Feasibility of Tropospheric Water Vapor Profiling Using Infrared Heterodyne Differential Absorption Lidar

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Continuous, high quality profiles of water vapor, free of systematic bias and of moderate temporal and spatial resolution, acquired over long periods at low operational and maintenance cost, are fundamental to the success of the Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART) program. The development and verification of realistic climate model parameterizations for clouds and net radiation balance and the correction of other CART site sensor observations for interferences due to the presence of water vapor are critically dependent on water vapor profile measurements. Application of profiles acquired with current techniques have, to date, been limited by vertical resolution and uniqueness of solution (e.g., high resolution infrared [IR] Fourier transform radiometry), poor spatial and temporal coverage, and high operating cost (e.g., radiosondes), or diminished daytime performance, lack of eye-safety, and high maintenance cost (e.g., Raman lidar). In the study reported here, we develop system performance models and examine the potential of IR differential absorption lidar (DIAL) to solve some of the shortcomings of previous methods using parameterizations representative of current technologies. These models are also applied to diagnose and evaluate other strengths and weaknesses unique to the DIAL method for this application.

The DIAL technique has been implemented to determine the concentration of water vapor and other species at many laboratories. In its simplest form, DIAL is based on comparing the transmission through the atmosphere of beams at two wavelengths which are absorbed differently by the species being monitored. The ratio of the attenuations of the two beams is given by the Lambert-Bouguer law as $\exp[-n\sigma r]$ where n and σ are the concentration and differential absorption cross-section of the specie and r is the path length. In a lidar, the transmitted beams are reflected back to the receiver by atmospheric backscatter, resulting in a measurement of the column content 2nr within the (identical) outgoing and return paths along the line of sight; returns over different column lengths can be compared to determine the range-resolved concentration. Most DIAL systems used for monitoring water vapor have operated at wavelengths of about 700 nm (Grant 1990a).

Recent developments in infrared laser and detector technology make possible compact systems at eye-safe wavelengths. The problems with earlier infrared lidars operating at 10 µm that used direct detection were in part that photodetectors in the infrared are relatively insensitive. Their principal noise sources arose from background radiation on the photodetector and thermal noise. To overcome noise sources, large, high-pulse-power lasers were needed to act as transmitters. Even so, the ranges achieved have been short. This difficulty can be overcome by use of heterodyne receivers. Heterodyne systems are insensitive to background light and are essentially photon-limited so that pulses of rather low energy can be transmitted. Their principal noise source is coherent fading or speckle in the return signal itself, and a heterodyne lidar must be designed to average this out. It is usual, therefore, to consider that these lidars operate at high pulse repetition frequency (PRF). Only recently have suitable laser sources become available (Pearson 1992; Grund 1995).

Simulations have been used here to compare the likely performance of direct detection and heterodyne lidars using what are essentially currently available infrared lasers operating at 2 µm and 10 µm. Simplifying assumptions are made where possible and where attempts to be unnecessarily exact prejudice understanding of the fundamental problems. We concentrate on statistical sources of error. Absorption data (absorption coefficients and their temperature and pressure dependence) are taken from the HITRAN data base, which may be a source of some systematic error (Grant 1990b). In the simulations shown here, atmospheric parameters have been based on the values specified in the U.S. Standard Atmosphere Model. Water vapor concentrations have been randomized about these values to add realism and make the processing problem more challenging. Useful range-resolved estimates cannot usually be obtained simply by differencing column content values because of the noise level, so that the range-smoothing and differencing operations needed for both column content and range-resolved estimates are combined using a Kalman filter algorithm (Rye and Hardesty 1989). This also provides as an output an estimate of the standard deviation σ of the water vapor measurement. The backscatter model is one developed previously (Kavaya et al. 1989).

Properties of the systems considered in this summary and parameters of the measurements are listed in Table 1. The total transmitted energies of the systems assumed are 50 J for the CO_2 lidars and 300 J for the 2-µm lidars. The 50-J, CO_2 systems represent data accumulation over about 10 secs, which would be appropriate for monitoring at lower altitudes (say up to 3 km), and the 300-J, 2-µm systems accumulate data over about 5 mins, appropriate for higher altitudes. The reason for choosing CO_2 lidars for the lower altitude measurements quoted in this summary and vice-versa is arbitrary; all four types of systems having been evaluated for both applications in the full report (Rye et al. 1995). Examples of range-resolved water vapor concentrations obtained using the four systems considered are shown in Figures 1-4.

Some of the further differences between the heterodyne and direct detection systems are

- diffraction-limited optics are usually used in heterodyne lidars, and the aperture and focusing of these optics should be at least approximately matched to the strength and range of the return; the limited field of view reduces background light, but direct detection systems can make use of larger optics

- the heterodyne signal-to-noise ratio (SNR) is approximately constant out to long range and can be optimized at long range by focusing, whereas the direct detection SNR falls rapidly with range; consequently, very good DIAL results can be obtained using direct detection at short ranges, but the long range results are impaired.

Thus somewhat smaller optics can be used for the heterodyne systems (Table 1), and at 10 µm the results from the smaller heterodyne system are superior to those from the direct detection lidar at long range but inferior at short range (Figures 1 and 2). In the absence of daylight background (not included in this assessment) and at these transmitted energy levels for the 2-µm lidars, either of the two receivers might be used on the basis of Figures 3 and 4. A heterodyne 10-µm system would produce similar results. Other simulations suggest that small heterodyne lidars at both wavelengths, using only 10-sec integration and small optics, should be satisfactory for near-horizontal measurements to ranges of 5 km. The larger systems of Figures 3 and 4 are needed for vertical measurements because of the rapid reduction of backscatter with altitude.

Table 1. Properties of simulated lidar systems.

Laser	CO_2		**2 µm**	
Wavenumbers	974.62, 975.93 cm^{-1} (10R18, 10R20)		4943.887, 4948.046 cm^{-1}	
Range Gate	60 m			
No. of Range Gates	100			
Receiver	**heterodyne**	**direct**	**heterodyne**	**direct**
Pulse Energy	5.0 mJ	500 mJ	5.0 mJ	100 mJ
PRF	1 kHz	10 Hz	200 Hz	10 Hz
Number of Pulses	10,000	100	60,000	3,000
Receiver Diameter	0.3 m	1.0 m	0.5 m	1.0 m
Receiver Efficiency	8%	10%	8%	10%
Sampling Frequency	2.5 MHz	2.5 MHz	12.5 MHz	2.5 MHz
Photodetector Noise Equivalent Power	--	6×10^{-13} W/Hz$^{1/2}$	--	1×10^{-13} W/Hz$^{1/2}$

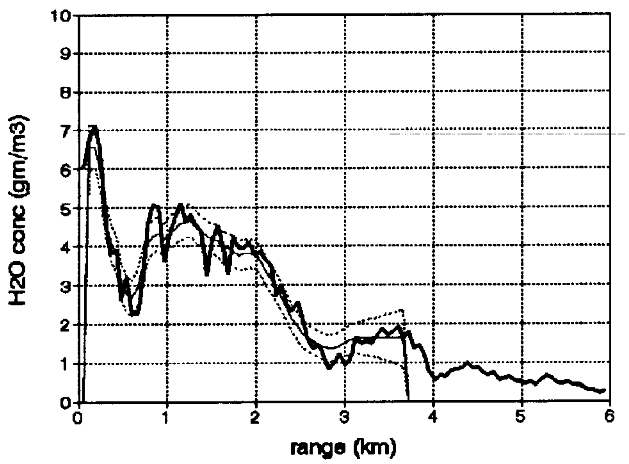

Figure 1. Performance of a "small" CO_2 heterodyne system with a 0.3-m mirror pointing vertically and focused at 3 km, integrating the return from 5-mJ, 1-kHz lidar over 10 secs (50 J total). The heavy solid line shows the "true" water vapor concentration, the solid line shows the lidar estimate, and the dotted lines are $\pm$ 1 σ around the estimate. Only 60 (out of 100) range gate data points are processed.

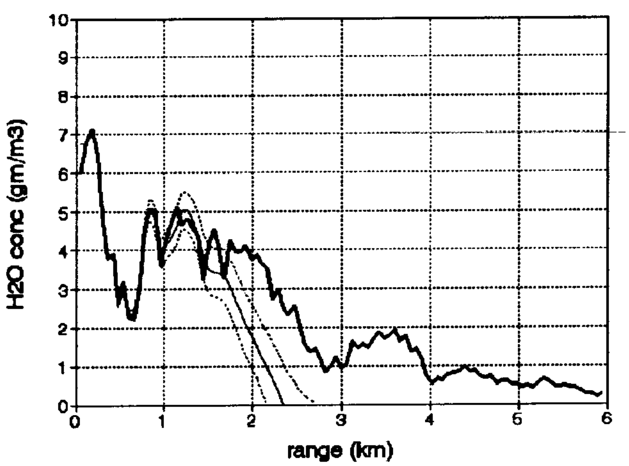

Figure 2. Performance of 50-J CO_2 direct detection lidar for comparison with data of Figure 1. Using a TEA laser, this system might be realized with a 0.5-J laser operating at 100 Hz for 10 secs. A 1-m diameter receiving dish is assumed.

Our results, as exemplified in the figures here, suggest that the reluctance to use IR DIAL based on the likely performance of direct detection 10-µm lidars is well-founded, but that compact heterodyne systems operating at either 2 µm or 10 µm with modest current technologies could provide useful, eye-safe, day and

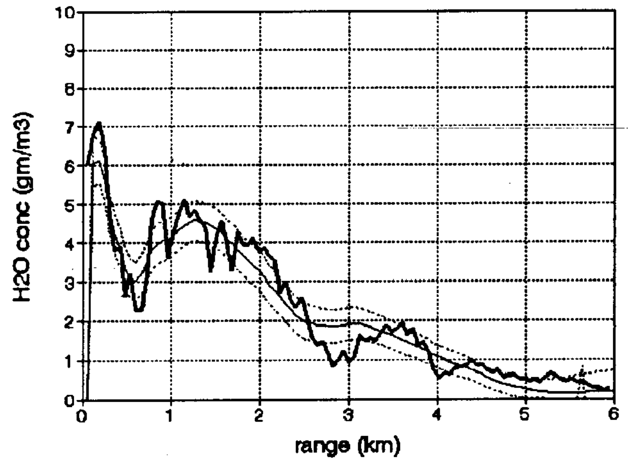

Figure 3. Performance of a 300-J 2-µm heterodyne lidar (5 mJ at 200 Hz for 5 mins) pointing vertically and focused at 5 km. Transmitter and receiver dishes are assumed to be of diameter 0.5 m. Improved results at shorter ranges could be obtained by focusing.

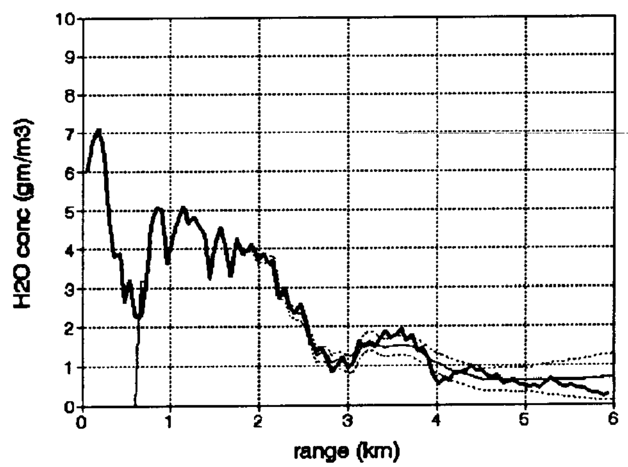

Figure 4. Performance of 300-J (e.g., 100 mJ at 10 Hz for 5 mins) direct detection 2-µm lidar for comparison with data of Figure 3. A 1-m receiver is assumed. The noise equivalent power (NEP) of the photodetector does not take account of daylight background.

night measurements at altitudes up to about 3 km. The statistical uncertainty of the water vapor estimates obtained is predicted to be less than about 20% or 1 gm/m^3, the range resolution less than about 200 m, and the time resolution 10 secs. The small 2-µm lidars that could be used for this purpose would have optics diameters as small as about 5 inches. At higher altitudes (up to 5 km) it is necessary to rely on long averaging times, and it would have to be demonstrated in practice whether this is feasible. Alternatively, we shall have to wait on development of more powerful laser sources. This work is to continue in the direction of evaluating yet smaller and lower-cost laser diode-based systems for routine monitoring of the lower altitudes using photon-counting detection methods.

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