P5.5 PRELIMINARY MEASUREMENTS WITH CODI: AN AUTOMATED COMPACT WATER VAPOR DIAL

Janet L. Machol*
University of Colorado / National Oceanic and Atmospheric Administration, Boulder, CO, USA

ABSTRACT

The design and preliminary tests of an automated differential absorption lidar (DIAL) that profiles water vapor in the lower troposphere are presented. The instrument, named CODI (for COmpact DIAL), has been developed to be eye safe, weatherproof, and portable. The lidar design and its unattended operation are described. Nighttime intercomparisons with *in situ* sensors and a radiosonde are shown.

1. INTRODUCTION

Water vapor profiles in the lower troposphere are essential to characterize low-level moisture transport, needed for improved weather forecasts as well as climate research. Although most atmospheric water vapor occurs in the lowest three kilometers, this region is not well observed. Currently, moisture profiles for operational use are obtained primarily from twice-daily radiosonde launches or from satellite retrievals. Automated weather data is also obtained from *in situ* sensors in some commercial aircraft. The infrequent radiosonde launches miss much of the variability in the low-level water vapor field, while the satellite measurements are also sparse and have limited vertical resolution at low altitudes. This impedes forecasts of meteorological conditions such as precipitation amounts, where accurate and timely identification of moisture levels is important.

Lidars have been used to profile water vapor and other trace gases since the 1960s. A differential absorption lidar (DIAL) uses absorption, as evidenced by reduced laser backscatter from greater distances, to measure the density of atmospheric gases. This is in contrast with a Raman lidar which detects the wavelength-shifted return due to inelastic backscatter from selected molecules. DIAL does not require calibration, but has stringent requirements on the laser bandwidth, wavelength, and stability, as well as an accurate knowledge of water vapor spectroscopy around the laser wavelength. A Raman lidar requires external calibration and a high power laser, but can have a simple transmitter design. Passive radiometric measurements at infrared wavelengths can also used to calculate profiles of humidity as well as temperature, although detailed water vapor structure is not obtained from the data inversion process. Another technique, under development, is the use of tomographic methods with arrays of GPS sensors to resolve water vapor structure.

Fig. 1. Photograph of CODI.

CODI (for COmpact DIAL), is an automated eye-safe DIAL which continuously measures water vapor profiles to several kilometers above ground (Machol et al. 2004). The lidar has been developed by the National Oceanic and Atmospheric Administration (NOAA) in conjunction with the National Aeronautics and Space Administration (NASA) and the National Center for Atmospheric Research (NCAR). Most existing water vapor lidars are large, expensive, and/or not automated (e.g., Goldsmith et al. 1998; Wulfmeyer 1998; Bruneau et al. 2001; Ismail et al. 2000; Ehret et al. 1993), although a few smaller designs have been tested (Rall 1994; Little and Papen 2001). Our goal has been to develop a compact, lower cost, and lower resolution DIAL that can be duplicated and deployed, ideally alongside boundary layer radar wind profilers, in unattended arrays. Such a network could measure horizontal water vapor transport in the lower atmosphere useful for better quantitative precipitation forecasts, and

* *Corresponding author address:* Janet Machol, NOAA-ET2, 325 Broadway, Boulder, CO 80305; email: janet.machol@noaa.gov.

observations of long-term trends in the water vapor field needed for climate studies. The DIAL vertical profiles could be extended with column-integrated precipitable water vapor observations obtained from either ground-based radiometer or GPS methods. The commercial cost for the lidar should be comparable to that of a boundary layer radar wind profiler.

2. SYSTEM DESIGN

Other than an external control computer, CODI is completely housed in a weatherproof, climate-controlled cabinet on wheels and has a turning mirror which permits the laser beam to be transmitted at any angle along one axis (Fig. 1). The specifications and requirements for the DIAL are shown in Table 1.

2.1 *Transmitter*

When selecting water vapor DIAL wavelengths (Boesenberg 1998), the absorption line should be isolated, away from absorption lines of other species, near a region of minimal absorption for the off-line wavelength, and relatively temperature insensitive. The laser requirements are stringent regarding frequency stability, spectral purity, beam-pointing stability, and linewidth (Wulfmeyer 1998). For varying atmospheric conditions, a tunable laser which can access multiple absorption lines is preferred.

The CODI transmitter is based on an amplified infrared diode laser (Walpole 1996). The seed laser is a single-mode linearly-polarized cw DFB laser manufactured by Sarnoff Corporation for NASA.

Table 1. Lidar Specifications and Requirements

Parameter	Specification	Requirement
Transmitter		
seed laser	823-nm DFB	
seed laser power	17 mW	
amplifier	diode flared amplifier	
prf	6-10 kHz	
pulse duration	600 ns	
transmit pulse power	0.15 mJ	
seed temperature	~24 ±0.003 C	
amplifier temperature	~20 ±0.2 C	
laser bandwidth	~12 MHz	<400 MHz
frequency stability	±80 MHz	±200 MHz
spectral purity	>99.9%	>99.5%
Receiver		
telescope diameter	35 cm	
far-field FOV	180 mRad	
filter bandwidth	160 pm	
far-field detector	APD (EG&G)	.

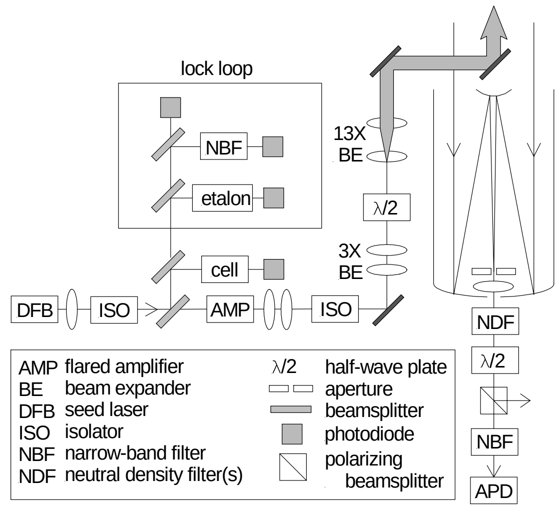

Fig. 2. Optical layout of the lidar.

The 823-nm system can access three water vapor lines (823.616, 823.689, and 823.960 nm) of varying line strengths which are appropriate for different atmospheric conditions with the optimal water vapor densities in the range of 0.5 to 10 g/m^3. The corresponding relative humidity ranges are from 5 to >95% at 10 C, and from 2 to 42% at 25 C.

The DFB laser is temperature-tuned to select the general wavelength region. Current tuning, as it is faster, is used to switch between the on- and off-line wavelengths. For DIAL operation, the averaging times before switching wavelengths are 45 seconds on line and ten seconds off line. Four percent of the cw beam is deflected to a frequency lock loop, while the remainder is coupled into a flared amplifier. Fig. 2 shows a schematic of the lidar optics. To lock the laser to the correct on-line wavelength, CODI uses an edge technique with an etalon that has been calibrated to a water vapor absorption cell measurement.

The single-pass pulsed flared amplifier diode (from an SDL 8630) pulses the output and increases the laser peak power. Because the amplifier is peak-power limited to 0.5 W, the mean output power is maximized with long pulse lengths and a high pulse repetition frequency (prf). In general, the lidar is operated with 600-ns pulses (which corresponds to a minimum range resolution of 90 m) and a prf of 8 kHz (or a range of 18.75 km). The laser beam is expanded to be eye-safe.

2.2 *Receiver*

The main receiver components are the telescope, filters, and an avalanche photodiode (APD). The lidar receiver telescope is a 35-cm-diameter f/11 Schmidt-Cassegrain (Celestron C14). The near-field channel is currently not installed. The light passes through a very narrow-band filter and is focused onto a single photon-counting APD with a quantum efficiency of 25% at 825 nm. A polarizing beamsplitter in the receiver, in combination with a pair of half-wave plates is used to discard about half of the background skylight.

3. MEASUREMENTS

To evaluate the lidar, we took both horizontal and vertical nighttime profiles in Boulder, Colorado, USA. Fig. 3 shows a horizontal water vapor profile, demonstrating an error of ±15% for a range on this day of about 1.7 km with 30-min and 180-m averages. The error bars on the data plots show the instrument-induced noise calculated with an autocovariance technique (Lenshow et al. 2000). Water vapor density measurements are presented here; the conversion factor from water vapor density to mixing ratio is 1.05 kg/m^3 at typical conditions for Boulder of 830 mB and 276 K.

During two all-night experiments, the DIAL measurements were compared with the water vapor density at three ground-based sensors, calculated from the measured temperature and relative humidity. Fig. 4 compares the value at the 1000-m range gate of the horizontal DIAL measurements with the *in situ* measurements. Autocovariance calculations show that the error in the DIAL water vapor measurements was about ±7% for 30-minute and 180-m averages. Based on the instruments' specifications, the errors in the water vapor densities calculated from the *in situ* measurements were less than 4%. The *in situ* measurements varied between the sites because the stations sample moisture at different heights. The Rocky Mountains, foothills, and canyon just to the west of Boulder presumably also generate variability in the temperature, winds, and water vapor across the city. The second experiment occurred on a windier night but had similar results.

Fig. 5 shows a comparison of a vertical DIAL profile with the water vapor density calculated from radiosonde measurements. The DIAL values were derived from 30-min averages and two sizes of range gates. The x-series Vaisala RS90-AG radiosonde was launched about 30 minutes after sunset. The profiles show good agreement to above 2.5 km. The conditions aloft were light winds (less than 6 m/s), which veered from the east to the southwest in the first 1 km and remained

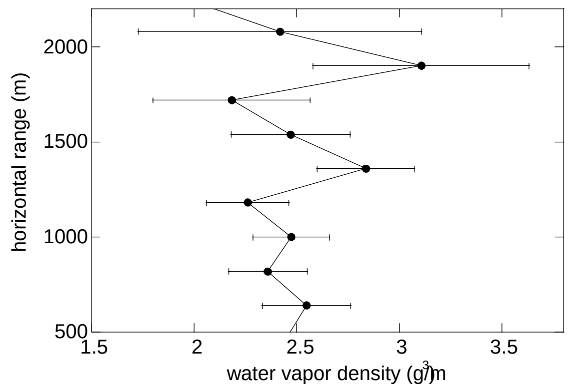

Fig. 3. Horizontal water vapor profile recorded at 20:24 (local time) on 3 February 2003 calculated with 180-m, 30-minute averaging.

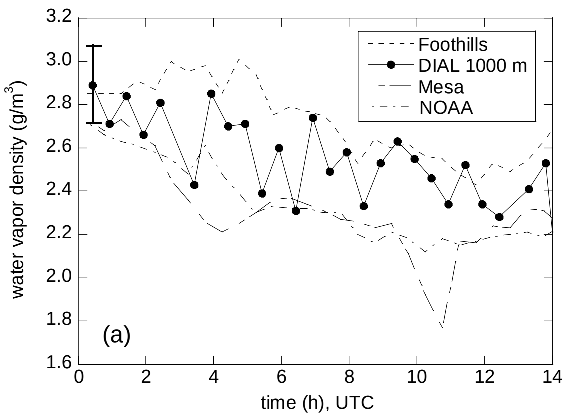

Fig. 4. A 14-h nighttime comparison of the horizontal DIAL measurements at the 1000-m range gate with ground-based *in situ* sensors. These measurements were made on 4 February 2003 UTC. The DIAL values were calculated with 180-m, 30-minute averaging. Local time can be obtained by subtracting 7 h from UTC.

southwesterly up to 2 km, after which they backed to the south. The lidar obtains good DIAL data at ranges as close as about 800 m, although only the far-field optics are in place. This is about 400 m below the region of full overlap and indicates excellent consistency in the beam-pointing between the on- and off-line wavelengths due to the single-mode waveguide structure of the amplifier. The nighttime errors are due to the low count rates, while the daytime errors are mostly due the background.

The measurements with CODI suggest several improvements to the instrument: a higher-power laser, the addition of a near-field channel, and improved climate control. The new laser design should permit the wavelength to be switched after each pulse, so as to reduce errors related to

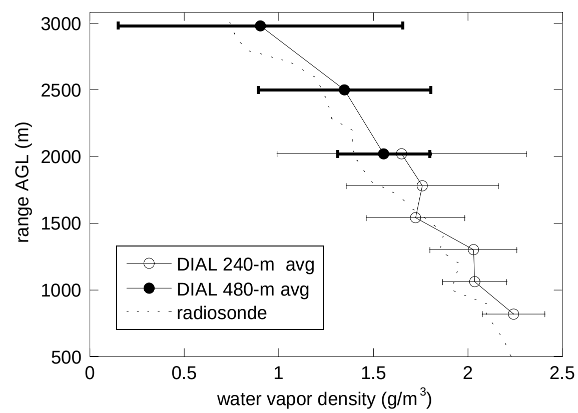

Fig. 5. Comparison of a nighttime vertical DIAL profile with radiosonde-derived values. Measurements were taken at 19:04 (local time) on 12 March 2003. The DIAL data is a 30-minute average.

atmospheric inhomogeneities. Also, the effects of intermittent clouds on long-time-averaged data need to be considered. Together, these upgrades will make the lidar a prototype instrument capable of 24-h ground-based measurements in a variety of conditions.

4. CONCLUSIONS

The horizontal and vertical intercomparisons were successful and show that the CODI automation works well. In general the water vapor measurements have at least 15% precision and a range of about two kilometers for 30-minute averaging times and 180-m range gates. Longer ranges can be obtained by increasing the averaging. The lidar single-channel backscatter profiles also provide cloud base heights and qualitative measurements of aerosols. In the future, with an upgraded laser, the lidar should provide better nighttime measurements and similar measurements during the day in a variety of conditions. Although CODI has less resolution and range, and requires longer averaging times than higher power lidars, the temporal and spatial resolutions are compatible with operational use.

ACKNOWLEDGEMENTS

Special thanks to James Abshire, Tom Ayers, Hector Bravo, Andreas Fix, Michael Hardesty, Leo Hollberg, Keith Koenig, Michael Krainak, Christoph Senff, Scott Sandberg, and Karl Schwenz. This project has been funded by the NOAA Environmental Technology Laboratory, the NOAA Office of Global Programs, NCAR, and the NASA Goddard Space Flight Center.

REFERENCES

Boesenberg, J., 1998: Ground-based differential absorption lidar for water-vapor and temperature profiling: methodology*, Appl. Opt,* **37**, 3845-3860.

Bruneau, D., P. Quaglia, C. Flamant, M. Meissonnier, and J. Pelon, 2001: The airborne lidar LEANDRE 2 for water vapor profiling in the troposphere, *Appl. Opt.*, **40**, 3450-3475.

Ehret, G., C. Kiemle, W. Renger, and G. Simmet, 1993: Airborne remote sensing of tropospheric water vapor with a near infrared differential absorption lidar system, *Appl. Opt.*, **32**, 4534-4551.

Goldsmith, J. E. M., F. H. Blair, S. E. Bisson, and D. D. Turner, 1998: Turn-key Raman lidar for profiling atmospheric water vapor, clouds, and aerosols, *Appl. Opt*., **37**, 4979-4990.

Ismail, S., E. V. Browell, R. A. Ferrare, S. A. Kooi, M. B. Clayton, V. G. Brackett, and P. B. Russell, 2000: LASE measurements of aerosol and water vapor profiles during TARFOX, *J. Geophys. Res*., **105**, 9903-9916.

Lenshow, D. H., V. Wulfmeyer, and C. Senff, 2000: Measuring second- through fourth-order moments in noisy data, *Oceanic Technol.*, **17**, 1330-1347.

Little L. M. and G. C. Papen, 2001: Fiber-based lidar for atmospheric water-vapor measurements, *Appl. Opt*, **40**, 3417-3427.

Machol, J. L., T. Ayers, K. T. Schwenz, K. W. Koenig, R. M. Hardesty, C. J. Senff, M. A. Krainak, J. B. Abshire, H. E. Bravo, and S. P. Sandberg, 2004: Preliminary measurements with an automated compact differential absorption lidar for profiling water vapor,. *Appl. Opt.*, **43,** 3110-3121.

Rall J. A. R., J. B. Abshire, D. Reusser, and M. Humphrey, 1994: Measurements of atmospheric water vapor using a compact AlGaAs laser based DIAL instrument, in *Conference on Lasers and Electro-Optics*, Vol. 8. 1994 OSA Technical Digest Series, Optical Society of America, Washington DC, 196.

Walpole J. N., 1996: Semiconductor amplifiers and lasers with tapered gain regions, *Opt. and Quant. Electr.* **28,** 623-645.

Wulfmeyer V., 1998: Ground-based differential absorption lidar for water-vapor and temperature profiling: development and specifications of a high performance laser transmitter, *Appl. Opt.*, **37**, 3804-3860.