Remote Sensing of Sulphur Dioxide Emissions of Sea-Going Vessels on the Westerscheldt Estuary

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ABSTRACT

RIVM developed a mobile lidar system to measure SO_2 emissions of sea-going vessels. In three field campaigns, the SO_2 emissions of a total of 110 ships on the Westerscheldt estuary were determined. As it turned out, a large number of those ships emitted large quantities of SO_2. Various measures have driven back emissions from other sources, such as traffic, industry and electricity generation. This causes the share of shipping in the total of the emissions to increase.

Sea-going ships are not allowed to use sulphur-rich fuel in territorial waters. This relatively cheap fuel may be on board, though, for use at sea. To what extend ship owners comply with this ban is not known. A breach is difficult to determine using traditional measurement methods because these require boarding the ship. This is a labour-intensive procedure, so only a small percentage of the ships can be visited. The lidar measures from the shore and will determine the emission of nearly every passing ship. In addition, boarding the ship will alert the crew that a measurement is taking place, so they may adjust the type of fuel used. The lidar measures unnoticed.

On land, sulphur dioxide emissions of industrial installations are limited by licences. Dutch law puts demands on sources that emit more than 0.56 gram per second. All measured ships emitted more than that, the highest emission being 36 gram per second. This indicates the importance of recognising ocean shipping as a source of air pollution, both when issuing rules and when enforcing them.

1. INTRODUCTION

Seagoing vessels are an important source of sulphur dioxide in the atmosphere. There are two reasons for this. Firstly, the contribution of other sources, such as electricity generation, industry and traffic, is declining due to stricter legislation. Secondly, the sulphur fraction in heavy marine fuels is rising. These causes are linked together. Due to the stricter "onshore" requirements, a steadily increasing proportion of the sulphur in crude oil is finding its way into marine fuels.

1.1 Problem Definition

Sulphur-rich fuels are significantly cheaper than sulphur-poor fuels. Ships may carry sulphur-rich fuels on board, but their use within territorial waters is forbidden. However, enforcing this restriction is difficult if monitoring can only be done on board. It is therefore conceivable that sulphur-rich fuels are being used on major shipping routes such as the Westerscheldt. In that case, the emissions are being significantly underestimated. A suitable enforcement instrument is lacking.

2. MATERIALS AND METHODS

2.1 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 elapsed between sending and receiving the light, the distance to the reflecting particles to the lidar can be derived. The lidar reported on here is mounted on a vehicle. Figure 1 shows the exterior and interior of this mobile lidar.

Figure 1. The mobile lidar, exterior and interior.

This lidar system 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

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from the first light pulse will be more strongly attenuated than the light from the second pulse. The SO_2 concentration at the location where 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, however, a value can be determined every 100 to 200 m, from about 350 m to about 2500 m from the instrument. 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 and Figure 3.

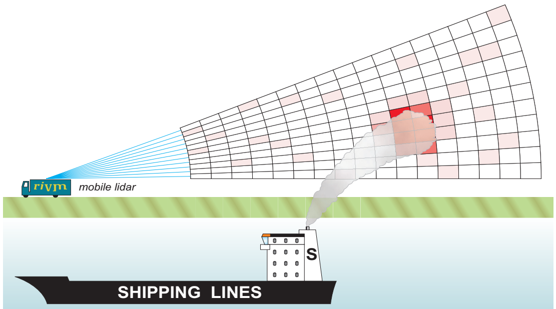

Figure 2. Schematic overview of the determination of the SO_2 concentration in a vertical plane. The measurement directions are shown in blue, the white to red cells indicate segments for which a concentration is determined.

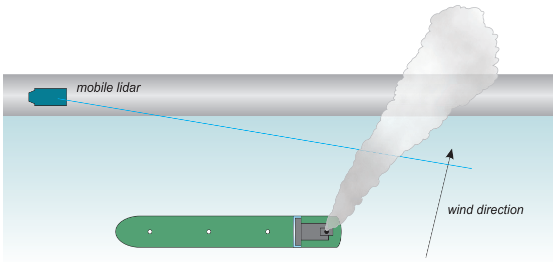

Figure 3. View from above of the situation during an emission measurement.

2.2 Measurement Procedure

The measurements discussed in this report were all conducted on seagoing vessels on the Westerscheldt. Hansweert was chosen as a measurement location because the channel runs close to the shore and because the scanning plane can be located both parallel to the direction of travel and perpendicular to the most likely wind directions. See Figure 4 for an overview of the measurement location, and Figure 5 for a photograph of the mobile lidar.

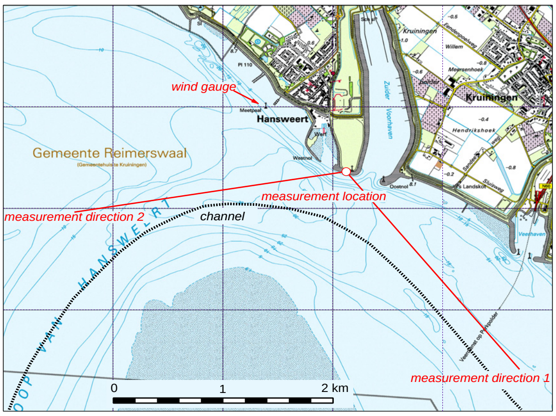

Figure 4. Measurement location at Hansweert, with measurement directions shown. Wind gauge: measurement mast of the Directorate for Public Works and Water Management.

Figure 5. The lidar at the measurement location.

An automated wind gauge is located near this measurement location; this wind gauge is part of the ZEGE measurement network (Zeeland tidalwaters). This measurement network is maintained by the Hydro Meteo Centrum Zeeland (HMCZ), a sub-department of the Rijkswaterstaat Zeeland Directorate. The wind and tidal data are published on the Internet http://www.hmcz.nl and were used to calculate the emission factors presented here. The wind speed was calculated at the elevation at which the lidar measurement indicated that the smoke plume was present; this was done by using a logarithmic wind profile, the measured wind speed and the measured water level.

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 factor was determined for every scanning plane measurement. Because the exhaust of all ships was visible in a sequence of scanning plane measurements, more than one emission factor 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 plume of ships was visible.

2.3 Determining the emission

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

In the lidar signal, the soot and other particulate matter in the exhaust 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 factor, these two results – the concentration and the area – are multiplied by the wind speed.

2.4 Determining an Emission Factor from a Measurement

As an example, the determination of the emission factor for one of the ships measured at the Westerscheldt estuary, the approach to the harbour of Antwerp. 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 6. 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 stretched with respect to the horizontal axis; in reality the scanning plane is much more elongated than it appears in this figure. The colour of the plane indicates the concentration of SO_2.

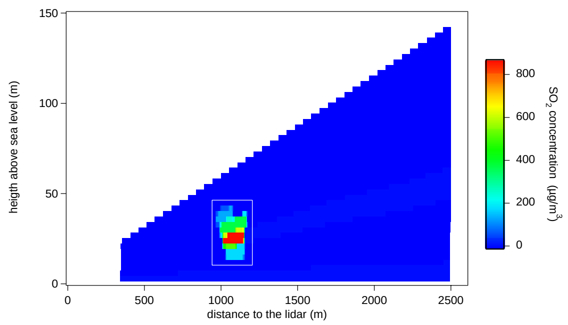

Figure 6 Cross section through the exhaust plume of the example ship. The colour indicates the concentration of SO_2 in the air. The white rectangle shows the plume as it was used in the further analysis.

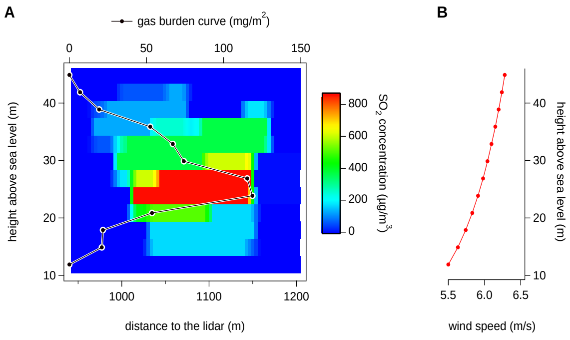

Figure 7 A: cross-section from Figure 6 the exhaust of the example ship and the corresponding gas burden curve. B: logarithmic wind profile.

To process this data into an emission factor, the plume is selected in Figure 7 (the white rectangle; this selected area is shown in Figure 6). For every height, the total quantity of SO_2 at that height is determined. This results in a gas burden curve (also shown in Figure 7). By multiplying this by the wind profile (Figure 7B), corrected for the angle between the wind direction and the scanning plane, and then adding up all values, the emission factor can be found. For this ship at that time, the emission factor was 7.1 gram SO_2 per second.

3. RESULTS

In 2006, during five measurement days, measurements were conducted on a total of 42 ships. An emission factor could be determined for 24 ships; these are shown in Figure 8. The results from the 2007 and 2008 measurement campaign will be presented soon.

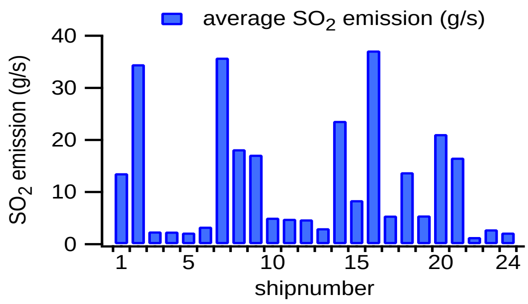

Figure 8. SO_2 emissions per ship, measured in the 2006 campaign.

A more detailed version with all individual results of each ship can be found at http://www.rivm.nl/bibliotheek/rapporten/609021039.html in section 3.

3.1 Lower limit of quantification

The lower limit of quantification was ascertained by determining an emission factor 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 gram of SO_2 per second. Usually, the emissions measured in this study were significantly above this limit.

4. CONCLUSIONS

This study has shown in practice that it is possible to make remote measurements from the shore of the sulphur dioxide emissions of seagoing vessels while they are underway. This methodology is fully operational and is available for ships that use sulphur-rich and sulphur-poor fuels.

At this time, the instrument has a range of 2.5 km and a lower limit of quantification of 0.1 g per second.

An important disadvantage is that only a limited number of wind directions can be measured from a single measurement location. To increase the usability of the method and to allow the measurement sessions to be scheduled more effectively, it is therefore desirable to have access to multiple measurement locations that are suitable for various wind directions.

On land, the sulphur dioxide emissions of industrial installations are limited by means of permits. These permits are based on the Netherlands Emission Guidelines for Air (NeR, April 2003), which imposes additional demands on sources that emit more than 2 kg sulphur dioxide per hour (0.56 g per second). In all 24 cases, the measured emission of the seagoing vessels exceeded this level. The highest measured emission was 36 g per second. Attention to ocean shipping as a source of air pollution is therefore important for both making regulations and enforcing them.