# THE RIVM MOBILE LIDAR – DESIGN AND OPERATION OF A VERSATILE SYSTEM FOR MEASURING ATMOSPHERIC TRACE GASES

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## ABSTRACT

This paper describes the RIVM mobile lidar system. This lidar system uses the DIAL technique to measure atmospheric trace gases. It is housed in a fully self-supporting mobile laboratory, so that measurements can be taken anywhere. Its intended uses are measuring industrial emissions and satellite validation.

The lidar uses a dye laser as light source, with a grating driven by a fast piezoelectric actuator to tune between the DIAL wavelengths. It is designed for maximum flexibility, a wide variety of trace gases can be measured while the instrument still has a high uptime.

Two applications are described. The lidar is used to validate the $NO_2$ vertical column measurements of the OMI satellite instrument by measuring vertical $NO_2$ concentration profiles. A second application is the measurement of $SO_2$ emissions from seagoing ships. This is done from the shore, on a harbour approach waterway.

## 1. INTRODUCTION

This mobile lidar system uses the DIAL technique to measure trace gas concentrations in the atmosphere. It was built with several applications in mind. The first is the remote monitoring of industrial emissions within the framework of the enforcement of environmental laws. A second application is the validation of satellite instruments, the lidar then measures vertical concentration profiles.

This lidar system is designed for maximum flexibility. The dye circulators, the emitter and receiver optics can easily be exchanged. This makes it possible to use the system to measure a wide variety of gases for a wide variety of customers, while still retaining a high uptime. Possible trace gases include $NO_2$, $SO_2$, $NH_3$, Hg, HCl, HF, benzene, toluene and xylene. Of these, $NO_2$ and $SO_2$ have been realised so far.

Similar lidar systems have been constructed in the past, see [1] – [3].

## 2. LIDAR SYSTEM DESIGN

The lidar system design is outlined in Fig. 1. It consists of an emitter unit, a receiver unit, a spectrophotometer unit and a processing and control unit (not shown). The entire system is housed in a fully self-supporting mobile laboratory.

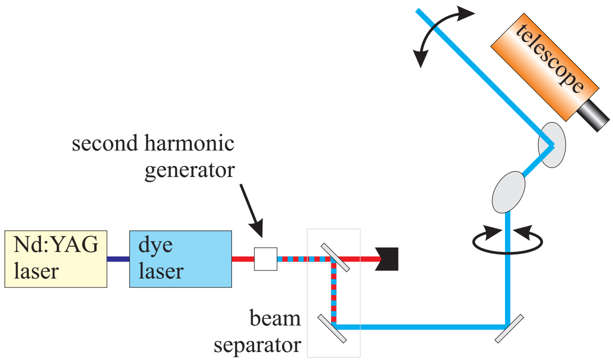


Fig. 1. Simplified scheme of the lidar system.

### 2.1. The Emitter Unit

Light pulses are emitted by a pump laser – dye laser combination. The pump laser is a Spectra-Physics Quanta-Ray Pro 250 Nd:YAG laser. It runs at 30 Hz and produces pulses of 8-10 ns, with an energy per pulse of about 420 mJ at 355 nm. This light is used to pump a Sirah PrecisionScan PRSC-D-30 dye laser. The resonator of this dye laser uses a single 1800 lines/mm grating, which results in a linewidth of 2.4 pm. If laser light in the UV range is required, a second harmonic generator is inserted in the beam path. The divergence of the laser beam is about 0.5 mrad. Output power depends on the dye used, but is typically 40 mJ/pulse for the fundamental beam, and 5 mJ/pulse for the frequency doubled beam.

The dye laser wavelength is tuned over a wide range using a stepper motor. In addition, a piezoelectric actuator is used to rapidly detune and retune the resonator by 1 nm (of the fundamental wavelength). This detuning takes place between two laser pulses. In this way, the system alternates between the two wavelengths required by the DIAL technique.

The system was designed with the fast switching between trace gases in mind. To achieve this, all wavelength-specific optics are mounted on kinematic base plates. Exchanging the laser dye is done by removing the dye cells from the laser and inserting cells with a different dye solution. For each dye, and thus for each trace gas, a complete set of dye cells and dye circulation pumps is available.

The laser beam is directed to the atmosphere through a set of mirrors and prisms. The final two of those are, together with the receiver optics, mounted on a movable platform, so that the beam can be pointed at any direction around the instrument: in the vertical plane from the horizon to the zenith, in the horizontal plane almost 360° around.

## 2.2. The Receiver Unit

The receiver unit consists of a telescope, a shutter, an interference filter and a photomultiplier tube (Fig. 2).

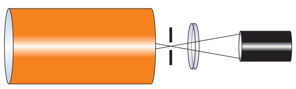


Fig. 2. The receiver unit, s: shutter/diaphragm, f: interference filter, PMT: photomultiplier tube.

The **telescope** is a Celestron C11 Schmidt-Cassegrain telescope. It has a clear aperture of 280 mm and a field of view of 1.1 mrad.

The **interference filter** blocks out the ambient light, it is different for each trace gas. When measuring in the visible region, daylight photons within the transmission band of the filter will still reach the detector. During daytime, this leads to a steady DC current from the photomultiplier tube, contributing to the noise of the measurements. The **shutter** is used to limit the load on the photomultiplier tube by excluding this remaining daylight when the system is idle between two laser pulses. It is open for about 6 ms. A full cycle takes 33.3 ms, so the duty cycle of the photomultiplier tube is 18%. Previous research has shown that the tube shows a more linear behaviour this way. When measuring using light below 350 nm, the shutter is left open.

The **photomultiplier tube** is a Thorn-EMI 9818 QA tube.

## 2.3. The Spectrophotometer Unit

The light emitted by this laser has a line width narrower than small features on some of the trace gases measured. This makes the instrument sensitive to small variations in wavelength calibration, such as might occur if the room temperature varies. The line width is also different from that of instruments used to determine literature values for the trace gas cross sections. To address these issues, a spectrophotometer unit (Fig. 3) is used to determine and monitor the cross section of the trace gas under investigation.

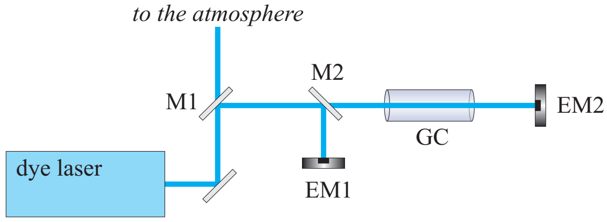


Fig. 3. The spectrophotometer unit, M1: beam sampler, reflectance 1%, M2: beam splitter, reflectance circa 50%, EM1, EM2: energy meters, GC: gas cell, filled with the trace gas under investigation.

A small portion of the outgoing laser beam is diverted and split in two. One part is directed onto an energy meter, capable of measuring the energy of a single laser pulse (EM1 in Fig. 3). The other part is passed through a gas cell containing the trace gas (GC in Fig. 3) before being measured by a second energy meter (EM2 in Fig. 3). By dividing the measurements of EM1 and EM2 an absorbance or transmittance value may be obtained.

Repeating this procedure at a range of wavelengths enables the measurement of a spectrum, from which instrument-specific cross sections are derived. Running this system during a DIAL measurement allows for on-line monitoring of the cross section; if it changes, the wavelength may be re-tuned.

## 2.4. The Processing and Control Unit

The instrument is fully computer-controlled. All functions – instrument control, data acquisition, data processing – are handled by an integrated dedicated program, written on the LabVIEW development platform.

Data acquisition is done using a Licel TR 40-160 40 MHz 12 bit transient recorder.

## 2.5. The Mobile Laboratory

The entire system is housed in a custom built mobile laboratory, 8 m long, 2.5 m wide and 2.3 m high, mounted on a vehicle (Fig. 4). It is fully self-contained: it has a generator, climate control and a system to provide the laser with cooling water. The complete emitter and receiver units, including the movable telescope, are mounted on a single aluminium frame (Fig. 5). When travelling, this frame is supported by actively damping bellows, filled with pressurised air, to reduce the risk of damage due to shocks or vibrations. When measuring, the air bellows are emptied of air and the frame rests firmly on the laboratory floor. This floor is stabilised by underpinning the entire vehicle with hydraulically retractable supports.

Fig. 4. The mobile lidar system, while measuring.

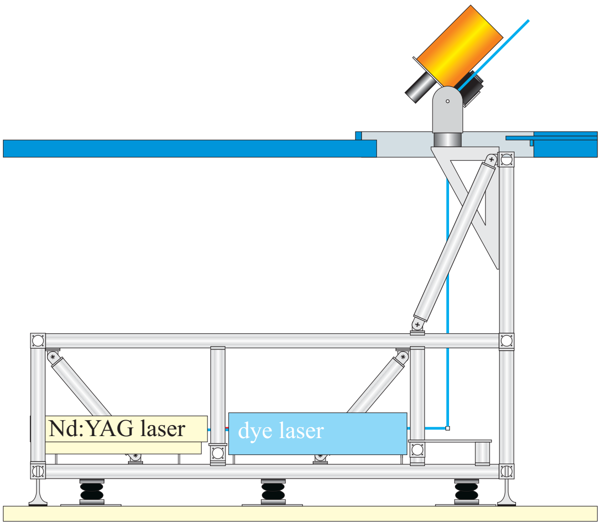


Fig. 5. Frame with emitter and receiver units, with the telescope platform in the elevated position.

The telescope and beam steering mirrors are mounted on a retractable platform. When measuring, this is lifted out of a hatch in the laboratory roof, allowing access to the atmosphere. When travelling, it is lowered and the hatch is closed, protecting the inside from the elements.

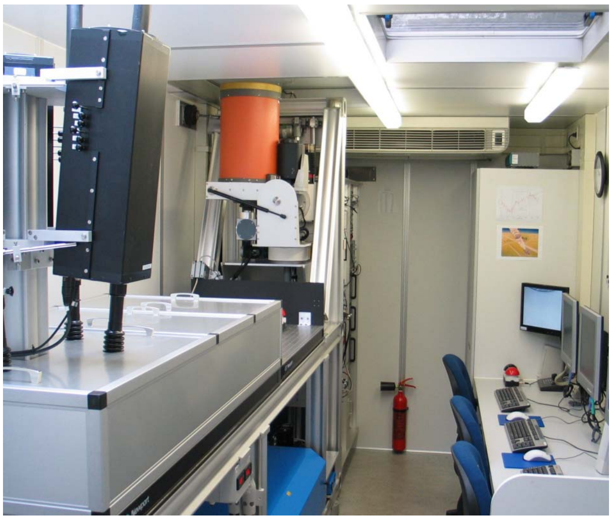

Fig. 6. Interior of the mobile laboratory.

### 2.6. Safety

The eye safety range of the laser beams used depends greatly on the wavelength. To avoid exposure of persons or objects outside the laboratory, the operator watches images from a CCTV camera, mounted on the movable platform and looking in the same direction as the laser beam is pointed. When someone or something enters the danger zone, the operator will press the emergency shutdown button.

## 3. APPLICATION 1: MEASUREMENT OF $NO_2$ VERTICAL PROFILES FOR SATELLITE VALIDATION

### 3.1. The DANDELIONS project

The DANDELIONS project (Dutch Aerosol and Nitrogen Dioxide Experiments for vaLIdation of OMI aNd Sciamachy) includes, among other activities, the validation of $NO_2$ vertical column measurements of the OMI satellite instrument, launched in July 2004, by comparison with ground-based lidar measurements. To do this, the mobile lidar is used to measure vertical $NO_2$ profiles. In May and June 2005, the mobile lidar participated in a validation campaign at CESAR (Cabauw Experimental Site for Atmospheric Research, located in the centre of the Netherlands). A second validation campaign is planned for September 2006.

### 3.2. Measurement Strategy

In principle, a vertical concentration profile could be made by measuring straight upwards. However, to enhance the vertical resolution, a profile is built up from a number of measurements, each taken at a different elevation. This is shown schematically in Fig. 7. First, a DIAL measurement is done in the direction dir1. A concentration is calculated over the range interval from r1 to r2 and is then attributed to the vertical interval from h1 to h2. The process is repeated for the direction of dir2, yielding a concentration attributable to the vertical interval from h2 to h3. The sequence dir1 - dir2 is then repeated and the results averaged to reduce the noise.

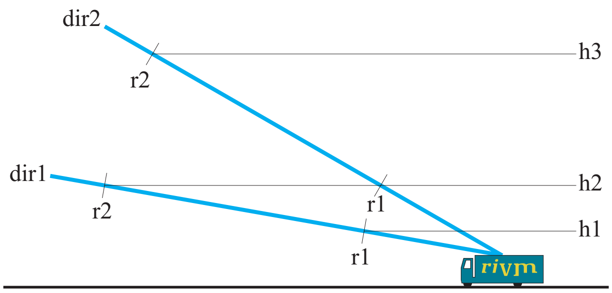


Fig. 7. Combining a number of measurements into a single vertical profile.

### 3.3. Instrument Performance

During the 2005 Dandelions campaign, the instrument was capable of measuring $NO_2$ concentrations with an accuracy of up to 1 μg/$m^3$, when derived from 1200 m intervals (r1 – r2 in Fig. 7). The maximum distance from which data was retrieved was 2500 m. The laser was tuned to 448.28 and 449.90 nm. A measurement sequence consisted of five directions. Profiles were reported consisting of four values inside the planetary boundary layer, and one or two above this layer. A typical profile is shown in Fig. 8.

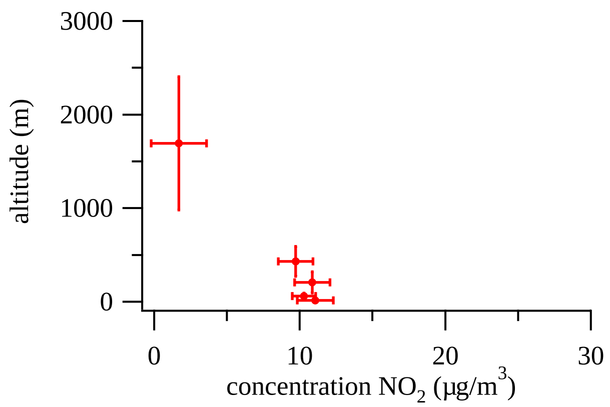


Fig. 8. $NO_2$ vertical profile, Cabauw, 9:59-10:36 UTC, 28 May 2005.

Since this campaign, several important improvements to the instrument have been made. During the 2006 Dandelions campaign, a greatly improved performance is expected.

## 4. APPLICATION 2: MEASUREMENT OF $SO_2$ EMISSIONS FROM SEAGOING SHIPS

### 4.1. Aim

On the open sea, there are no legal limits to the sulphur content of shipping fuel. As a results, ships sail on fuel that may contain 6 to 10% sulphur. Within territorial waters, use of this fuel is prohibited, so many ships carry cheap high-sulphur fuel for use at sea, and more expensive low-sulphur fuel for use near land. To check whether ships do indeed refrain from using their cheap fuel when near the harbour, use of the mobile lidar instrument was envisaged.

### 4.2. Measurement Strategy

Ship emissions are most accessible when ships sail at a short distance from the shore, as they do on the approach waterways towards a harbour.

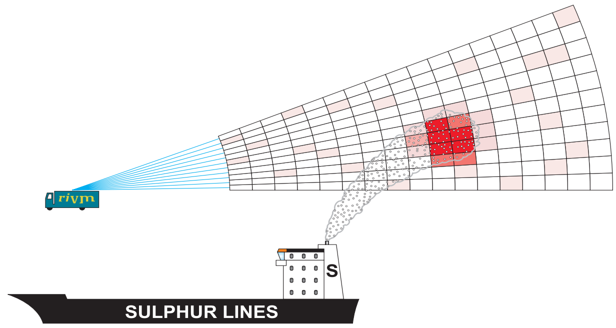


Fig. 9. Overview of measurement of ship emission.

In Fig. 9 the measurement strategy is depicted. The mobile lidar is positioned on the shore, near the waterway. It measures permanently the $SO_2$ concentration in the air, in a vertical plane. The wind carries the exhaust fumes of passing ships through this plane. The plume dimensions are taken from the vertical plane, and the speed with which it passes from a simultaneous wind speed measurement. From these figures, combined with the $SO_2$ concentration, the amount of $SO_2$ emitted by the ship is calculated.

### 4.3. Instrument Performance

At the time of writing, the first experimental measurements have just been performed. The laser wavelengths used are 300.0 and 299.5 nm. The maximum range is about 2000 m, the detection limit is 2-3 μg/$m^3$.

## 5. DEVELOPMENT

In the near future, the system will be extended with the possibility of measuring $NH_3$.

## REFERENCES

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