Initial results from a water vapor differential absorption lidar (DIAL) using a widely tunable amplified diode laser source

Michael D. Obland(1,2), **Amin R. Nehrir**(3), **Kevin S. Repasky**(3),
Joseph A. Shaw(3), **and John L. Carlsten**(1)
(1)*Physics Department, Montana State University,*
264 EPS Building, Bozeman, MT 59717, USA
(2)*NASA Langley Research Center, 100 NASA Road, Mail Stop 401A,*
Hampton, VA 23681, USA, Michael.D.Obland@nasa.gov
(3)*Electrical and Computer Engineering Department, Montana State University,*
610 Cobleigh Hall, Bozeman, MT 59717, USA, repasky@ece.montana.edu

ABSTRACT

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. Especially with the growing concern for understanding and predicting global climate change, detailed data of water vapor distribution and flux and related feedback mechanisms in the lowest 3 km of the troposphere, where most of the atmospheric water vapor resides, are required to aid in climate models. Improved capabilities to monitor range-resolved tropospheric water vapor profiles continuously in time at many locations are needed. 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, has developed a compact water vapor DIAL system that utilizes a widely tunable amplified external cavity diode laser (ECDL) transmitter. This transmitter has the ability to tune across a 17 nm spectrum near 830 nm, allowing it access to multiple water vapor absorption lines of varying strengths. A novel tuning system tunes and holds the ECDL to within +/- 88 MHz (0.20 pm) of the selected wavelength. The ECDL acts as a seed source for two commercial cascaded tapered amplifiers. The receiver uses commercially available optics and a fiber-coupled Avalanche Photodiode (APD) detector. Initial nighttime measurements of water vapor profiles taken over Bozeman, Montana, with comparisons to radiosonde-derived profiles will be presented.

Keywords: Lidar, diode lasers, remote sensing, differential absorption lidar, DIAL, tunable, water vapor

1. INTRODUCTION

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.[1] It is well understood that detailed boundary layer measurements of the vertical and horizontal distribution and flux of water vapor are necessary for increasing the accuracy of climate model predictions.[2] Therefore, a need exists to improve on and contribute to current methods and instruments for continuously monitoring tropospheric range-resolved water vapor profiles at many locations.[3]

Montana State University (MSU) is leveraging expertise in its laser source development group in an attempt to build a DIAL system that is cheaper, smaller, and more robust than existing field instruments and able to access a large selection of water vapor lines using a widely tunable laser transmitter. This transmitter, an External Cavity Diode Laser (ECDL), has 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 selectively probed based upon existing atmospheric conditions. The DIAL uses an all-semiconductor transmitter, with the ECDL acting as a seed laser source for two cascaded commercial tapered amplifiers to increase the output power. The receiver uses a fiber-coupled APD detector. Mostly commercial-off-the-shelf components are employed so that the system, including the transmitter, can be repaired quickly and relatively easily should a part fail, demonstrating a step towards the robustness needed for field deployment in multi-point arrays. The DIAL is low-power, compact, with a desktop-sized footprint, and has the ability to be made eye-safe. The goal of this project is to demonstrate that low-power DIAL instruments using widely tunable diode laser transmitters, which can be designed at multiple wavelengths, can achieve useful water vapor profiles and are acceptable candidates for use in multi-point lidar networks or satellite arrays to study water vapor flux profiles.

Horizontally pointing lidar experiments were performed to thoroughly test the DIAL transmitter.[4] After it was shown through the horizontal experiments that the ECDL and TA transmitter system would be able to successfully tune across a number of different water vapor absorption features, and taking into account the lessons learned from these experiments, a vertical DIAL system was designed and built. This paper gives a brief update on progress of the DIAL system. Section II provides a detailed physical description of the vertical water vapor DIAL. Tests for characterizing the performance of the DIAL are presented in Section III. Preliminary experimental results taken at night over Bozeman, Montana, with a comparison to a co-located radiosonde are shown in section IV. Concluding remarks are given in section V.

2. INSTRUMENT DESCRIPTION

The layout for the DIAL experiment is shown in figure 1. It closely follows and improves on the design of a previous horizontally pointing DIAL instrument also built at MSU[4,5] and is fully described elsewhere.[6] The laser and amplifiers were placed on the horizontal surface of a $2' \times 4'$ optical breadboard. The ECDL output was circularized by an anamorphic prism pair before passing through two optical isolators to prevent feedback into the laser diode. A half-wave plate and polarizing beam splitter (PBS) combination was used to send part of the ECDL beam to a wavemeter for monitoring, and the other part of the beam on to seed the first tapered amplifier (TA). The first TA output was sent through an optical isolator and second half-wave plate and PBS for monitoring. The ECDL transmit power is too low to fully saturate the TA that it seeds, limiting the maximum transmit power in previous experiments to $\sim$ 120 mW. Therefore, the first TA was used to fully saturate a second TA, allowing it to operate at its maximum output power of $\sim$ 400 mW. Two mirrors, widely-spaced irises, and a collimating lens were used to seed the second tapered amplifier. The output of this TA was similarly sent through an optical isolator and half-wave plate and PBS. The transmit light was focused and turned vertically onto a vertical breadboard via a mirror. All mirrors and optics were coated for infrared light near 830 nm to minimize scattering and raise system efficiency. The transmit beam up until this point was continuous wave (cw) and was sent through a acousto-optic modulator (AOM) for pulsing and then through an iris to block all light except the first-order diffraction pulsed beam out of the AOM. Several flipper mirrors and a fiber launch were included before and after the AOM for use in measuring the spectral purity, as described in section III below. The transmit beam was collimated to a diameter of roughly 9 mm after the iris and brought around the telescope for tranmission off of a 45-degree mirror epoxied to the top of the receiver telescope's secondary mirror housing. Sending the transmit beam off of the back of the secondary telescope mirror allowed the system to be coaligned at ground level, and took some of the alignment uncertainty out of the bistatic approach. After scattering off of a molecule or particle in the atmosphere, the transmit photons are collected by a commercial 28-cm diameter Schmidt-Cassegrain telescope, focused, collimated, and sent through a narrowband filter, and coupled into a fiber to be detected by a avalanche photodiode (APD) and counted by a multi-channel scalar (MCS) card. The fast single MCS card (ASRC Aerospace AMCS-USB) allowed the system to be pulsed with a repetition rate of 20 KHz.

To achieve accurate DIAL data with a low-power vertical system, collecting every return photon is important. For this reason, much care was put into the design of the DIAL system, especially the receiver. Optical design software, Zemax, was used to design the receiver optics. Since the APD active area is $170\,\mu m$ in diameter, its size dictated the type of fiber optic cable that could feed photons to it, to avoid over-filling the detector area. The fiber that was used was a custom multi-mode 105 μm core diameter fiber with a numerical aperture (NA) of 0.22. This fiber size and NA made it the field stop of the receiver system, and defined the full field-of-view (FOV) of the system to be 150 μrad. The rest of the receiver optics were responsible for collimating the collected photons and focused by the telescope for passage through the narrowband filter, and focusing them into the fiber to be carried to the APD for detection. The Zemax design is shown in figure 2. The vertical line on the left represents the focal plane of the telescope. A Newport PAC037 converging lens is placed a distance of 8.89 cm (3.5 inches) from the focal plane to collimate the beam to a diameter of 9 mm. The collimated space then

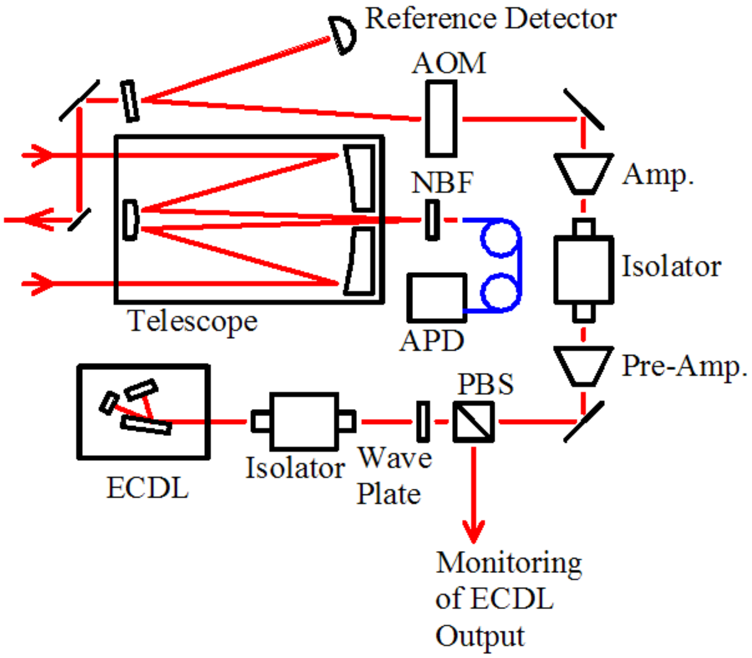

Figure 1. A general schematic of the DIAL instrument.

could contain several optics, including polarization optics for the future addition of a near-field channel, and a narrowband (NB) filter with a center wavelength of 828.0069 nm and bandwidth of approximately 250 pm (Barr Associates). Finally, two Thorlabs lenses (AC127-075-B and AC127-019-B) focused the beam down into the fiber optic cable. The receiver was originally designed to be 33.02 cm (13 inches) in length from the telescope focal point to the fiber launch.

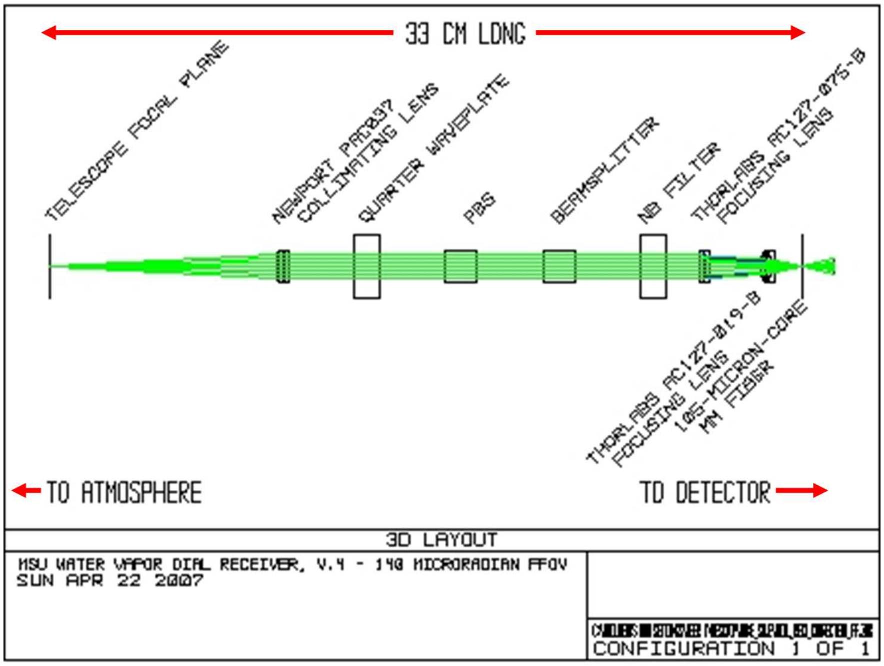

Figure 2. A plot produced by Zemax showing the design for the DIAL receiver.

Stable tuning of ECDL's is important for scanning across spectroscopic features, or for quickly changing between frequencies on and off of a spectroscopic feature, as in DIAL. To meet the frequency stability requirements necessary for DIAL measurements, and to ensure that mode hops do not occur in the laser wavelength (or at the very least are accounted for so that they can be removed from the data sets in post-processing), a fast, stable tuning method needed to be developed. Fortunately, a method for extending the continuous tuning range of a ECDL for use in oxygen absorption experiments[7] was able to be modified to provide the fast, stable tuning needed by the DIAL system. It makes use of an electronic feedback loop to suppress mode hops and extend the continuous tuning range of the ECDL. The system and associated tests as used in the water vapor DIAL system are described in detail in the literature.[8] This tuning system, along with the operational and analysis software, allowed the DIAL to become a mostly autonomous instrument.

LabVIEW was used to create the operational code for the water vapor DIAL, and operated in the following manner. The software, operating via GPIB connections, initialized the MCS card and all instruments. It then grabbed the date and time for the purposes of file labeling, and for time-stamping every second (20,000 laser pulses) of data. A custom waveform was selected on the arbitrary waveform generator (AWG) that created the desired pulse, a 1 μs pulsewidth at a repetition rate of 20 kHz. The AWG triggered the APD to begin collecting data but the laser pulse was not activated until 5 μs later, allowing for a background light measurement to be made. The ECDL piezo-electric tuner (PZT) voltage was set to zero to initialize it for tuning. The laser was allowed to settle for 5 seconds at the zero PZT voltage and the MCS memory buffer was cleared and readied for data collection. The laser was then tuned to the on-line wavelength and allowed to equilibrate for 5 seconds. The wavemeter feedback loop described in reference 8 tuned the laser wavelength until the on-line wavelength was reached. This wavelength and the reference power were measured. The MCS collected data for one second across 500 bins of 50 ns each. A time stamp, the wavelength and reference power, and the counts in each bin were recorded to a data file. This procedure of recording wavelength, reference power, and photon counts was repeated as long as desirable at this wavelength, typically 60 seconds, before the laser was tuned to the off-line wavelength and the procedure was repeated there, typically for 90 seconds for signal-to-noise purposes. The difference in averaging times helped alleviate the lower transmission of the off-line wavelength through the NB filter. This on- and off-line tuning continued as long as was desired, typically for 3-5 hours per data run. The LabVIEW code allowed for real-time display of the wavelength for monitoring tuning, the reference power, and the bin counts.

After the data were taken, MATLAB code was used to analyze them. The analysis code scanned the data set and removed data that did not fit within the wavelength stability requirement of ±160 MHz of the chosen wavelength. It then averaged the data spatially, binning the counts according to the resolution defined by the pulse width, or 150 meters for 1 μs pulses. After spatial averaging, the software normalized the counts with power and subtracted the background measurement from the overall data on a second-by-second basis to increase accuracy. Temporal averaging was typically performed over an hour of data to collect enough signal without allowing the atmosphere to change drastically. This averaging produced difficulties on nights when the atmosphere was changing rapidly, such as on windy nights or when a storm system was entering the area. The averaged and background subtracted counts were then used with absorption cross section values generated from radiosonde temperature and pressure measurements to calculate water vapor profiles using the DIAL equation.[9–11]

The requirements for DIAL measurements with an error due to individual laser properties of $< 3\%$ are stringent.[12] The requirements come about because the absorption cross section of water vapor absorption lines is highly dependent on the laser wavelength. If the laser linewidth, frequency stability, and spectral purity are not well known, errors will arise in the water vapor retrievals due to uncertainties in the actual absorption cross section of the transmitted laser light. These requirements are compared to the current MSU DIAL specifications in Table 1 and were met or exceeded by the final MSU DIAL instrument.

3. INSTRUMENT TESTING

Extensive testing was performed to ensure that all aspects of the DIAL system were operating at the tolerances required for DIAL measurements. Of particular importance was measuring whether the transmitted wavelength was reliably centered at the desired wavelength and whether the transmit beam was sufficiently spectrally pure.

Parameter	Measured Value	Requirement (at 830 nm)
On-/Off-line Wavelength (nm, vacuum)	828.187/828.287	
Repetition Rate (kHz)	20	
Pulse Width (μs)	1.0	
Pulse Power (μJ)	~ 0.25	
Linewidth (FWHM; MHz)	< 0.300	< 298
Frequency Stability (MHz)	± 88	± 160
Spectral Purity	0.995	> 0.995
Telescope Diameter (cm)	28	
Far-field Full Field of View (μrad)	150	
Filter Bandwidth (pm)	~ 250	

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.

Testing to ensure that the wavelength of the transmit beam after being passed through the AOM was the same as that of the ECDL, which is used to control tuning, was performed by measuring both wavelengths and forming their ratio for comparison as the ECDL tuned. As expected from previous measurements, the results show that the wavelength output of the DIAL agrees with the wavelength being measured from the ECDL to within the uncertainty of the wavemeter making the measurement, ± 0.1 pm.

The spectral purity of the MSU DIAL was measured by integrating the power in the laser linewidth directly from a power spectrum taken by an optical spectrum analyzer (OSA), and comparing that to the overall power output of the laser beam. This provides a lower limit for the spectral purity of the transmitter. Tests were run to first show that the spectral purity of the system was not changed by the use of the AOM or by the OSA measurement technique itself.

After the method for measuring spectral purity was thoroughly tested and understood, the final OSA measurements were made, and are shown in figure 3. Initial spectral purity measurements of the DIAL transmitter showed that the system without the use of a narrowband filter had a spectral purity of 0.872. This value is not surprising since diode lasers and amplifiers based on semiconductor technology tend to have broad spectrums and large amplified spontaneous emission (ASE), hence the use of external cavities to force the diode laser output to be more monochromatic. Adding a narrowband filter to the receiver of the DIAL drastically improves the spectral purity of the system, as only the light that passes through the filter is measured and a large amount of the ASE is blocked. With a NB filter in place, the spectral purity of the transmitter improves to >0.995 at the on-line wavelength. These tests show that the spectral purity of the DIAL is adequate for accurate water vapor retrievals.

4. RESULTS

Alignment of the system FOV with the transmit beam was accomplished by placing a mirror at roughly 45 degrees over the roofport hatch through which the DIAL was transmitting, and sending the transmit beam across the roof of the building, hitting the edge about 30 meters away. A visible helium-neon beam was sent backwards through the receiver fiber optic cable to simulate the FOV, and the transmit beam was able to be reasonably aligned within the FOV across a 30 meter path length.

This method was successful, and bistatic DIAL data were taken. Examples of data containing clouds averaged over time is shown in figure 4. The graph shows range or altitude above ground level on the x-axis and photon counts on the y-axis. Negative ranges correspond to the time before the laser fires, which is used to measure the background light level without the laser pulse present. In the left graph, the effect of background subtracting can be seen as the bins used for background determination, located below zero altitude, are very near to zero. The flash of the laser pulse is seen at zero, and lasts much longer than the 75 meters that would be expected if the beam were not scattering off of atmosphere in the near field of the receiver. The initial flash of the laser is so weak that a correction factor for the APD counts was not needed, as the APD was not close to saturation. Clouds are visible from 500 meters in altitude and up. The off-line signal is stronger at the clouds because it has not been absorbed by water vapor during its transit from the ground to the cloud and back. The right graph

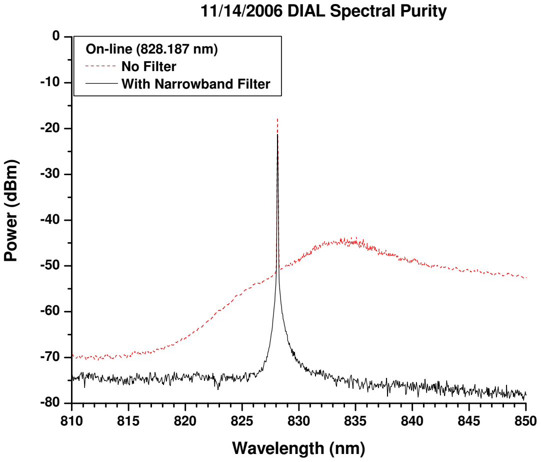

Figure 3. An optical spectrum analyzer trace showing the spectral purity of the DIAL receiver when using a narrow band filter.

shows the raw counts before background subtraction. The averaged counts such as these are used in the DIAL equation to calculate water vapor density.

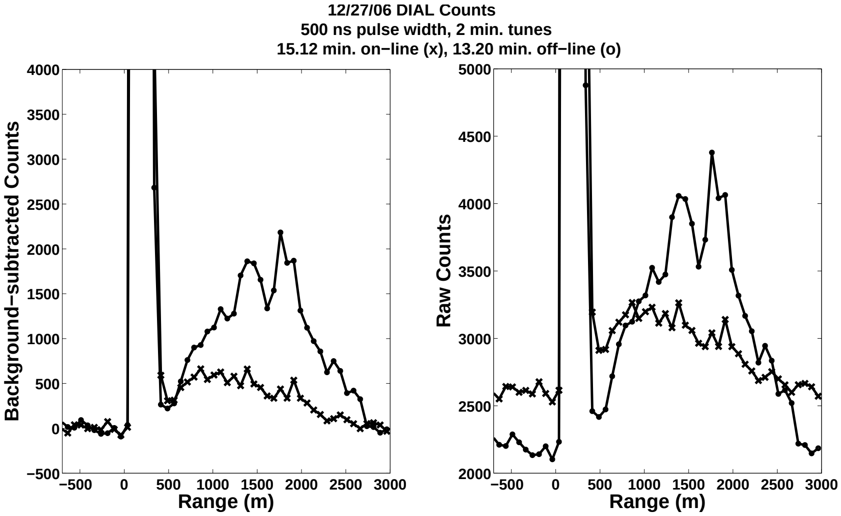

Figure 4. Time-averaged raw counts (right) and background-subtracted counts (left) showing the initial laser pulse, atmospheric returns, and cloud returns.

With the system in alignment, analysis of the data for producing water vapor profiles could be commenced. To verify that the water vapor DIAL was measuring the accurate amount of water vapor, radiosondes were launched with each DIAL data run, to give an *in situ* measurement of temperature and relative humidity, which were then converted to water vapor number density.

Several water vapor profiles were taken while the DIAL was in alignment that agreed reasonably well with the results from a colocated radiosonde. One example is shown in figure 5. The data were averaged over about 1 hour with pulse widths of 1 μs. Below 500 meters, the data does not agree within the error bars, probably due to a background light leakage into the detector, which has the effect in the DIAL equation of reducing the amount of water vapor. The error bars were produced by a simple differential analysis of the DIAL equation. Current work with the DIAL system includes improving the alignment technique to ensure that the received signal is maximized. The amplifiers will eventually be replaced with higher-power versions, increasing the output transmission power to close to 1 watt average power. Research is also being done on ways to improve the background light rejection of the system using etalon filters. These improvements should lead to better signal-to-noise ratios and better repeatable measurements of water vapor. Nonetheless, this figure shows the ability of the low-power DIAL system to achieve meaningful water vapor profiles up to about 2 km. While the DIAL returns are not exactly accurate yet, the ability to produce such a close result is a major step towards proving the viability of this system for field deployments, and will only improve with future versions of the instrument.

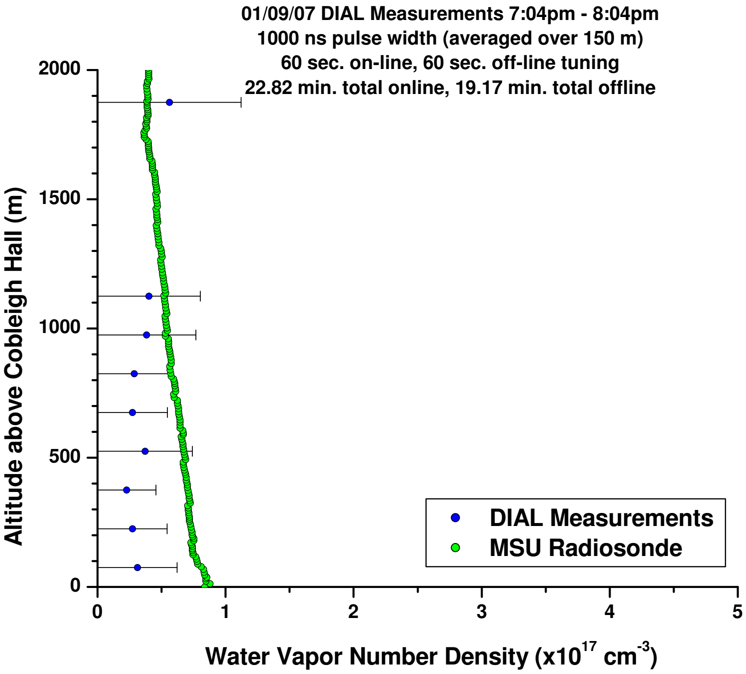

Figure 5. A water vapor profile from the DIAL compared to a MSU radiosonde.

5. CONCLUSION

A compact, low-power differential absorption lidar (DIAL) using a widely tunable diode laser was built, tested, and used to produce profiles of atmospheric water vapor up to an altitude of 2 km above ground level. The transmitter for the DIAL used a external cavity diode laser (ECDL) that was built through the expertise of the laser source development group at Montana State University (MSU) coupled with a commercial tapered amplifier (TA). The ECDL has the capability of tuning across a 17 nm spectrum near 830 nm, giving it access to numerous water vapor absorption lines.

The ECDL was coupled with two cascaded TA's, and used in a vertically-pointing DIAL. The DIAL used an acousto-optic modulator (AOM) to pulse the cw beam from the transmitter. The receiver made use of a commercial Schmidt-Cassegrain telescope with a diameter of 28 cm, an extremely narrow band (NB) filter with a band pass of $\sim$ 250 pm, and a fiber-coupled, photon counting avalanche photodiode (APD) detector, and had a narrow, 150-μrad field of view (FOV). The DIAL system was almost completely autonomously controlled using LabVIEW software and a novel tuning system that quickly tuned the ECDL between the on-line vacuum wavelength of 828.187 nm and off-line vacuum wavelength of 828.287 nm. The tuning mechanism was extensively tested, showing that the laser wavelength could be held stable to within ±88 MHz. The spectral purity was measured to be >0.995, within allowable tolerances.

Pulses with widths of 1.0 μs and energies of ~0.25 μJ , at a repetition rate of 20 kHz, were used to probe the lower troposphere up to 2 km, resulting in water vapor profiles that were compared to co-located radiosonde measurements. The measurements agreed with the radiosonde measurements to within an order of magnitude, with the discrepancies being explainable and potentially fixable in future DIAL modifications. Making these changes to the DIAL would create a second-generation instrument capable of accurate nighttime water vapor profiles up to at least 2 km, and potentially capable of daylight profiles.

This DIAL instrument has demonstrated that low-power DIAL instruments using widely tunable diode laser transmitters, which can be designed at multiple wavelengths, can achieve useful water vapor profiles. The system is robust, can be repaired quickly and relatively easily, compact, and can be made eye-safe, all necessary requirements for an autonomous field or satellite instrument. It is hoped that this DIAL will lead to the development of next-generation, widely tunable DIAL instruments that in the future may be acceptable candidates for use in multi-point lidar networks or satellite arrays to study water vapor flux profiles.

6. ACKNOWLEDGEMENTS

When this research was performed, Michael D. Obland was a graduate student at Montana State University, and was supported through a NASA Graduate Student Research Project (GSRP) Fellowship. He is now a NASA Postdoctoral Fellow at Langley Research Center, administered by Oak Ridge Associated Universities through a contract with NASA. This work was supported by NASA grant No. NNX06AD11G.

REFERENCES

1. J. E. Harries, "Atmospheric radiation and atmospheric humidity," *Quarterly Journal of the Royal Meteorological Society* **123**, pp. 2173–2186, Oct. 1997.
2. J. A. Kington, "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**, pp. 935–936, June 2000.
3. M. J. Rycroft, "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**, pp. 711–712, May 2000.
4. M. D. Obland, K. S. Repasky, J. A. Shaw, and J. L. Carlsten, "Preliminary testing of a water-vapor differential absorption lidar (DIAL) using a widely tunable amplified diode laser source," in *Proceedings of the 23rd International Laser Radar Conference*, C. Nagasawa and N. Sugimoto, eds., pp. 249–252, July 2006.
5. M. D. Obland, L. S. Meng, K. S. Repasky, J. A. Shaw, and J. L. Carlsten, "Progress toward a water-vapor differential absorption lidar (DIAL) using a widely tunable amplified diode laser source," in *Lidar Remote Sensing for Environmental Monitoring VI. Proceedings of the SPIE, Volume 5887*, U. N. Singh, ed., pp. 205–215, Aug. 2005.
6. M. D. Obland, "Water vapor profiling using a highly tunable amplified diode laser differential absorption lidar (DIAL)," *Ph.D. Thesis* , Apr. 2007.
7. K. S. Repasky, A. R. Nehrir, J. T. Hawthorne, G. W. Switzer, and J. L. Carlsten, "Extending the continuous tuning range of an external-cavity diode laser," *Appl. Opt.* **45**, pp. 9013–9020, Dec. 2006.
8. M. D. Obland, A. R. Nehrir, K. S. Repasky, J. L. Carlsten, and J. A. Shaw, "Application of extended tuning range for external cavity diode lasers to water vapor differential absorption measurements," *Optical Engineering* , accepted for publication, 2007.
9. R. M. Schotland, "Some observations of the vertical profile of water vapor by means of a ground based optical radar," in *Proceedings of the Fourth Symposium on Remote Sensing of the Environment*, pp. 273–283, University of Michigan, Ann Arbor, Mich., 1966.
10. R. M. Measures, *Laser remote sensing: Fundamentals and applications*, New York, Wiley-Interscience, 521 p., 1984.

11. V. A. Kovalev and W. E. Eichinger, *Elastic Lidar: Theory, Practice, and Analysis Methods*, New Jersey, Wiley-Interscience, 615 p., 2004.
12. J. Bösenberg, "Ground-Based Differential Absorption Lidar for Water-Vapor and Temperature Profiling: Methodology," *Appl. Opt.* **37**, pp. 3845–3860, June 1998.