InGOS - Integrated non-CO_2 Observing System
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Integrated non-CO_2 Greenhouse gas Observing System

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SUMMARY

Our lidar instrument has been designed with the goal of making range-resolved measurements of greenhouse gases such as carbon dioxide and methane as well as probing the structure of the atmospheric boundary layer. The key component is a tunable laser source based on an optical parametric oscillator (OPO) covering the wavelength range 1.5–3.1 µm. This range includes absorption lines of methane and carbon dioxide enabling the application of the differential absorption lidar (DIAL) technique, whilst also being suitable for eye-safe aerosol lidar. We also report here on the use of an avalanche photodiode detector with high sensitivity and low noise.

The OPO output was characterized to assess the beam quality and spectral properties. The M squared parameter and beam divergence were measured with a beam-profiling camera. To confirm the divergence of the transmitter, the beam diameter was also measured at an extended distance from the instrument. The wavelength, tuning curve, spectral width and stability of the free-running OPO were also determined.

Field tests of the prototype instrument were performed, recording continuous lidar traces over periods of up to half an hour. The data were digitized at 8 traces per second and corrected for pulseto-pulse fluctuations in the OPO output energy using the signal from a pyroelectric sensor mounted inside the laser transmitter. Scattering from aerosols and molecules was detected to a maximum range of 2 km, whilst scattering from cloud was recorded at up to 6 km. The data are plotted as timeversus-range images to show the dynamic state of the atmosphere evolving over time.

These results demonstrate that the lidar achieves key requirements for aerosol scatter and DIAL: tunability of the transmitter wavelength, sensitivity to molecular and aerosol scattering and alignment stability over extended periods. We also discuss further work to narrow the spectral width of the OPO by injection seeding and the use of active stabilization for locking the wavelength to a specific gas absorption line.

WP13. DIAL for Methane.

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Summary of progress to date.

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1. Introduction

Differential absorption lidar (DIAL) is the lidar technique best-suited to making greenhouse gas concentration measurements. Our goal is to use DIAL to make measurements of methane and carbon dioxide concentration with CH4 being the focus for the InGOS project. Section 3 provides an outline of the DIAL technique, and discusses the choice of laser wavelength for CH_4 and CO_2. Section 4 describes the development of instrument and Section 4 presents the results of field tests.

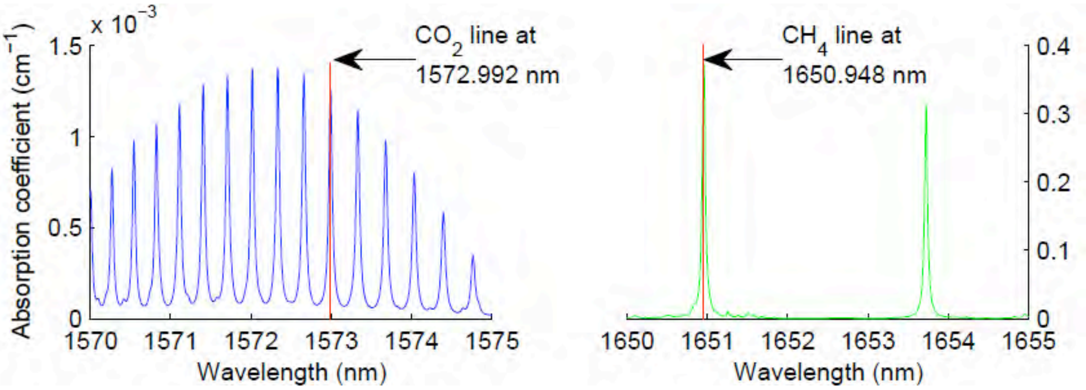

Figure 1. An overview of the positions and intensities of lines in the absorption spectrum of carbon dioxide and methane using data from the HITRAN 2008 database. The selected on-line wavelength for DIAL is also shown.

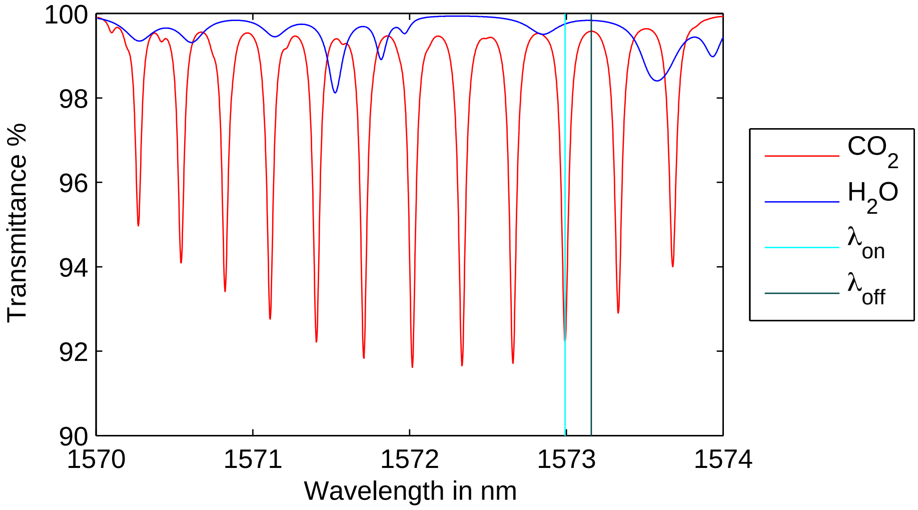

Figure 2. Simulation of the spectral transmittance of the atmosphere over a path length of 2 km for an atmosphere at pressure 1 atm with a CO_2 concentration of 314 μmol/mol.

1.1 DIFFERENTIAL ABSORPTION LIDAR (DIAL)

In a DIAL measurement, pulses at two wavelengths are fired into the atmosphere sequentially. The first at the off-line wavelength, λ_{off}, is scattered in the atmosphere, the second at the on-line wavelength, λ_{on}, is absorbed as well as scattered. If the differential absorption cross section, $\sigma(\lambda_{on})-\sigma(\lambda_{off})$, is known, the concentration of the absorbing gas as a function of range may be calculated. The process of using two wavelengths removes dependencies on instrumental parameters and atmospheric backscatter coefficient provided that these values remain unchanged between the on-line and off-line pulses. The two wavelengths must therefore be close in wavelength and switching between the two must be rapid to avoid temporal changes.

To measure CH_4 and CO_2 the on-line wavelength must be precisely tuned match a line in its absorption spectrum. At the same time the off-line wavelength must suffer minimal absorption. The

High-resolution Transmission database (HITRAN) provides spectroscopic parameters that can be used to identify absorption lines, and calculate or simulate an absorption spectrum. Figure 1 shows an overview of CO_2 and CH4 absorption lines from the 2008 edition of the database as an example.

The choice of wavelength is motivated by several factors. For relative eye-safety infrared wavelengths above 1400 nm are preferred as the maximum permissible exposure is relatively high in this spectral region. Due to limited options for detectors in the 2000 nm wavelength region hetrodyne detection is generally required. CO_2 DIAL has been demonstrated using an absorption line near 1570 nm and although these absorption lines are substantially weaker than lines near 2000 nm (see Figure 1) the use of this wavelength enables the use of high-sensitivity direct detectors such as avalanche photodiodes (APDs) and photomultiplier tubes. These devices are readily available, in part because this wavelength is common in telecommunications devices.

The on-line wavelength of 1572.993 nm is labelled in Figure 1. The HITRAN database gives the width of this line (at a pressure of 1 atm) as 2.34 GHz (19.3 pm). To determine the differential optical transmission of the atmosphere, the absorption spectrum must be simulated using a line shape. The tool *HITRAN on the Web* was used to simulate the transmittance of the atmosphere in the spectral region around this wavelength. The results of this simulation are shown in Figure 2 for a 2 km path at atmospheric pressure with 314 μmol/mol CO_2 concentration (similar calculations have been performed for CH_4). The transmittance at the online wavelength is 89.97 %. At the offline wavelength shown, 1573.16 nm, the transmittance is 99.86 %. The transmittance of water is also shown as it is a potential interfering species.

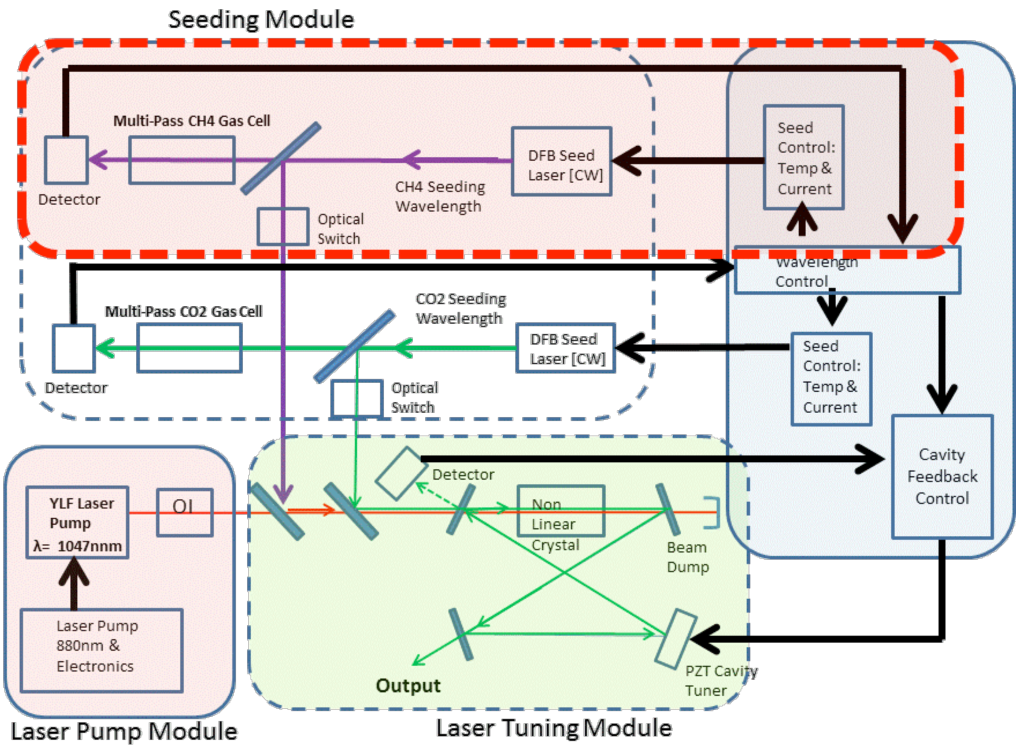

Figure 3. Diagram of the lidar instrument. The OPO is pumped by a Nd:YLF laser. The signal wave is separated by two dichroic mirrors (DM) and expanded before transmission

to the atmosphere. The transmitted power is monitored with a pyroelectric sensor (Pyro). The received signal is focused by a Newtonian telescope into an avalanche photodiode (APD), amplified and digitized with a storage oscilloscope.

2. THE LIDAR INSTRUMENT

The instrument consists of a laser transmitter, receiver telescope and detector. A diagram is shown in Figure 3. A schematic of the instrument is shown in Figure 4.

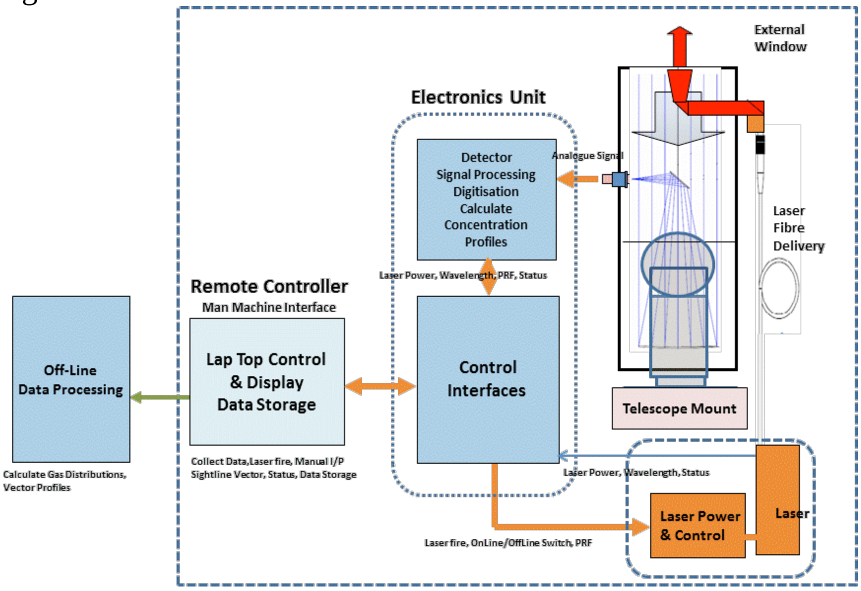

Figure 4. A schematic of the UEDIN DIAL instrument showing the main modules involved.

A diode-pumped neodynium-doped yttrium lithium flouride (Nd:YLF) provides the pump beam at a wavelength of 1047 nm. The Nd:YLF laser is Q-switched and emits pulses of 4.5 mJ energy at a repetition rate of 50 Hz. The OPO nonlinear crystal is potassium titanyl phosphate (KTP+) with type-II noncritical phase matching. The OPO shifts the pump wavelength to signal and idler wavelengths near 1.6 μm and 3.0 μm respectively. These wavelengths are tunable (though not independently) by rotating the crystal whilst measuring the wavelength with a diffraction grating. The signal wavelength at 1570 nm was separated from the idler by reflection from a pair of dichroic mirrors. For the experiments described here the (3 μm) idler wavelength was not used. Part of the signal wave was picked off and used to monitor the transmitter power with pyroelectric sensor (PY-ITV-SINGLE-TO39(2+1), Pyreos). This sensor is fast enough to measure the energy of every transmitted pulse. A p-i-n photodiode (G8370-05, Hamamatsu) was used to provide a timing reference signal for triggering the signal acquisition.

The beam was transmitted into the atmosphere along the axis of a custom-built Newtonian telescope with a 380 mm primary mirror and a focal ratio of 3.08. The signal was detected with an avalanche photodiode (APD) module (C30659-1550-R2AHS, Excelitas) consisting of a 0.2 mm diameter indium gallium arsenide APD with an integrated pre-amplifier. A bias voltage of 48.4 V was applied to the module. At this voltage the specified response is 340 mV/μW. The module's bandwidth is 50 MHz. The output was then amplified by a two-stage voltage amplifier (AD8066, Analog Devices) with a total gain of 29 and a bandwidth of 24 MHz. The signal was digitized by a storage oscilloscope (WaveSurfer 454, LeCroy) at a sample rate of 2 MS/s.

3. FIELD TESTS

Field tests of the instrument were performed to determine its performance and stability. The elastic-backscatter lidar signal was recorded over ranges up to 2 km. A typical return signal is shown in Figure 4. This measurement was made on a cloudy day in Edinburgh with the instrument pointed skyward at an elevation of 20° to horizontal in a westerly direction (273°). The transmitter pulse energy was 390 μJ. The returned signal was averaged over 50 pulses, to give one signal per second. The optical power (in nW) was calculated from the specified response of the avalanche photodiode the calculated gain the amplifier circuit.

Little signal is observed for the first 200 m. This is largely due to the beam remaining within the shadow of the secondary mirror preventing the telescope from efficiently focusing the return signal within this range. The beam begins to emerge from this shadow around 200 m, and the return signal intensity reaches a maximum around 350 m. Beyond this the signal starts to fall off due to the one-over-R-squared dependence on the range. The obscuration caused by the secondary mirror is a feature of Newtonian telescopes and due in part to the small size (0.2 mm diameter) of the detector. Using a larger detector, a 1 mm diameter p-i-n photodiode (G8370-01, Hamamatsu), we observed this peak closer, at 140 m range. However, the optical limitations on the telescope imposed by the small size of avalanche photodiodes are outweighed by their high sensitivity.

The return signal up to 920 m is due to atmospheric scattering by molecules and aerosols. At this wavelength, we expect aerosol scattering to be the dominant contribution.

Around 1 km from the instrument, a strong return signal from cloud was detected. Immediately after this peak, the signal becomes slightly negative. This is caused by overshoot of the detector and is due to the limited bandwidth (24 MHz) of the detector amplifier and also the fact that the signal is ac coupled. This kind of overshoot and related ringing effects are commonly observed in lidar return signals from cloud. The maximum range from which cloud scattering was observed was 5.7 km, indicating that the beam quality allows for long-range propagation.

The noise level of the detector during field tests was found by measuring the standard deviation of the detector signal before the laser fired, giving a value of 110 pW. With averaging of 50 traces, the specified detector noise in a 24 MHz bandwidth is expected to be in the range 60 to 113 pW, indicating that the detector achieved its specified noise performance.

To study the stability of the return signal over time, lidar signals were recorded continuously over an interval of 9 min at a rate of 1 signal per second. The data are plotted as a time-versus-range image in Figure 5. The atmospheric scattering signal appears as a band (0.2 to 1 km). The sporadic cloud signal is seen at around 1.1 km, as is seen to vary on a timescale of seconds. The structure visible in the region between 0.5 and 1 km suggests particles are being swept away from the instrument over time. This is consistent with a measurement of wind direction made at a weather station (280 m from the instrument) which reported an easterly wind (78°) at 2.4 m/s.

DIAL relies on the scattering being constant whilst switching between the online and offline wavelengths. Though broadly stable over time, there are some short term fluctuations in the scattering signal, especially at 1.3 min and 5.2 min. Significant variations (>10 %) were observed over timescales of 7 seconds. This illustrates the importance of sub-second switching between the online and offline wavelengths for DIAL to ensure the atmospheric back-scatter does not change between the two.

It was found that the transmit–receive channel alignment was susceptible to drift over periods of tens of minutes. This is likely due to temperature changes in the instrument and could be improved by better temperature control and reducing the overall size of the laser transmitter. Delivering the transmit beam through an optical fibre is also a possibility.

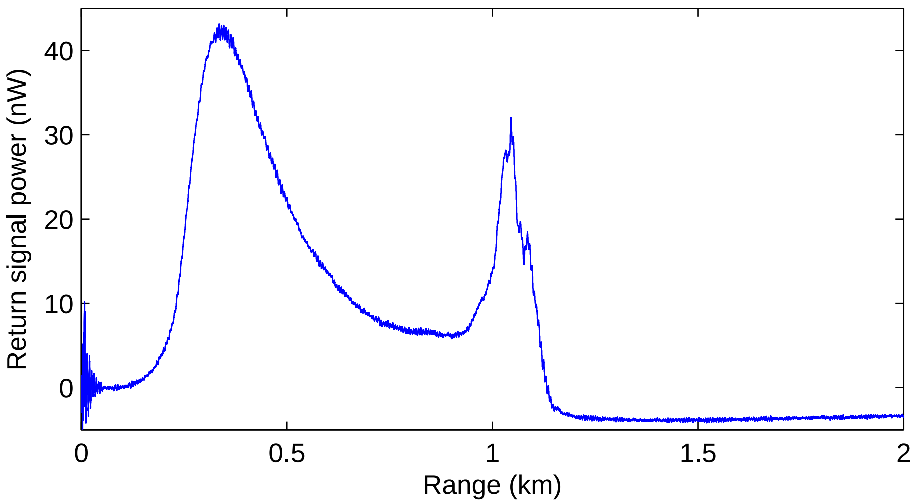

Figure 4. Return signal measured during lidar field test. The instrument was directed at an elevation of 20° to the horizontal. The signal around 1 km is due to cloud. The transmit pulse energy was 390 μJ. The signal was detected with an avalanche photodiode.

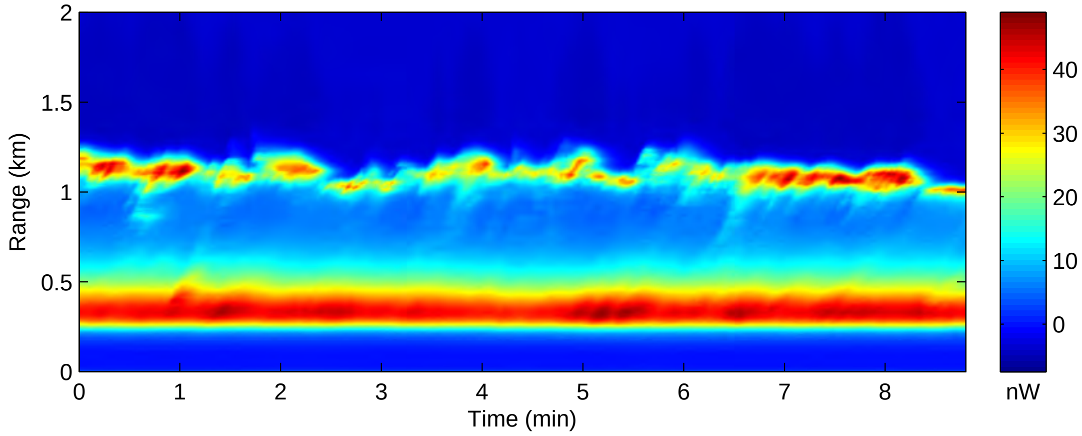

Figure 5. A time-versus-range image showing variation in the return signal power over an interval of 9 min.

4. WORK REMAINING

In brief, a versatile lidar instrument based on an optical parametric oscillator laser source and avalanche photodiode has been developed. Field tests of the prototype instrument have been conducted recording the elastic-backscatter signal over intervals of 10 min. Atmospheric scattering was detected at ranges up to 2 km, and cloud scattering from up to 5.7 km.

The tunable output of the OPO can provide wavelengths suitable for a variety of applications. For measurement of carbon dioxide and CH4 with DIAL the laser is able to produce the required wavelengths near 1570 nm and 1659 nm respectively. Ongoing work is to develop the system to narrow the spectral linewidth of the laser to be able to target the appropriate absorption lines. This will involve injection seeding the OPO with a frequency-stabilized diode laser locked to the online wavelength.

We are currently integrating the seed lasers (for CO_2 and CH_4) into the prototype and the first performance test of the instrument is scheduled for 1st quarter 2015. The first field test will be under NERC's GREENHOUSE proposal at two field sites in Dumfries and Northumberland. At both these test sites, the University of Edinburgh's research aircraft will be making vertical profile measurements of CH_4 and CO_2 by bag-sampling and direct concentration measurement and these will be used to validate the DIAL system. These tests will be more useful than running the DIAL at Tall Tower Angus (in the original InGOS plan) and will supplant these tests. We also expect to run the DIAL system at a petrochemical complex in mid-late 2015. The current instrument has also been enhanced by the addition of an automated scanning mount (Figure 6) capable of pointing to an accuracy of better than an arc-minute over a hemisphere and improved opto-mechanical design to enable robust alignment of laser and telescope beams. Tests of the new system will also occur over peatland with a comparison against conventional micrometeorological flux measurements (in collaboration with NERC CEH, Edinburgh). This is scheduled for late 2014.

ACKNOWLEDGEMENTS

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FIGURE 6. THE NEW TELESCOPE AND ITS AUTOMOUNT.