PRELIMINARY TESTING OF A WATER-VAPOR DIFFERENTIAL ABSORPTION LIDAR (DIAL) USING A WIDELY TUNABLE AMPLIFIED DIODE LASER SOURCE

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ABSTRACT

Water vapor plays an enormous role in Earth's atmospheric dynamics through cloud formation, precipitation, and interactions with electromagnetic radiation, especially its absorption of longwave infrared radiation. Detailed data of water vapor distribution and flux and related feedback mechanisms are required to better understand and predict local weather, global climate, and the water cycle. One method of obtaining this data in the boundary layer with improved vertical resolution relative to passive remote sensors is with a Differential Absorption LIDAR (DIAL) utilizing a compact laser diode source. Montana State University, with the expertise of its laser source development group, is engaged in experiments leading to a water vapor DIAL system that utilizes a widely tunable amplified external cavity diode laser (ECDL) transmitter. This transmitter will have the ability to tune across a 17 nm spectrum near 830 nm, allowing it access to multiple water vapor absorption lines of varying strengths. Because of this wide tunability, the optimal absorption line for the DIAL technique in this region can be used based upon existing atmospheric conditions. This paper highlights the progress made in several areas at Montana State University (MSU) towards characterization, design, and construction of a water vapor DIAL using this widely tunable amplified ECDL transmitter.

1. INTRODUCTION

It is widely agreed that water vapor is one of the most important gasses in the atmosphere with regards to its role in local weather, global climate, and the water cycle. Detailed knowledge of its concentration profiles and fluxes is required to aid in forecasting and model predictions [1]. Radiosondes are the current standard method used to obtain routine water vapor profiles, but this technique can only provide information at one location at one point in time and cannot easily be used to monitor the spatial and temporal changes of the water vapor concentrations. Improved capabilities to monitor water vapor profiles in the boundary layer, where it primarily resides, continuously in time at many locations are also needed [2]. Several studies have shown that Differential Absorption LIDAR (DIAL) is one technique that may be able to accomplish this task. DIAL systems can achieve improved vertical resolution compared to passive remote sensors even at very low powers. While these low-power systems do not typically have the resolution capabilities of larger LIDARs, low-power DIAL systems can be built much smaller and more robust at less cost, increasing their usefulness for deployment in multi-point arrays. Recent experiments with small, low-power DIAL systems have shown promise but have called for "a new laser [with] a tuning range that accesses a larger selection of good water-vapor lines..." [3].

We are leveraging expertise in the Montana State University (MSU) laser source development group to create a widely tunable laser transmitter for use in a DIAL system that will be able to access a large selection of water vapor lines. The requirements for DIAL measurements with an error due to individual laser properties of $< 3\%$ are stringent [4], yet should still be met or exceeded by the final MSU DIAL instrument. These requirements are compared to the current MSU DIAL transmitter specifications in Table 1.

The transmitter is based on an amplified external cavity diode laser (ECDL) configured in a Littman-Metcalf configuration, and has a continuous wave (cw) output power of 20 mW with a side-mode suppression of greater than 45 dB as measured on an Optical Spectrum Analyzer (OSA). The spectral purity was initally measured to be 0.966 after a commercial tapered amplifier being seeded by the ECDL, and 0.872 after an Acousto-Optic Modulator (AOM) being used to pulse the beam (see section 2 for a description of the system design). This value is lower than desired for DIAL applications [5]. Techniques will need to be employed to either improve the spectral purity of the transmitter, or to calibrate out the spectral impurity. The full-width at half-maximum (FWHM) linewidth is less than 200 kHz, as determined by beating experiments. Since the ECDL has cw output, the wavelength will be continuously monitored by a Burleigh WA-1500 wavemeter. A tuning feedback loop will be used to control the wavelength output to within the resolution of the wavemeter, < 50 MHz. Members of our research group are developing electronic tuning techniques to ac-

Table 1. Laser transmitter requirements for water-vapor DIAL measurements with an error due to individual laser properties of $< 3\%$ compared to the Montana State University DIAL transmitter specifications.

Parameter	Requirement (at 830 nm)	Measured Value
Linewidth (FWHM; MHz)	< 298	< 0.200
Frequency Stability (MHz)	± 160	± 50
Spectral Purity	> 0.995	0.872

complish on- and off-line switching times of < 1 s.

With a center wavelength of 832 nm, a coarse tuning range of 17 nm from about 824 nm to about 841 nm, and a continuous tuning range greater than 20 GHz, the ECDL is able to scan across several available water vapor absorption lines. This technology can be applied to most commercially available laser diodes, opening up many atmospheric constituents for study using the DIAL technique in the visible and near-infrared spectral regions.

Horizontal-pointing experiments were performed to characterize the performance of the laser transmitter in a LIDAR system and to assess whether tuning the ECDL in LIDAR conditions was even feasible. Those experiments are described in section 2, with results in section 3. The proposed vertical DIAL system design utilizing the transmitter is discussed in section 4.

2. HORIZONTAL PATH-INTEGRATED ABSORPTION EXPERIMENTS

Prior to attempting vertical-pointing water vapor DIAL experiments, horizontal-pointing LIDAR experiments were completed to test and verify various components similar to those that will be used in the vertical water vapor DIAL system, including in particular, the actual tuning mechanism. CW measurements were made as an initial test of the system before pulsed measurements were attempted. These early measurements as well as a full description of the ECDL and LIDAR setups are described elsewhere [6]. Results from the pulsed experiments are discussed in detail here. The horizontal LIDAR transmitter used the same External Cavity Diode Laser (ECDL) and seeded tapered amplifier, operating near 830 nm, that will be used in the vertical water vapor DIAL system. It was aimed at hard targets, increasing the return signal by orders of magnitude over a vertical-pointing LIDAR that only receives backscattered photons from the atmosphere, allowing the tuning to be tested without needing to optimize a weak return signal.

The ECDL was used to injection seed a commercial tapered amplifier with a maximum cw output power of 500 mW. This power was never achieved in practice, however, as the seed power from the ECDL was only about 5 mW after traveling through two Faraday isolators. Also, the ECDL power was intentionally kept lower than the maximum allowed to extend the diode's lifetime and improve the tuning characteristics. Even with low seed power, the spectral characteristics of the ECDL are transferred to the output of the tapered amplifier. Pulsing of these amplifiers at the speeds necessary for DIAL measurements has so far proven unreliable. To circumvent this problem, an AOM was used to pulse the continuous-wave beam exiting the amplifier. The advantages to using an AOM include that there is no frequency chirp in the transmitted beam and each pulse is a near-perfect square shape in time. The drawback is that only about 70% of the light input to the AOM is transmitted through it into a pulsed beam, reducing the transmit power of an already low-power system. The final transmit power from this system was typically between 80 mW and 120 mW. About 4% of the transmitted beam was sent to a reference power detector to monitor changes in the transmit power as the transmitter tuned. These fluctuations were normalized out of the final data.

The LIDAR receiver used a commercially available Schmidt-Cassegrain telescope, a 10 nm bandpass filter, an Avalanche Photo-Diode (APD) detector operating in photon-counting mode, and a Multi-Channel Scalar (MCS) used to bin the photoelectron counts received from the APD. Laser tuning and data acquisition were operated via computer control. The control program simultaneously measured both the wavelength of the transmitted laser light and the reference beam power, initialized the MCS and other instruments used to operate the experiment, and began data collection. The reference power was measured before and after the data collection time in order to average out any output power drifts that might occur while data is being collected. Both reference powers, the return signal counts in the target bin, and the laser frequency were recorded to a data file at one wavelength after which the computer tuned the laser by adjusting the voltage applied to a piezo-electric tuner within the ECDL. The MCS counter was cleared and the data acquisition process reinitiated until a scan across an absorption feature was completed. The temperature of the ECDL was adjusted manually when necessary to provide a scan of greater than 50 GHz.

3. LIDAR TUNING RESULTS

Pulsed absorption measurements have been taken by this system on three water vapor absorption lines, 829.022 nm, 831.615 nm, and 831.850 nm, at varying distances. The LIDAR was aimed through a window, which unavoidably reduced the transmission power by reflecting a portion of the output light. Metal surfaces of various

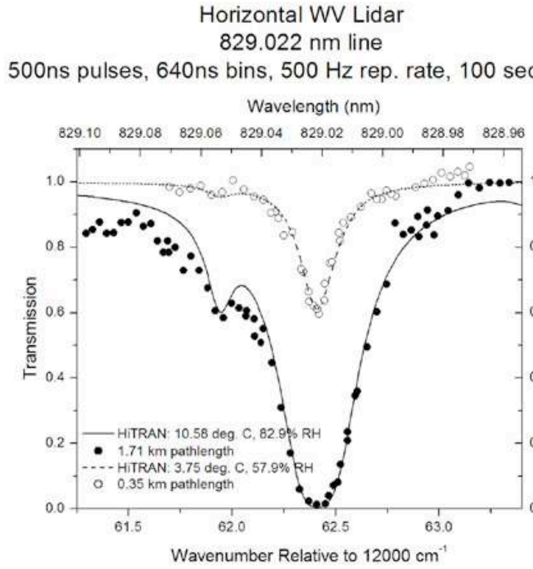

Figure 1. A plot of the relative transmission through the atmosphere as a function of wavelength near 829.022 nm. The open (closed) circles represent measurements made for a 0.35 km (1.71 km) path length. The solid and dashed lines are theoretical calculations using HITRAN with the measured temperature, humidity, and path length.

buildings were used as hard targets. Data taken on the 831.615 nm absorption line proved to be too weak to be reliable and so the LIDAR was coarse-tuned to the slightly stronger 831.850 nm line instead, demonstrating the powerful flexibility of a system able to tune to several absorption lines. Pulses 500 ns wide, leading to 75 m long rangebins and average pulse energies of 50 nJ per pulse, were transmitted at a repetition rate of 500 Hz. The repetition rate was limited by the data collection speed of the MCS. Signal averaging of typically 100 seconds was used to increase the return signal and smooth out short-timescale variations. An average of the off-line data was taken and used to normalize the entire data spectrum.

Data sets from two water vapor lines compared to HiTRAN predictions illustrating the system tunability are shown in Fig. 1 and Fig. 2. Fig. 1 shows tuning data taken across the 829.022 nm water vapor line at pathlengths of 1.71 km and 0.35 km. Fig. 2 shows tuning data taken across the 831.850 nm water vapor absorption line at pathlengths of 1.67 km and 0.35 km. The varying pathlengths can be thought of as equivalent to the system response to varying relative humidities, as the absorption lines would become more or less pronounced depending on the water vapor density present in the atmosphere. The temperature and relative humidity measurements were made by a weather station located about 5 meters above the lidar and were averaged over the typically 1 hour or more needed to take all of the data points.

Taken together, these figures show the capability of the transmitter to selectively probe different water vapor absorption lines depending on current atmospheric conditions. The experimental results show that a DIAL system utilizing this ECDL and tapered amplifier combination will have an unprecedented ability to select which water vapor lines to scan depending on the prevailing atmospheric conditions.

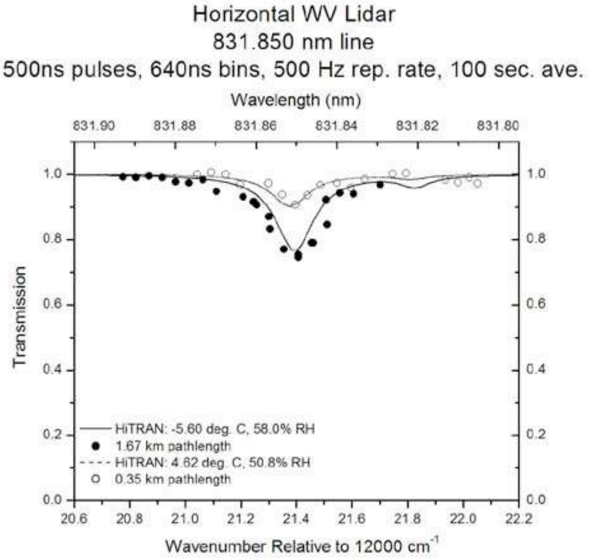

Figure 2. A plot of the relative transmission through the atmosphere as a function of wavelength near 831.850 nm. The open (closed) circles represent measurements made for a 0.35 km (1.67 km) path length. The solid and dashed lines are theoretical calculations using HITRAN with the measured temperature, humidity, and path length.

4. VERTICAL DIAL EXPERIMENT PLANS

With preliminary testing of the DIAL components complete, construction of the final instrument has commenced. The DIAL instrument is being built on a 2 foot by 4 foot optical breadboard, with a 1 foot by 3 foot optical breadboard mounted vertically to support the receiver telescope and most of the receiver optics, as well as the final segment of the transmitter optics. The majority of the transmitter optics will be placed on the horizontal breadboard. All receiver optics and most of the transmitter optics (excluding the final beam steering mirrors) will be contained in separate light-tight boxes to significantly reduce stray signal from the system. The vertical breadboard will also act as a barrier to further isolate the receiver from the transmitter.

The DIAL instrument transmitter will, for the first time in any known DIAL instrument, use a highly-tunable ECDL as a seed laser source for two cascaded commercial tapered amplifiers. Since the ECDL is too weak to saturate the tapered amplifiers by itself, it will seed one amplifier, which will then be used to seed a second amplifier with enough power to bring it to saturation. The expected system transmit power in this configuration is expected to be at least 500 mW and may reach 600 mW or more, a factor of about 5 times more power than in the horizontal experiment described in Section 2. For the same reasons as in the horizontal experiment, the transmitted laser beam will be pulsed using an AOM. The cascaded tapered amplifiers should provide enough power to overcome the efficiency loss incurred by the AOM. Custom designs for tapered amplifiers that can be pulsed are also being studied as an alternative.

The receiver will use a large (~28 cm diameter) Schmidt-Cassegrain telescope to collect return photons, an extremely narrow bandpass (~200 pm bandwidth) filter to block background light, two optical channels for near and far field signals operating simultaneously, and a photon-counting APD detector. The MCS used in previous experiments will be replaced by a much faster version, allowing the transmitted repetition rate to increase from 500 Hz to typically 10 KHz, which increases the allowable average output power by a factor of 20.

The transmitter will have the capability of tuning over a range of ~17 nm to selectively probe several available water vapor absorption lines, depending on current environmental conditions. Initial water vapor profiles, taken in the Bozeman, MT, area, will be analyzed. Fine-temporal-scale fluctuations of water vapor will be compared with twice-daily radiosondes to study the variations in water vapor profiles that standard radiosonde measurements miss. Spatial water vapor flux measurements will also be studied.

5. CONCLUSION

Pulsed measurements of relative absorption across water vapor absorption lines using a widely tunable amplified diode laser source in a horizontal LIDAR system have been demonstrated. The laser transmitter consists of an ECDL in a Littman-Metcalf configuration, developed at Montana State University, injection seeding a commercial tapered flared amplifier. The laser transmitter is able to tune from 824 nm to 841 nm and produce 100 mW of cw power, allowing it to selectively probe several available absorption lines. Absorption spectra near 829.022 nm and 831.850 nm were probed with horizontal roundtrip pathlengths of up to 1.71 km, showing the powerful tuning capability of this transmitter. The measured absorption spectra showed close agreement with those predicted by HiTRAN.

Development of a vertical water vapor DIAL system utilizing this widely tunable ECDL transmitter is underway. The proposed system will utilize two cascaded tapered amplifiers increasing the average cw transmit power to 500 mW, or pulse energies of 0.5 μJ per pulse when operating with 1 μs pulse widths. The receiver will allow two field-of-views, one for the near-field and one for the far-field, to be simultaneously recorded. The tuning capabilities of the transmitter will be taken advantage of in order to probe the optimal absorption line in the 830 nm region based on current atmospheric conditions. Data will be taken up to several kilometers to study fluctuations of water vapor in space and time on faster temporal scales than is currently feasible with radiosonde systems. The ability of the laser development group at Montana State University to build this type of transmitter around most commercially available diode lasers allows this wide tunability to be utilized in DIAL systems probing much of the visible and near infrared spectral region, where numerous interesting and valuable absorption features exist.

REFERENCES

[1] Kington, J. A. THE ATMOSPHERIC SCIENCES ENTERING THE TWENTY-FIRST CENTURY, Board on Atmospheric Sciences and Climate Commission on Geosciences, Environment and Resources, National Research Council, USA, National Academy Press, Washington, DC, 1998. No. of pages: xvi+364. Price: #34.95. ISBN 0-309-06415-5 (hardback). *International Journal of Climatology*, 20:935–936, June 2000.

[2] Rycroft, M. J. Global environmental change: research pathways for the next decade - by Committee on Global Change Research of the US National Research Council, National Academy Press, 1999, 595 pp. ISBN: 0 309 06420 1, (hb) @$39.95. *Journal of Atmospheric and Terrestrial Physics*, 62:711–712, May 2000.

[3] Machol, J. L., Ayers, T., Schwenz, K. T., Koenig, K. W., Hardesty, R. M., Senff, C. J., Krainak, M. A., Abshire, J. B., Bravo, H. E., and Sandberg, S. P. Preliminary Measurements with an Automated Compact Differential Absorption Lidar for the Profiling of Water Vapor. *Appl. Opt.*, 43:3110–3121, May 2004.

[4] Bösenberg, J. Ground-Based Differential Absorption Lidar for Water-Vapor and Temperature Profiling: Methodology. *Appl. Opt.*, 37:3845–3860, June 1998.

[5] Ismail, S. and Browell, E. V. Airborne and spaceborne lidar measurements of water vapor profiles - A sensitivity analysis. *Appl. Opt.*, 28:3603–3615, September 1989.

[6] Obland, M. D., Meng, L. S., Repasky, K. S., Shaw, J. A., and Carlsten, J. L. Progress toward a water-vapor differential absorption lidar (DIAL) using a widely tunable amplified diode laser source. In Singh, U. N., editor, *Ultraviolet Ground- and Space-based Measurements, Models, and Effects V. Edited by Bernhard, Germar; Slusser, James R.; Herman, Jay R.; Gao, Wei. Proceedings of the SPIE, Volume 5887*, pages 205–215, August 2005.