Towards low-cost water-vapour differential absorption lidar

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ABSTRACT

At Adelaide we are developing a low-cost differential absorption lidar (DIAL) for profiling water vapour in the lower part of the atmosphere. Water vapour concentrations in the lower atmosphere are highly variable; they can change significantly on timescales of 15 minutes, and on horizontal scales of tens of kilometres. Low-cost eye-safe DIAL could be readily replicated helping to improve the spatial and temporal resolution by supplementing existing hygrometry, or replacing techniques with high operating costs. Such an instrument is very desirable for several reasons, including quantitative precipitation forecasting, fog prediction and assessment of bushfire danger.

Our system uses diode lasers in the 825nm wavelength region, and differs from previously constructed water DIAL systems in having two master lasers with active stabilisation of both laser wavelengths. The transmitted energy of 500 nJ, in 1 µs pulses, is easily rendered eyesafe.

Measurements of the backscatter coefficient of the urban aerosols that predominate over Adelaide have been used in a sensitivity analysis. Our initial DIAL measurements, with a water line that is too strong, agree reasonably well with a sensitivity analysis in giving a maximum range of about 800 m.

1. INTRODUCTION

It is extremely important to quantify trace gases in the atmosphere in order to form a proper understanding of the earth's climate and meteorology. Water vapour is especially challenging because it continually changes phase, which leads to rapid temporal and spatial variability of the vapour phase concentration. Because of this variability, water presents a challenge in making sufficiently frequent measurements for high-resolution models.

Cost is one of the practical problems in measuring water vapour with high resolution. Lidar is an attractive technology in this regard because it potentially has low recurrent costs, and is capable of very high temporal resolution. Two techniques are used, differential absorption lidar (DIAL) and Raman scattering lidar. We concentrate here on DIAL, where two wavelengths are transmitted, one more strongly absorbed by the water vapour between the lidar and the scatterer in the atmosphere. The profile of the intervening water vapour concentration can be inferred from the difference in received powers. Most DIAL systems that have been developed for measuring water vapour have been relatively expensive high power systems. These typically incorporate titanium doped sapphire lasers [1], alexandrite lasers [2] or optical parametric oscillators [3].

For water vapour lidar to become useful in providing data for meteorological models the instrument costs must come down. Then a sufficient number of systems can be deployed in any given region. The DIAL technique lends itself more readily than the Raman technique to the use of low power lasers, but this introduces some interesting constraints. The main one is that the relatively small transmitted laser pulse energy means that a trade-off between range resolution and signal to noise ratio must be addressed.

Two water vapour DIAL systems based on relatively low power diode lasers have been reported [4,5]. One uses an external cavity diode laser (ECDL), and the other a differential feedback (DFB) laser, as the master oscillator. Both use semiconductor optical amplifiers to boost the laser power and both of these designs rely on switching the master oscillator laser between the on-line and off-line wavelengths.

Our strategy is to use <u>two</u> low-cost CW Fabry-Perot laser diodes as master oscillators, which remain stabilised to their respective wavelengths. We use a semiconductor optical amplifier to boost the transmitted pulse energy. We require relatively high beam quality in order to keep the transmitted laser pulse within the field of view of the receiving optics, which at present implies a limit in the output power of a few hundred milliWatts. We compensate for this by having a fairly high pulse repetition rate (up to 3 kHz).

In the context of differential absorption lidar (DIAL), a more fundamental problem that has been outstanding is the frequency or wavelength control of the laser. There are two laser wavelengths that are used, one being absorbed more than the other. The absorption cross-sections at the two must be tightly specified, so as to avoid systematic errors in the retrieved concentration profile. The most novel feature of our design in the stabilisation of the wavelength of the laser that is detuned from the resonance.

Working with lower pulse energies has the advantage that eye safety is more achievable and remote operation is easier. A potential disadvantage is that the range of operating wavelengths is reduced, because the small pulse energies imply small return signals that make very low-noise single photon counting necessary. This restricts the wavelengths to those in which photomultipliers and silicon avalanche photodiodes operate.

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2. LOW-COST DIAL DESIGN

It is difficult to achieve fine frequency control of pulsed lasers without using a master-slave configuration where the master is CW, because of transient effects associated with gain or frequency switching. We present such an approach here, based on single-mode CW Fabry-Perot diode lasers (Hitachi HL8325G), and using a semiconductor amplifier (Sacher Lasertechnik). The on-line master laser is (presently) stabilised to a water absorption line near 823 nm, and the frequency difference between the on-line and off-line lasers is stabilised using a simple, novel and robust technique based on locking the beat frequency to the pass-band of a microwave bandpass filter.

The water linewidth varies from around 6 GHz (full width at half maximum) at sea level, to 3 GHz at an altitude of about four kilometres. The necessary precision in the laser frequency is then about 200 MHz [6]. The short-term stability of diode lasers is typically about 50 MHz, but as with most lasers slower frequency drifts do occur and active stabilisation becomes necessary. Another important aspect of the laser spectrum is the energy in the spectral wings. If the laser is tuned onto the peak of the absorption, energy that is far enough out in the wings is not absorbed and this gives an effective absorption cross section that is lower than the actual one. The on-line wavelength is stabilised to the peak of an absorption resonance in a multipass water vapour cell, by dithering the laser frequency so that lock-in detection can provide an error signal. The second wavelength must then be set at a suitable value away from the resonance. Active stabilisation of both wavelengths is necessary because of laser drift and the necessity to know the absorption cross sections.

A design for a DIAL to measure CO_2 has recently been presented [7] in which an offset locking technique was used to stabilise the on-line laser to a particular detuning with respect to a reference laser, which in turn was locked to the peak of an absorption line. In that work the off-line was allowed to drift. Although the off-line laser can be tuned well away from the absorption line of interest, the density of molecular states can be quite high, so that this laser will likely be in the wings of some other absorption line and its absorption cross section could vary significantly if the off-line wavelength were allowed to drift. In our design the on-line and off-line lasers are maintained at a frequency difference of 16 GHz, this being a compromise between a value that is many times larger than the absorption linewidth (HWHM) of a water line, and is not so large that the cost of microwave components is too high.

We stabilise the frequency difference to 16 GHz by combining the light from the two lasers, on-line and off-line, and detecting the beat signal using a photodiode with a bandwidth of 25 GHz. The beat signal is stabilized to the peak of a bandpass microwave filter, which has a peak transmission at 16 GHz. A Schottky diode is used to detect the beat signal level. The error signal in the stabilisation circuit is derived by using phase sensitive detection of the dither frequency component in the output of the detector diode. The dither of the beat frequency arises from the dither that is applied to the on-line laser when it is stabilised to the water vapour resonance. An integration stage completes the feedback loop to the current control of the off-line laser. The temperature of each laser is independently stabilised. We measure the upper limit of the RMS difference between the off-line frequency and the average on-line frequency to be less than 2 MHz.

The laser pulses are formed with acousto-optic modulators. The 80 MHz frequency shift imposed on the the pulses leads to a potential systematic error in the measured mixing ratio that is less than 1% for altitudes below 4 km.

The receiver is a 40 cm Schmidt-Cassegrain telescope with a dielectric bandpass filter (Barr Assoc.) and photomultiplier (PMT). The filter has bandwidth of 1nm, maximum transmission 70%, and is angle tuned to shift its centre wavelength to 823 nm. The PMT (Hamamatsu R7400U-20) has a quantum efficiency of about 10% and a low dark count rate (~100 s^{-1}). The data acquisition system was made by Licel GmbH (TR20-10). It is capable of both photon counting and analogue operation, but the low signal levels that we encountered meant that the latter was unused.

3. RECEIVER CALIBRATION

The number of photons recorded by the lidar receiver from the range interval r to $r+\Delta R$ is

$$N\left(r, r+\Delta R\right) = \Delta R \frac{N_t A \beta \eta}{r^2} \exp\left\{-2\int_0^r \alpha\left(r'\right) dr'\right\} \qquad (1)$$

where N_t is the number of photons in the transmitted pulse, A is the receiver aperture, α is the attenuation coefficient, β is the backscatter coefficient and η is the receiver efficiency. It is important to measure β and η because they help to determine the noise level and thus the ultimate sensitivity and precision of a DIAL system.

To calibrate the lidar receiver, pulses of known energy from a laser near 823 nm wavelength were attenuated with a neutral density filter and directed at a scattering target. Two targets were used, the first with a Teflon disk of 2mm thickness mounted in front of a mirror with a high reflectance coating. The result of this measurement was $\eta = 8.2\times10^{-4}$. The second calibration target was a diffuse reflector made of Spectralon†, illuminated in the same way as before. In this case we measured $\eta = 7.0\times10^{-4}$.

We ran the lidar in several night time mini-campaigns, between two and four weeks in length, using a single medium power diode laser with simple current modulation to form laser pulses. The transmitted pulses were 1 µs long. The laser was operated at a wavelength of about 823 nm, and was not actively stabilised in wavelength, though its temperature was stabilised.

The receiver oversamples at 50 ns intervals, so the data in figure 1 are range averaged with 1 µs wide bins (150 m range resolution) corresponding to the

† trademark of Labsphere, Inc.

transmitted pulse length. The data in figure 1 show high cloud fluctuating in altitude around 5000 m, and a layer of aerosols near the ground that fluctuates somewhat in thickness.

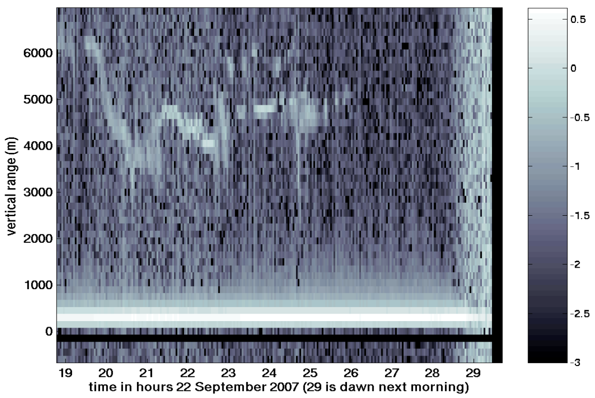

Figure 1.. *Single wavelength lidar data from the night of 22 September 2007, above the Adelaide central business district. The transmitted energy was 90 nJ per pulse. The scale bar gives the base 10 logarithm of photon counts per µs per 150 m.*

The results of the calibration measurements were used to establish backscattering coefficients for the aerosols above the Adelaide central business district (CBD). For example on 24 September 2007, β varied exponentially from ca 5 x 10^{-6} $sr^{-1}m^{-1}$ at about 200 m altitude to 10^{-7} $sr^{-1}m^{-1}$ at 1000 m altitude. These measurements were then used as input to a sensitivity analysis. At other times we have measured values of backscatter coefficient, that were higher by a factor of about five.

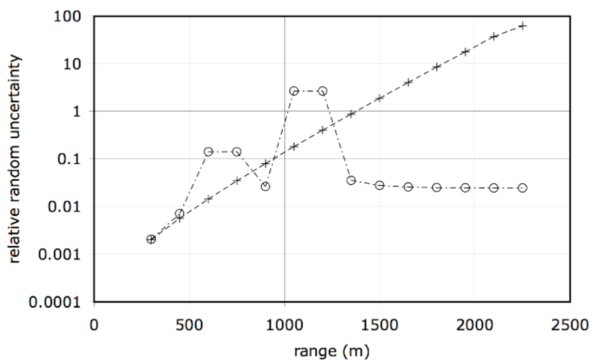

Figure 2. *Relative random uncertainty (sensitivity) in retrieved water vapour concentration as a function of range (altitude), for our laser and receiver parameters (with k* = 1.2 x 10^6*). Two values of background photon counting rates are also compared, zero (circles) and 0.01 µs^{-1} (crosses).*

4. SENSITIVITY ANALYSIS

The sensitivity analysis is a calculation of random uncertainty [8] for the water concentration, which is a function of the numbers of detected photons $N_\lambda(r)$ at two ranges r_1 and r_2, for each of the two laser wavelengths λ, on-line and off-line;

$$n = \frac{1}{2\Delta R\left(\sigma_{on} - \sigma_{off}\right)} \ln\left(\frac{N_{off}(r_2) N_{on}(r_1)}{N_{on}(r_2) N_{off}(r_1)}\right). \tag{2}$$

The random uncertainties in the absorption cross-sections σ_{on} and σ_{off} $\left(\sigma_{off} = 0\right)$, and in the range interval $\Delta R = r_2 - r_1$, are neglected. The variance in *n* is

$$\sigma_n^2 = \left(\frac{1}{2k\Delta R\sigma_{on}}\right)^2 \left[\frac{\bar{N}_{on}(r_1) + \bar{N}_b}{\left(\bar{N}_{on}(r_1) - \bar{N}_b\right)^2} + \frac{\bar{N}_{off}(r_2) + \bar{N}_b}{\left(\bar{N}_{off}(r_2) - \bar{N}_b\right)^2} + \frac{\bar{N}_{on}(r_2) + \bar{N}_b}{\left(\bar{N}_{on}(r_2) - \bar{N}_b\right)^2}, + \frac{\bar{N}_{off}(r_1) + \bar{N}_b}{\left(\bar{N}_{off}(r_1) - \bar{N}_b\right)^2}\right. \tag{3}$$

where the mean number of background photons counted in the 1 µs laser pulse width is $\bar{N}_b$, and the mean signal photon numbers are calculated according to equation (1). The number of laser pulses used in the averaging is *k*. Laser speckle as a source of noise is neglected.

A graph of $\sqrt{\sigma_n^2} / n$ as a function of range is shown in figure 2. The water absorption line assumed was that at 822.922 nm for which the line intensity is $S = 3.9 \times 10^{-23}$ $\mathrm{cm}^2/\mathrm{cm.molecule}$. We use the profile of backscatter coefficient derived from our measurements of 24 Sept. 2007. A uniform water concentration of 1×10^{23} m^{-3} (mixing ratio of approx 2.6 g/kg at sea level) is assumed for these calculations. The point at which the uncertainties for the nonzero background cross the curve for the zero background indicates where the background is stronger than the signal. At greater ranges that this, for the nonzero background level, the calculated uncertainty becomes meaningless.

5. INITIAL DIAL RESULTS

Using the dual wavelength DIAL system described above, we have made preliminary observations of water vapour above the Adelaide CBD. In figure 3 we show the return signals for the on-line and off-line laser wavelengths. The data recording begins 5 µs before the laser pulse was transmitted, which allows us to assess the background signal. This background signal was calculated by averaging the first 100 data and then the background was subtracted from the whole data set.

The axis of the transmitted laser beam is approximately parallel to that of the receiver telescope, but separated by about 50 cm. In the data an approximately flat portion immediately between ranges zero and 150 m is seen. This is due to light scattered by the 45° mirror. Between 150 m and 300 m both on-line and off-line signals continue to increase – this being due to the increasing overlap between the laser beam and the field of view of the receiver. After about 300 m range the laser remains entirely within the field of view of the receiver. The effect of water vapour in the atmosphere is to make the on-line received signal fall off with range faster than the off-line signal.

It can be seen that the scattered signal for the on-line wavelength has reached the noise floor at about r = 1000 m, while the off-line signal is still significantly higher. This indicates that the strength of the water absorption resonance that we chose is too great, for the humidity and aerosol concentration that obtained on that night. There is however a fairly wide range of line strengths available at nearby wavelengths.

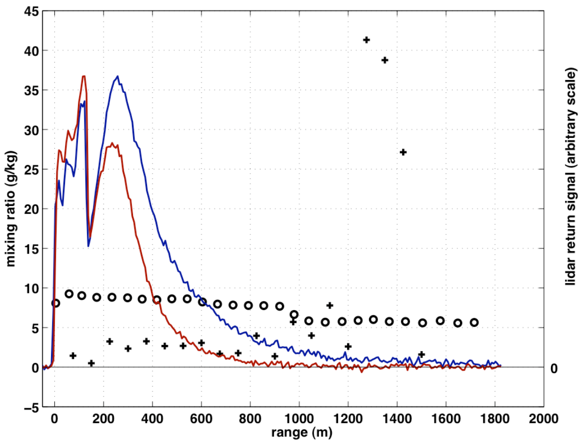

Figure 3. *Lidar returns from above Adelaide ca. 10:30 16 December 2008 (local time). The solid lines are the lidar returns at the on-line (red) and off-line (blue) wavelengths. The circles are water mixing ratios from a nearby radiosonde launch at about the same time, and the crosses are mixing ratios obtained from the lidar data under the assumption that the on-line laser is tuned to 829.922 nm.*

The difference between the two curves represents absorption of the on-line laser wavelength by water vapour in the atmosphere between the lidar and the scattering altitude. The lidar was pointed vertically. The laser pulse energy was 500 nJ and the on-line and off-line pulse rates were 1.5 kHz; i.e. the total pulse rate was 3 kHz. The data shown were averaged over 1 hour. Range averaging over 75 m intervals has been applied in this figure to obtain the mixing ratios shown, which correspond to 2x oversampling.

The discrepancy between the lidar derived mixing ratios shown in figure 3, and those from the radiosonde, are partly explained by a lack of spectral purity in the laser [9]. Work to resolve this is ongoing.

6. CONCLUSION

The conclusion of this work is that provided there is a favourable profile of scatterers in the lower atmosphere, and the correct choice of water absorption line (weaker than that used here), the prospects of a low power DIAL measuring water vapour concentrations in the lower atmosphere up to two kilometres are very good. However our current instrument will need attention in the areas of background level and choice of water line in order to achieve this. Further improvements would include the use of distributed feedback lasers to avoid the need for wavelength selection of the Fabry-Perot diode lasers.

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