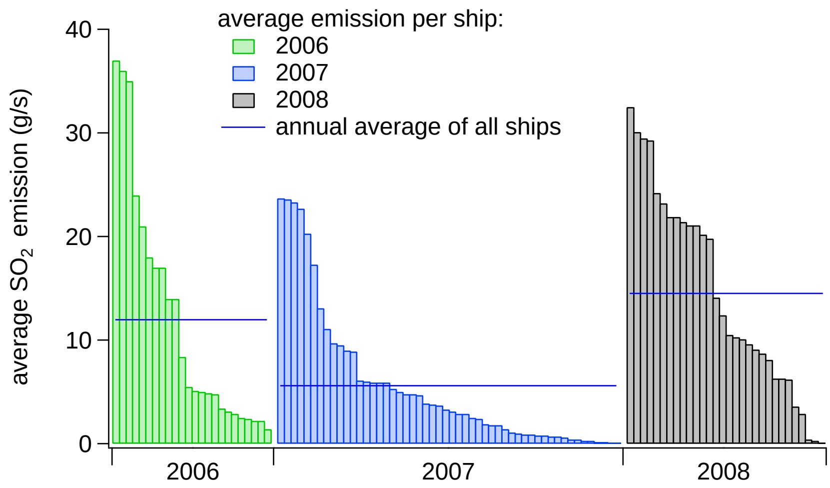

Figure 3-1. The historical development of the emissions
Each vertical bar represents a ship for which an average emission value was measured. For each year the emissions are sorted into a declining order. For each year the average emissions for all ships measured that year are shown.

On 21 November 2006, which was after the first measurement campaign, stricter regulations on the emissions of ships on the North Sea came into force (see also section 1.2). Did the stricter regulations affect these measurements? To answer this question, all measured emission values (see Table 3-22) in Figure 3-1 have been graphed over time. In 2007 a small decline could be seen relative to 2006, but this decline was more than reversed in 2008. It is difficult to draw a definitive conclusion from these results. Emissions depend greatly on the size of a ship, and it is unknown whether in 2007 smaller ships were measured than in 2006 and 2008. Useful comparisons are possible only by measuring the percentages of sulphur in the fuel.

4 Discussion and recommendations

In this chapter the most important characteristics of the Lidar method are discussed. In Section 4.1, the factors that determine the success of the Lidar measurement, i.e. where the measurement yields a value for the sulphur dioxide emission, are analysed. In Section 4.2 a number of performance characteristics of the method – such as measurement uncertainty, lower limit of quantification and selectivity – are discussed. Section 4.3 contains a discussion on how the sulphur content of the fuel that was used can be estimated based on the Lidar measurements. The chapter ends with the most important conclusions of the entire study.

4.1 Factors that determine the success of a Lidar measurement

During the study, the measurement technique yielded an emission value for approximately half of the passing ships (Table 3-21 on page 39). The following discussion addresses the factors that determine whether or not an emission value can be obtained with the Lidar technique. At the end of the chapter, the results are summarised in a text box.

4.1.1 The role of wind direction

During the first measurement campaign, in 2006, the inspection vehicle operated from virtually the same measurement location near Hansweert. Due to the position of the shipping route with respect to this location, it turned out that suitable measurements could be conducted only with the wind blowing from the southwest to southeast (approximately 90 degrees on the compass). It is only with these wind directions that the scanning planes could be positioned more or less perpendicular to the smoke plume and that they were close enough to the ships to conduct a measurement. Fortunately, the wind frequently blows from these directions in the Netherlands. Nevertheless, during this measurement campaign, the wind direction was an important constraint on the use of the measurement technique. This was partly due to an unfortunate coincidence: during the measurement weeks that were reserved for the study, the wind blew more than average from the wrong direction. After this measurement campaign, it was concluded that having access to multiple locations suitable for various wind directions would be desirable for operational purposes. It would then be easier to realise a planned number of measurement days during a given period.

For the campaigns in 2007 and 2008, in addition to Hansweert, a second location was therefore used on the Western Scheldt, adjacent to the harbour of Walsoorden. At the second location, measurements can be conducted with winds ranging from southeast to northeast (once again approximately 90 degrees on the compass rose). As a result, there were indeed more days on which the instrument could be used successfully.

4.1.2 The role of wind speed

The first measurement campaign, in 2006, had five measurement days. On three of these days, virtually all measurements resulted in a SO_2 emission value. However, on the other days, fewer measurements resulted in an emission value, ranging from less than half to only a few. The essential difference appeared to be caused by the wind speed (see Table 3-20). On days with little wind, there were a number of factors that worked against a successful SO_2 measurement:

- the plumes of the ships spread out more, and were consequently larger and more diffuse;
- the wind speed itself was more difficult to determine. This directly affected the uncertainty of the measurements;
- at low wind speeds, the wind direction is often more variable. This also affected the measurement result. Moreover, the data for a number of ships could not be used because the plume crossed the measurement plane insufficiently or not at all.

The study showed that at a minimum wind speed of 5 m per second, equivalent to 3 Beaufort, these problems no longer play a role. Certainly on the coast and at sea, lower wind speeds seldom occur. The fact that this occurred during the first measurement campaign was due to two reasons. Firstly, it was initially assumed that low wind speeds would actually be advantageous, since the concentrations would be higher. Secondly, due to the approaching deadline at the end of the campaign, measurement days with less suitable conditions had to be used.

4.1.3 *Coordination with other measurement methods*

In 2007 and 2008, the attention shifted to the comparison with the direct determination of the sulphur content in samples that were taken while on board. During those years, an attempt was made to measure the emissions of all ships from which fuel samples were taken. For this purpose, the use of the Lidar instrument was coordinated with IMG, which took the samples. For the sampling, IMG cooperated with the National Police Services Agency (KLPD), which transported the sampling superintendents by police boat to the ships that were to be measured. The use of this boat had to be reserved long in advance, for which a series of two or three sequential days was always planned. Consequently, there were few possibilities to choose optimal weather conditions for using the Lidar. To maximise the probability of overlap between taking the Lidar measurements and taking the physical samples, the Lidar was used on days when the weather was not optimal. Days with insufficient or variable winds occurred regularly. This explains why the percentage of successful measurements in 2007 and 2008 was lower than in 2006, despite the availability of another location and the recent awareness that low wind speeds are not beneficial.

4.1.4 *Other limitations*

The only other serious limitation is precipitation. Rain has a negative influence on the optical echoes used in Lidar. Moreover, the measurement set-up is not entirely rainproof. In the Netherlands, it rains approximately six percent of the time, and somewhat less on the coast.

Finally, it should be noted that the same inspection vehicle is also being used for other environmental measurements (see section 1.4). As a result, the instrument is not always available on call. However, it is possible to reserve the instrument for a specific period.

Summary of the measurement success rate

The meteorological situation ultimately determines the measurement success rate. There must be sufficient wind, and the wind must blow from a suitable direction for the measurement location. The weather must also be dry. If these conditions are met on a measurement day, then there is a very high probability that a large number of ships can be successfully measured.

It is essential that a number of measurement locations are available that are suitable for various wind directions. If this condition is met, then most of the limitations will be removed.

However, it is still impossible to guarantee beforehand that measurements can be conducted on a specific date.

4.2 Performance characteristics of Lidar emission measurement

In this section a number of performance characteristics of the Lidar emission measurement are discussed, such as measurement uncertainty, lower limit of quantification and selectivity. At the end of the chapter, the results are summarised in a text box.

4.2.1 Measurement uncertainty

In Chapter 3, the results of the various scans for a large number of ships are presented; these scans lasted approximately 45 seconds each. Each scan can be thought of as an independent measurement of the emission. For most ships, more than one scan could be conducted, which means that more than one emission value could be determined. These figures sometimes show a large deviation. What causes this deviation and how does this affect measurement uncertainty?

4.2.2 The role of emission variability

First of all, it should be noted that in a number of cases, the measured differences can be correctly attributed to actual differences in the emission. Regarding the measurements taken on the Western Scheldt (measurement locations Hansweert and Walsoorden), the ships sailed a circuitous route through the sea lane. During the measurement days, sudden changes in soot emissions were repeatedly observed, which indicated that the ships were ‘applying full throttle’. The actual emission was therefore not always constant.

4.2.3 The measurement uncertainty of the Lidar method itself

As with any other method, Lidar measurement is also subject to uncertainty. Factors that play a role in this uncertainty include the variability of the wind (the direction and the wind speed), the meandering of the smoke plume and the uncertainty of the concentration measurement due to the Lidar method. Appendix 1 addresses these aspects in greater detail.

Based on the study, it was not possible to determine which of the above factors – the real emission variations or the measurement uncertainty – made the largest contribution to the deviation of the results of the various scans. However, an upper limit of the uncertainty of the Lidar measurement can be derived if it is assumed that the emissions of the ships do not vary at all. This analysis is shown in Appendix 1. The upper limit of the measurement uncertainty of the Lidar method is approximately 20%. However, this upper limit also includes the variability of the actual emission while the plume of a ship was being measured. There are indications that the Lidar method itself is more precise, because much more precise measurements were obtained for a number of ships.

4.2.4 *Lower limit of quantification*

As discussed in Section 3.2, the lower limit of quantification was ascertained by determining an emission value in the portion of the atmosphere where no smoke plume was present in the scanning plane. The lower limit of quantification was determined to be 0.1 g of sulphur dioxide per second. As a rule, the ship emissions measured in this study were significantly above this limit.

4.2.5 *Selectivity*

The selectivity of the Lidar method is determined by the presence or absence of gases other than the target gas (in this case SO_2) for which the Lidar is sensitive. As explained in Section 2.1, Lidar is sensitive to a gas that – similar to the target gas – differentially attenuates the two colours of light emitted by Lidar. The difference in attenuation per unit of gas determines the sensitivity. For each target gas, the colours are chosen in such a way that the sensitivity for the target gas is maximised and the sensitivity for other gases is minimised. Nevertheless, it is impossible to eliminate beforehand the possibility that another gas could also differentially attenuate the colours of light used, and therefore could result in a false-positive or false-negative measurement. Such a gas would affect the sensitivity of the smoke plume measurements discussed in this report only if it is present in the smoke plume in a sufficient quantity.

The most obvious gas with a possible influence on sensitivity is nitrogen dioxide (NO_2). Interference caused by this gas has been investigated. For other gases that undoubtedly appear in the smoke plume, such as water vapour, carbon dioxide, nitrogen monoxide, carbon monoxide and hydrocarbons, spectroscopic interference is less likely. However, these possibilities have not been investigated specifically.

The sensitivity for NO_2 turned out to be much lower than that for SO_2. With the colours of light used in the study, the Lidar is more than 400 times more sensitive for SO_2. The sensitivity is opposite in sign: a NO_2 concentration of + 428 μg/m^3 is seen as a SO_2 concentration of -1 μg/m^3. The presence of NO_2 in the smoke plume therefore leads to an underestimation of the SO_2 emission. The NO_2 emission of the ships was decidedly lower than 10 g per second; otherwise, yellow plumes would have been clearly visible, and these were never observed. The emission of nitrogen oxide is therefore similar to, or smaller than, the emission of sulphur dioxide. Consequently, considering the 400 times greater sensitivity of Lidar to SO_2, the possibility of underestimation due to the presence of NO_2 is negligible.

As part of a more extensive validation study, the selectivity could be investigated in greater detail by analysing a typical smoke plume with conventional analytical chemistry methods, and then determining the effect on the Lidar measurement of each component found. However, such a study was beyond the scope of the present research.

Summary of the performance characteristics of Lidar measurement

In the first part of the study, a passing vessel could be scanned four times on average. Based on these four scans, the sulphur dioxide emission could be determined with a measurement uncertainty of approximately 20%. This value is an upper limit.

The smallest sulphur dioxide emission that the method can detect was determined to be 0.1 g per second. As a rule, the ship emissions measured in this study were significantly above this limit.

Limited research has suggested that the method is largely unaffected by other trace gases in the ship emissions. Specifically, the possibility of nitrogen dioxide distorting the measurement has been eliminated.

4.3 Determining the percentage of sulphur in the fuel

As discussed in Section 2.7, the sulphur dioxide emissions of a ship as measured with Lidar can be used to determine the percentage of sulphur in the combusted fuel. For this purpose, the fuel consumption of the corresponding ship must be known at the time the emission was measured. This can be modelled: the required parameters are the nominal fuel consumption and the speed of the ship (Jalkanen et al., 2009). Nominal fuel consumption of ships is tracked by organisations such as Lloyd's, and is available from them. The current speed of most ships is broadcast by the ships themselves via the Automatic Identification System (AIS). This is a system that automatically sends out a radio signal with data such as the position, course and speed of the ship. These data can be received with simple equipment. The SOLAS convention (International Convention for the Safety of Life at Sea) requires all oceangoing ships with a gross register tonnage of 300 or more and all passenger ships to have an AIS transmitter on board. This means that the current speed of virtually every passing ship can be determined with an AIS receiver.

During the research described in this report, an AIS receiver was not available. The inspection vehicle is now equipped with such a receiver. Consequently, in follow-up research, an estimate of the sulphur content in the fuel can be made for many more ships than in the present study. Because the fuel consumption can then be estimated much more accurately, the estimated sulphur content will also be much more precise than the estimates shown in Section 3.4.

4.4 Cost-effectiveness of the Lidar method

4.4.1 Cost-effectiveness research

In 2008, the Andersson Elffers Felix consultancy bureau performed a cost-benefit analysis of the use of mobile Lidar to enforce regulations related to the sulphur dioxide emissions of oceangoing ships (LIDAR, 2008). This study identified the costs and benefits of the current enforcement practice – using a patrol boat of the National Police Services Agency (KLPD) to board oceangoing ships from which fuel samples are taken – and the costs and benefits of the Lidar method combined with a patrol boat.

The main conclusion of the study was that using Lidar combined with a patrol boat leads to improved monitoring and a much higher probability of catching violators. In this way, the enforcement of emissions legislation can be improved, which leads to lower emissions and thereby to positive environmental effects. In addition, the more intensive monitoring provides improved insight into the total emissions of oceangoing ships. This information can then be used to arrive at stricter legislation concerning the emissions of oceangoing ships in an international context.

Besides the above-mentioned societal benefits of using the Lidar method, the financial benefits and corresponding costs were also studied. It was concluded that five ships per day could be checked with the standard monitoring method using a patrol boat only. The costs of this method were determined to be €2806 per day for personnel and for the analysis of fuel samples.

The financial benefits are from the fines that are imposed on violators. The study conducted by Andersson Elffers Felix was based on a total of 35 passing ships per day. On average, 15% were assumed to be in violation. However, due to the 'gut feelings' of the crew of the patrol boat, violators would have a somewhat higher chance of being checked, so that 19% of the monitored ships were expected to be in violation. Assuming an average fine of €2250, that would yield €2109 in fines per day, based on a monitoring rate of 14% and a probability of being caught of 3%. The financial result is negative on balance: the monitoring would cost €697 more per day than it would yield in fines.

However, by using Lidar as a screening instrument to indicate the targets for the patrol boat, the financial aspects are very different. The Andersson Elffers Felix study assumed that the Lidar measurement could ascertain the sulphur emissions of 80% of the passing ships. The patrol boat could then be used to check the boats with the highest emissions. In that case, the majority of boarded ships (the study assumes 75%) would be in violation. The financial benefits would then increase to €8398, the monitoring percentage would rise to 80%, the monitoring would take place more objectively and the probability of catching violators would nearly quadruple, to 11%.

In the Andersson Elffers Felix study it was assumed that one measurement day with Lidar would cost €10,000. However, this includes the costs of a detailed post-analysis and writing a report. If the Lidar were used exclusively to indicate potential violators to enforcement personnel on board a patrol boat, this post-analysis would no longer be required. The total cost of one day of Lidar measurement would then be €5000 for the first day in a measurement campaign and €3000 for each subsequent day. The costs for the patrol boat and for sampling would remain the same. The first day in a measurement campaign would then yield a positive balance of €592, which would rise to €2592 for each subsequent day.

These figures are also shown in Table 4-1. The table shows the costs and benefits per day for three scenarios.

Table 4-1. Cost-benefit analysis[9]

Scenario	1	2	3
Ships			
Passing	35	35	35
Boarded	5	5	5
violation percentage boarded ships	19%	75%	75%
Costs			
patrol boat (€)	2806	2806	2806
Lidar (€)		5000	3000
total (€)	2806	7806	5806
Benefits			
fines (€)	2109	8398	8398
Results			
daily result (€)	-697	592	2592
monitoring percentage	14%	80%	80%

Scenario 1: patrol boat, no Lidar
Scenario 2: patrol boat and Lidar, first day
Scenario 3: patrol boat and Lidar, each subsequent day

4.4.2 *Conclusion*

The conclusion of Andersson Elffers Felix was that the use of Lidar costs money on balance. As explained above, this conclusion was based on an excessively high estimate of the costs of using Lidar. Based on the correct costs, however, using Lidar in combination with a patrol boat of the KLPD would earn money immediately. The first day of the measurement campaign using Lidar and a patrol boat together would yield €1289 more[10] than the use of a patrol boat by itself. On each subsequent day, the difference would be even greater: €3289.

In addition, the study supports the conclusion that the use of Lidar has societal benefits, such as increasing the monitoring percentage from 14% to 80%, and quadrupling the probability of catching violators, from 3% to 11%.

4.5 Suggestion for future research

The Lidar measurement method is operational within the indicated framework and can be used as such in subsequent studies where the sulphur dioxide emissions of oceangoing vessels are determined with a measurement uncertainty of approximately 20%. In this regard, the technology is certainly suitable for use as a surveillance and detection instrument.

If the technology is to be used as an enforcement instrument, a more extensive validation of the measurement method as a whole would be desirable. Important aspects in this regard are ascertaining the *precision* and *accuracy* of the method itself. This study should preferably be conducted using a stationary source with a known, constant sulphur dioxide emission. As part of the study, the Lidar technology would be compared with other, more conventional techniques for ascertaining the emissions.

In addition, the use of this technology in law enforcement will require further verification of its selectivity, although at this time strongly interfering gases are

[9] The data in this table are largely derived from LIDAR (2008).
[10] This is a net benefit of €592 instead of a net cost of €697.

not expected to be found. The best method is the above-mentioned complete plume analysis, with a calculation of the effects on the Lidar measurement. However, most components can be evaluated in a simple fashion by means of a limited literature study or a brief spectroscopic analysis.

Now that the instantaneous speed of every ship can be easily determined, the estimates of the sulphur content of the fuel are expected to be much more accurate than was previously possible. Of course, it is desirable to test this assumption in a follow-up study. This study has now begun as part of the previously mentioned project of the Joint Research Centre (Section 1.4).

5 Conclusion

The study demonstrates that it is possible under actual conditions to use the shore-based mobile Lidar of the RIVM to determine the sulphur dioxide emissions of passing ships. The measurement system used in this study is mounted on an inspection vehicle that is entirely autonomous. The method is fully operational and is available for inspection purposes as a detection and screening technology to distinguish between ships using high-sulphur and low-sulphur fuel.

The most important advantage of the method is that the measurements can be conducted remotely. As a result, virtually every passing ship can be measured – unlike with conventional methods such as patrol boats. This provides a major improvement in efficiency.

When used as a screening method, the measurement instrument is highly cost-effective. The Lidar can identify potential violators; as a result patrol ships can be deployed much more efficiently than is now the case. Because the probability of catching violators is greatly increased, the number of violations is expected to decrease.

Lidar measurements of sulphur dioxide emissions from a ship can also be used to determine the sulphur content of the fuel. The additional data required for this – the speed of the ship at the time of measurement and the nominal fuel consumption – are now available. A follow-up study is currently being conducted into the accuracy of the sulphur content determined in this way.

The Lidar instrument has a range of 2.5 km and a lower limit of quantification of 0.1 g per second. For a typical emission determination for a single ship, an upper limit of measurement uncertainty of approximately 20% was ascertained when using the Lidar technology. This upper limit of 20% also includes the variability of the actual emission while the plume of a ship was being measured. The results from several individual ships suggest that the precision of the Lidar method itself is higher, possibly much higher.

Within current legislation, which focuses primarily on the sulphur content of the fuel, the Lidar method will initially have a role as a detection and screening instrument. During this process, the instrument would be used in combination with conventional methods. If legislation was in force that specified not only the sulphur content of the fuel, but also the actual sulphur emissions, the Lidar method could provide an even better contribution to enforcement. As an independently operating enforcement instrument, the Lidar method is presently usable for ascertaining exceedances where an estimated fuel consumption is sufficient to demonstrate that fuel with an excessive sulphur content is being used. In view of the large differences in sulphur content between fuels that are permitted and forbidden, this application also appears to be realistic.

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Acknowledgements

The authors would like to express their appreciation for the cooperation and hospitality of the staff of the Hansweert centre of Rijkswaterstaat. We would also like to thank Bram Baas of the Directorate for Public Works and Water Management for providing secure parking on their property for the inspection vehicle.

As part of this study, we also used wind measurements from the automated wind gauge at Hansweert, which are made available to the public by the Hydro Meteo Centrum Zeeland on the internet (www.hmcz.nl).

Appendix 1

In Chapter 3, the results of the various scans for a large number of ships are presented; these scans lasted approximately 45 seconds each. Each scan can be thought of as an independent measurement of the emission. During the 2006 measurement campaign, all ships that were successfully measured were scanned more than once. Consequently, more than one emissions factor could be determined for these ships. These figures sometimes show a large deviation. This deviation is discussed below.

The role of emission variability

First of all, it should be noted that in a number of cases, the measured differences can be correctly attributed to actual differences in the emission. Regarding the measurements taken on the Western Scheldt (measurement locations Hansweert and Walsoorden), the ships sailed a circuitous route through the sea lane. During the measurement days, a sudden change in soot emission showed a number of times that the ships were applying full throttle. Their emissions were therefore not constant.

The role of wind variability and the uncertainty of wind measurement

When measuring the emission, the determination of the wind speed plays an important role. If the wind speed is overestimated or underestimated by a specific percentage, then the estimated emission value becomes too high or too low by the same percentage. For each scan, the local wind speed during the 45 seconds that the plume is scanned is the most important. However, for the measurements taken on the Western Scheldt, data from a measurement mast operated by Rijkswaterstaat were used (see section 2.4). This facility is located in the water several kilometres from the smoke plume (see also Figure 2-4). A study of the variability of these wind data showed that this distance resulted in an uncertainty in the emission value of approximately 10%. The variability in the wind direction played a much smaller role, as long as the plume was located more or less perpendicular to the scanning plane.

The role of smoke plume meandering

During the Lidar scan, which lasts approximately 45 seconds, the laser beam moves in nine or more steps from the bottom to the top of the scanning plane. At every measurement direction, the beam remains still for five seconds and measures the concentration distribution in that direction. The entire scanning plane is therefore not measured simultaneously, but is scanned from the bottom to the top. However, during these 45 seconds the plume also moves: the plume axis often moves both up and down and from left to right and back again. This movement is called meandering and can be seen clearly in Figure B-1. Due to this meandering, it is possible that the plume in the scanning plane could coincidentally move with the scan (from bottom to top), or could move opposite to the scan (from top to the bottom). In the first case, the plume would remain in the picture too long and an excessive emission would be measured; in the second case the measured emission would be too low. The magnitude of this effect is difficult to quantify, but could be significant for individual scans if the meanders are large. However, it is clear that this effect quickly averages out in sequential scans. With a strong wind, the meanders are smaller.

Figure B-1. The Jilihu, with a meandering smoke plume

The role of measurement uncertainty in concentration measurement

The remote measurement of concentration with Lidar has its own uncertainties. Because only a brief measurement time for each measurement direction is available, the concentration measurements are based on a relatively noisy echo signal. The measurement uncertainty of the ascertained quantity of SO_2 in the plume is approximately 10% with heavily loaded plumes. With lightly loaded plumes, the uncertainty is larger.

Precision of the method as a whole

It is difficult to quantify the precision of the method as a whole. Traditionally, precision is determined by calculating the statistical variation based on an adequate number of sufficiently accurate measurements repeated on the same sample. This was not possible in the present study because the sample was always different. Nevertheless, it was possible to determine an upper limit of the precision based on the present study. This took place as follows, whereby data acquired during the 2006 campaign (24 measured ships) were used:

(1) Virtually all of the above-named factors that play a role in the variability were found to lead to a relative variation in the result, regardless of the source strength itself. If each ship could be normalised with its true source strength, then we would consider all ships to be equal in statistical terms. The only real exception is variability caused by human actions (applying full throttle).
(2) For every ship, the average emission was determined based on all successful scans from 2006 (Table 3-22). Each scan was then normalised using this average. After this, each scan was expressed as a percentage of the average for the corresponding ship, so that all averages totalled 100%.
(3) Next, the clearest cases of applying full throttle were eliminated. These were the ships where one or several scans strongly deviated from the others. All data from these ships were eliminated from further analysis. This was done in cases where the highest scan value was five times or more larger than the average of the other scans for that ship. This concerned 2 of the 24 ships in the campaign: the Betsy S and the Jilihu.
(4) Finally, the statistical variation of the total set of remaining scans was analysed. This concerned 86 scans of 22 ships.

The results are shown in a histogram (Figure B-2).

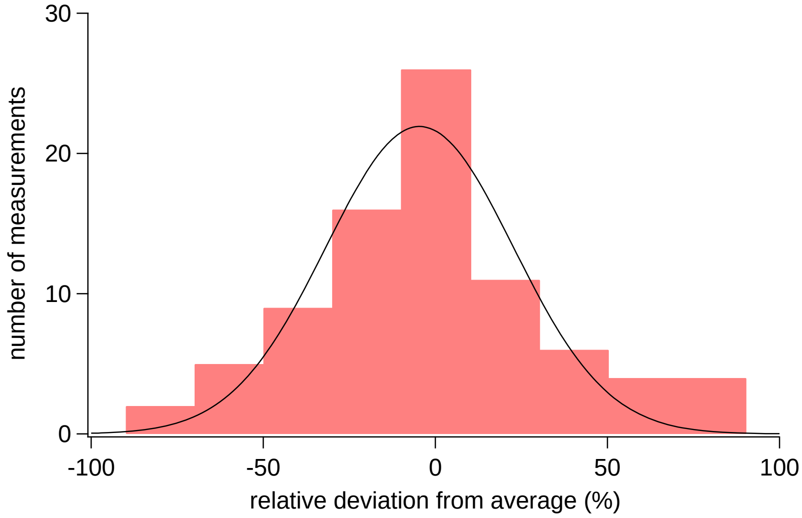

Figure B-2 Histogram
The histogram shows the distribution of the results of individual scans, expressed as a percentage of the average result for the corresponding ship. In black, a Gausse curve is fitted to the histogram. The relative standard deviation is 38%.

It can be concluded that the individual scans have a relative standard deviation of 38%. A typical emission value for a ship, as shown in Table 3-22, was calculated as the average of four scans and therefore has a precision of 19%.

It should be noted that 19% is an estimate for the upper limit of the precision of the Lidar measurement method based on virtually all successful scans in the 2006 measurement campaign. It is an upper limit because the observed deviation has been calculated including the variation in source strength (the change in actual emission from scan to scan), and it is unknown how large this variation is. It is quite possible that the Lidar measurement itself is significantly more precise and that the observed deviation was primarily the result of variations in the actual emission. The significantly better results from some individual ships seem to point in this direction (Tai Shan: 18 ± 1 g per second, in contrast to MSC London: 24 ± 6 g per second, in both cases five scans and a comparable emission). To determine the precision of the Lidar measurement itself, repeated measurements of a source with constant strength are required. This was not a part of the current study, but has been proposed as a follow-up study.

**A.J.C. Berkhout | D.P.J. Swart | G.R. van der Hoff |
J.B. Bergwerff**

Rapport 609021119/2012

This is a publication of:

**National Institute for Public Health
and the Environment**
P.O. Box 1 | 3720 BA Bilthoven
The Netherlands
www.rivm.nl

March 2012

003606