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Field deployable diode-laser-based differential absorption lidar (DIAL) for profiling water vapor

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Abstract

A field deployable water vapor profiling instrument that builds on the foundation of the preceding generations of diode-laser-based differential absorption lidar (DIAL) laboratory prototypes has been constructed and tested. Significant advances are discussed, including: a unique shared telescope design that allows expansion of the outgoing beam for eye-safe operation with opto-mechanical and thermal stability, multi-stage optical filtering enabling measurement during daytime bright-cloud conditions, rapid spectral switching between the online and offline wavelengths enabling measurements during changing atmospheric conditions, and enhanced performance at lower ranges by the introduction of a new filter design and the addition of a wide field-of-view channel. Performance modeling, testing and intercomparisons have been performed and are discussed. In general, the instrument has 150 m range resolution with 10 min temporal resolution – 1 min temporal resolution in the lowest 2 km of the atmosphere is demonstrated. The instrument was shown capable of autonomous long term field operation – 50 days with a > 95 % uptime – under a broad set of atmospheric conditions and potentially forms the basis for a ground-based network of eye-safe autonomous instruments needed for the atmospheric sciences research and forecasting communities.

1 Introduction

The planetary boundary layer (PBL), the lowest part of the troposphere, contains the majority of the atmospheric water vapor (hereafter WV). The rapidly changing spatial and temporal distribution of WV influences dynamical and physical processes that drive weather phenomena, general circulation patterns, radiative transfer, and the global water cycle. The ability to continuously measure the WV distribution within the lower troposphere has been identified as a high priority measurement capability needed by both the weather forecasting and climate science communities. In particular, two

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receiver aperture due to the small scattering cross section associated with nonlinear Raman scattering. Furthermore, Raman lidar typically require a calibration technique based on an ancillary measurement for quantitative WV retrievals.

Differential Absorption Lidar (DIAL) is another active remote sensing technique. It utilizes a laser transmitter capable of operating at two closely spaced wavelengths, one wavelength which is located at or near the absorption feature for the molecule of interest, referred to as the online wavelength and the other located away from the same absorption feature, referred to as the offline wavelength. If the online and offline wavelengths are closely spaced, then the only difference between the return signals results from molecular absorption. Having a priori knowledge of the differential absorption cross section of the molecule of interest e.g., via the HITRAN molecular spectral database (Rothman et al., 2009), the ratio of the online and offline return signals over a selected range within the atmosphere is related to the molecular number density. The advantages of the DIAL technique include no calibration or ancillary measurements and a direct retrieval of the WV number density. However, the DIAL technique requires a pulsed laser with high spectral fidelity and frequency agility – capable of operating at two separate wavelengths.

The DIAL technique has been successfully demonstrated for ground-based water vapor profiling based on injection seeded Ti-sapphire laser systems as discussed in Ertel et al. (2005), Bösenberg and Linné (2006), Vogelmann and Trickl (2008) and Behrendt et al. (2010). However there remains a need for a low-cost laser system capable of autonomous operation – which requires eye-safe operation. In the spectral region most commonly used for water vapor DIAL (700 to 950 nm) eye-safety is brought about by low pulse energies and expansion of the laser beam. Initial modeling by Reagan et al. (1993) indicated that low pulse energy, high pulse repetition rate DIAL measurements of WV in the lower troposphere are feasible. This modeling of micro-pulsed DIAL instruments resulted in the initial development of a WV DIAL instrument by Machol et al. (2004) that utilized a distributed feedback (DFB) laser to injection seed a tapered semiconductor optical amplifier (TSOA) to achieve the needed spectral

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fidelity for DIAL measurements. Machol et al. demonstrated nighttime water vapor profiles up to 2.5 km with 30 min integration periods. Building from this initial modeling and instrument development, researchers at Montana State University (MSU) developed a series of diode-laser-based WV-DIAL instruments. The first generation utilized an external cavity diode laser (ECDL) and a passively pulsed amplifier (Nehrir et al., 2009). A second generation instrument achieved a factor of 10–20 greater energy (1–2 μJ) with a pulsed dual stage TSOA in a master oscillator power amplifier (MOPA) configuration (Nehrir et al., 2011). This version provided the first demonstration of daytime water vapor measurements with a diode-laser-based DIAL. A third generation, utilizing a pair of ECDLs connected via a fiber coupled MEMS switch to an improved single stage TSOA achieved an even greater pulse energy of 7 μJ (Nehrir et al., 2012). In all of these versions, the receiver utilized a commercial telescope to direct the collected light to an avalanche photodiode (APD) operating in the Geiger mode. Two narrow-band filters, each with a 250 pm full width half maximum (FWHM) bandpass were used to filter solar background allowing clear-sky daytime measurements to approximately 3 km.

Since the summer of 2011, the researchers at Montana State University (MSU) and the National Center for Atmospheric Research (NCAR) have collaborated to advance and evaluate the capability of the diode-laser-based WV-DIAL technique. In 2012, the MSU third generation WV-DIAL was modified to allow for unattended operations in a laboratory environment; replacing the external cavity diode lasers with more temperature robust distributed Bragg reflector (DBR) lasers, and expanding the beam to be eye-safe at the exit port. The redesigned transmit path for this temporary prototype used a series of large turning mirrors to reflect the expanded eye-safe beam into the receiver field-of-view and was subject pointing instability with environmental temperature fluctuations. Nevertheless, the modified prototype was field tested over a wide range of atmospheric conditions to evaluate its performance. The evaluation indicated that the technology was well-suited for autonomous, long term measurements of water vapor; however, as noted in Repasky et al. (2013), improvements to the instrument

were needed to achieve continuous atmospheric coverage – particularly during bright cloud conditions and at lower ranges.

In this paper – having addressed the needed advancement in performance given by Repasky et al. (2013) – a next (fourth) generation diode-laser-based WV-DIAL is presented which is capable of autonomous long term field operation under an expanded set of atmospheric conditions. Major improvements with respect to the older versions of the system are discussed and include

- a unique shared telescope design that allows expansion of the outgoing beam for eye-safe operation with mechanical and thermal stability
- improved performance during daytime and cloudy conditions by introducing a high finesse etalon into the receiver optical train
- improved performance during rapidly changing atmospheric conditions through increased switching rates between the online and offline wavelengths, and
- improved performance at short range by the introduction of a near-range, wide field-of-view, channel.

This paper is organized as follows. Section 2 contains a complete description of the instrument highlighting differences between the 3rd and 4th generations. A performance model of the diode-laser-based WV-DIAL instrument is presented in Sect. 3. In Sect. 4, field data and inter-comparisons are presented from when the instrument was operated at the Boulder Atmospheric Observatory (NOAA Physical Sciences Division, 2014) during the Front Range Air Pollution and Photochemistry Experiment (NCAR Atmospheric Chemistry Division, 2014) between 1 July 2014 and 19 August 2014. Data from this field campaign are presented to demonstrate the capability of the WV-DIAL to provide continuous water vapor profiles for extended periods of time in a variety of atmospheric conditions. Furthermore, data collected during this observation period are used to validate the instrument performance model described in Sect. 3. Some brief concluding remarks are presented in Sect. 5.

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2 Description of the field prototype

The instrument, shown schematically in Fig. 1, utilizes a diode-laser-based MOPA configured transmitter capable of rapid wavelength switching (red shading), a shared telescope transmitter and receiver to achieve opto-mechanically stable eye-safe operation (purple shading), and a multi-stage filtered two channel receiver for the near and far range returns (blue shading). The system parameters are outlined in Table 1.

2.1 Laser transmitter

The laser transmitter utilizes two DBR laser diodes, one operating at the online wavelength (828.2 nm) and the other operating at the offline wavelength (828.3 nm) These lasers operate in the continuous wave (cw) mode, produce up to 80 mW of power, and have a measured linewidth less than 1 MHz. The output from each diode is collimated using an aspheric lens and passes through a Faraday isolator to prevent unwanted feedback from affecting the power output and spectral stability. This seed laser light is then fiber coupled to allow for splitting and switching prior to pulsed amplification in the TSOA.

The third generation WV-DIAL instrument used a fiber coupled MEMS switch to alternate between the online and offline wavelength which exhibited a 1 ms 10/90 switching time as discussed in Nehrir et al. (2012). The data acquisition system utilized a single channel of a four channel scaler photon counting card which had 2 buffers to allow for continuous read and write operations to occur. To avoid mixing the signals within the data acquisition system – one laser frequency was transmitted for 3 s, followed a 3 s dead time when the wavelength switch was changed, then the other laser frequency was transmitted for 3 s. This switching method worked well, but it created several performance limitations. First, the dead time resulted in a 60 % duty cycle (i.e., the reported water vapor integration time of 20 min was equivalent to a 33 min temporal resolution). Second, wavelength switching on timescales of several seconds can result in errors due to decorrelation between the online and offline signals from fluctuations in

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the backscatter coefficient as discussed in Wulfmeyer and Walther (2001a). Therefore, the next generation instrument was designed to use faster optical switches – electro-optic-based components capable of 100 ns 90/10 switching times. The new switching method – combined with RF switches in the receiver (details in the receiver section to follow) – allows the instrument to run at nearly 100 % duty cycle and thereby enables a significant improvement in temporal resolution. A pair of fast optical switches are used for each wavelength; a 1×1 switch is used to turn on the cw seed lasers only when the TSOA current is applied and a 2×1 switch is used to alternate the modulated online and offline seed signals to the TOSA at high repetition rates. The switches were connected as shown in Fig. 1. This two-stage optical switch arrangement provides 40 dB isolation between the online and offline (each switch has 20 dB crosstalk) to maintain a high spectral purity in the transmitted pulses. The instrument has typically operated with the two wavelengths interleaved at 60 to 100 Hz.

The TSOA stage for this instrument is the same as in its third generation predecessor (Nehrir et al., 2012). The output of the seed laser delivery fiber is collimated and passed through a Faraday isolator. A half waveplate is used to set the polarization needed by the TSOA. This light is incident on an aspheric lens and focused into a 4 mm long TSOA used to amplify and pulse the laser transmitter. The TSOA is driven with a commercial pulsed current driver (Directed Energy, Inc, PCX-7420) with a programmable pulse duration, pulse repetition rate, and peak pulse current. Standard setting for this instrument used a pulse current of 10 A with a 1.1 μ s pulse duration and a 9 kHz pulse repetition frequency. The pulsed current driver is used as the master clock for the DIAL instrument. The leading edge of the current pulse to the TSOA is used to simultaneously trigger the 1×1 switches, the I/O digital counter (which in turn triggers the 2×1 switch and RF switches in the receiver), and the multichannel scaler card (MCS). Therefore, although a 1.1 μ s current pulse is applied to the TSOA, the resulting amplified laser pulse has a 900 ns duration due to the 200 ns rise time of the 1×1 switch driver. Because of the astigmatic geometry of the output facet of the TSOA, the output requires a beam shaping pair of lenses (spherical and cylindrical) to achieve

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would require oversight and compliance with Federal Aviation Administration (FAA). The ANSI regulation sets the single-pulse maximum permissible exposure (MPE) for a 1 μ s duration pulse at the 830 nm wavelength at 900 nJ cm^{-2} (from Table 5a in Z136.1-2007). A repetitively pulsed lidar system must be less than both the multiple energy and multiple power MPEs – which for this system, operating at the 9 kHz repetition rate, is 52.0 nJ cm^{-2} and 0.47 mW cm^{-2} ; respectively. For eye-safety at the exit port (i.e., a 0 m range MPE), the TSOA amplified beam was expanded 2 \times , shaped with an axicon pair, and expanded an additional 20 \times with the shared receiver optics. The 1/e diameter was measured before the axicons and telescope expansion to be 5.7 mm. After the 20 \times telescope expansion, the transmitted beam has an effective diameter of 114 mm (180 mm diameter with a 70 mm hole.) The entire transmitted beam area was checked with a 1 cm \times 1 cm square calibrated detector to verify the 0.47 mW cm^{-2} MPE was not exceeded.

2.3 Optical receiver

Light scattered in the atmosphere is collected by the telescope and is incident on the 60 mm focal length lens which collimates the light collected from infinity. The received light is then incident on the elliptic mirror with the bored hole. This mirror only collects light from a diameter of greater than 200 mm at the primary mirror of the telescope, providing excellent isolation from the transmitted beam. The ability of the receiver to discriminate signal photons against a bright background requires a state-of-the-art multi-stage filter that suppresses the background while minimally affecting the signal. This is a difficult task during daytime and cloudy conditions where the high background signal can easily saturate the photon counting detector. For this instrument, the background suppression is achieved through a combination of interference filters and an etalon. The passband of the filters, etalon, and the combined far-range filter-etalon passband are shown in Fig. 2. Figure 2a shows the transmission curve for the 500 pm (blue) and 750 pm (black) FWHM bandpass filters. The transmission of the 750 pm filter remains relatively constant between 828.2 and 828.4 nm to both maximize the online

and offline throughput while minimizing angle tuning effects for the filter transmission at lower ranges that can affect the accuracy of the number density retrieval as discussed in Nehrir et al. (2009) and Wulfmeyer and Bösenberg (1998). Figure 2b shows the etalon transmission measurements and a fit to the data based on

$$T_{\text{etalon}} = \frac{(1 - R)^2}{1 + R^2 - 2R \cos \theta} \quad (1)$$

where, R is the etalon mirror reflectivity, and $\theta = 4\pi \frac{nL}{\lambda}$ is the round trip phase accumulation. The free spectral range (FSR) of the etalon is related to the optical cavity spacing by $\text{FSR} = \frac{c}{2nL}$ and was measured to be 0.0994 nm (43.3 GHz). The etalon was designed to allow transmission of the online and offline radiation in adjacent cavity modes. The finesse (F) of the etalon is related to the mirror reflectivity by $F = \frac{\pi\sqrt{R}}{1-R}$ yielding a finesse of $F = 43$. Figure 2c shows the combined passband for the far range receiver channel including both interference filters and the etalon.

The etalon is housed in a temperature controlled mount that integrates with the tube assembly housing of the receiver optics. A change in temperature of 22.4 °C is needed to tune the etalon through a full free spectral range. The operating temperature of the etalon is controlled via a thermoelectric cooler (TEC) using a commercial temperature controller with a temperature stability of 0.01 °C. The operating temperature of the etalon is adjusted to be resonant with the transmitted wavelengths. A plot of the resonant wavelength as a function of temperature is shown in the left panel of Fig. 3. The black circles represent measured values and the red line represents a linear fit showing a temperature tuning rate of $d\lambda/dT = 0.00441 \text{ nm}^\circ\text{C}^{-1}$. A plot of the cavity transmission as a function of finesse is shown on the right panel of Fig. 3. The locking stability of the injection seeding laser and the temperature stability of the etalon affects the etalon transmission. The effects of the locking stability on the cavity transmission can be modeled using the above equation with $\theta = \pi \frac{\Delta\lambda}{\text{FSR}_\lambda}$ where $\Delta\lambda$ is the detuning from the resonant peak in wavelength, and FSR_λ is the free spectral range in wavelength. The temperature stability of the etalon can be modeled using the measured

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temperature tuning rate, $d\lambda/dT$, through the above equation as well with $\theta = 2\pi \frac{d\lambda/dT \Delta T}{FSR_1}$ where $T = 0.01^\circ\text{C}$ is the temperature stability for the etalon.

Following the filters 90 % of the received light is directed to a narrow field-of-view (FOV) fiber coupled detector module and 10 % of the light to a free space receiver using a beam-splitting cube (as shown in Fig. 1). The light transmitted through the beam-splitting cube is incident on a 20 mm focal length lens focusing it onto a free-space avalanche photodiode (APD). The active area of the APD acts as the field stop resulting in a $451\ \mu\text{rad}$ field-of-view. The light reflected from the beam-splitting cube passes through an interference filter with a 500 pm FWHM passband (passband is shown as the blue curve in Fig. 2a). The diameter of the beam is reduced approximately $4 \times$ with a beam reducing pair of optics (80 mm and 19 mm local length; respectively) to not exceed the numerical aperture (NA) of the fiber then focused with an 11 mm focal length lens into an multimode optical fiber with a $105\ \mu\text{m}$ core diameter and a NA of 0.22. The optical fiber acts as the field stop producing a FOV of $115\ \mu\text{rad}$. The optical fiber guides the received light to a fiber coupled APD.

For each detector module, full overlap occurs when the image of transmitted beam diameter is less than the diameter of the field stop. As shown in Fig. 4 the narrow field-of-view receiver (far range channel) has full overlap at ranges greater than 2.75 km, whereas the wide field-of-view receiver (or near range channel) achieves full overlap at approximately 700 m. The collected light has a r^{-2} dependence therefore the near range channel will have a larger signal at low ranges. However, it will also have substantially higher noise during daytime as it collects 16 times more background light compared to the far channel (solid angle $\propto \text{FOV}^2$). Thus only the lowest range gates of the wide field-of-view channel are useful during daytime. As discussed later, this receiver channel is most useful when operating the instrument at short temporal and spatial resolutions (e.g., 1 min and 75 m; respectively).

2.4 Data acquisition and post processing

The output signal from the photon detection modules are connected to RF switches as shown in Fig. 1. The RF switch is used to separate the signals generated from the photon counting module between the online and offline transmitted laser pulses so as to eliminate the buffer crosstalk problem previously mentioned for the third generation system. A digital I/O counter tracks the number of pulses from the current pulse driver and sends a TTL state change to the pair of RF switches after a prescribed number of pulses are counted at each wavelength. In the standard configuration, the current pulse generator operates at 9 kHz, so there are 150 pulses at each wavelength with 60 Hz switching. The outputs of each RF switch are connected to two separate channels on the MCS. For near and far range all four channels of a 20 MHz MCS (Sigma Space Corporation) are used. 10 000 samples are accumulated with a bin duration of 500 ns and 220 bins for a maximum range of 16.5 km with 1.1 s acquisition time. The approximate 1 μ s pulse duration is over-sampled by the MCS, yielding 2 data points per 150 m, which corresponds to a sampled vertical range resolution of 75 m. The summing of these 75 m bins is performed during postprocessing where 2 bins are grouped together to yield a 150 m range resolution for the DIAL measurement.

Note that the large number of scattered photons from the outgoing pulse prohibits measuring the atmospheric return during the initial 1.1 μ s (i.e., while the current pulse is applied to the TSOA). Therefore, in the standard operational configuration, the lowest usable range gate is 225 m. However the current driver is easily reconfigurable so, for example, if it were programed for a 500 ns duration pulse, the lowest usable gate could be reduced to 75 m range. The amplified laser pulse would be 300 ns in duration with roughly 1/3 of the energy per pulse.

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3 Model performance of a photon counting DIAL

In what follows, we consider a photon counting DIAL system. The precision of the water-vapor measurement can be estimated by the propagation of independent error in the DIAL equation given by

$$n_{\text{wv}}(r) = \frac{1}{2\Delta r(\sigma_{\text{on}}(r) - \sigma_{\text{off}}(r))} \ln \left[\frac{N_{\text{on}}(r)}{N_{\text{on}}(r + \Delta r)} \frac{N_{\text{off}}(r + \Delta r)}{N_{\text{off}}(r)} \right] \quad (2)$$

where n_{wv} is the number density of water vapor, Δr is the range bin size, σ is the absorption cross section at the online and offline wavelength (subscripts on, and off; respectively), and N is number of online and offline (subscripts on, and off; respectively) backscattered photons received.

The number of signal counts is given by

$$N_{\text{s}}(r, \lambda) = \frac{E\lambda A_{\text{r}}}{2h r^2} (\beta_{\text{a}}(r) + \beta_{\text{m}}(r)) \eta_{\text{r}} \eta_{\text{d}} O(r) \left[\exp \left(-2 \int_0^r (\alpha_{\text{a}} + \alpha_{\text{m}} + (\sigma(r, \lambda)) n_{\text{wv}}) dr \right) \right] \quad (3)$$

where E is the pulse energy of the laser, λ is the laser wavelength, h is the Planck constant, A_{r} is the area of the receiver telescope, β is the backscatter coefficient for aerosol and molecular (subscripts a and m; respectively), η is the efficiency of the receiver and detector (subscripts r and d; respectively), $O(r)$ is the overlap function, α is the extinction coefficient of the aerosol, molecular and water vapor (subscripts a, and m; respectively).

The number of background counts is given by

$$N_{\text{B}} = S_{\text{b}} \Omega_{\text{r}} \Delta_{\text{f}} A_{\text{r}} \eta_{\text{r}} \eta_{\text{d}} \frac{\lambda}{hc} \quad (4)$$

where S_{b} is the sky radiance, Ω_{r} is the receiver field-of-view solid angle, Δ_{f} is filter bandpass width, A_{r} is the area of the receiver telescope, η is the efficiency of the receiver and detector, and c is the speed of light.

The DIAL random error is given by

$$\sigma_n = \frac{1}{2\Delta r(\sigma_{\text{on}}(r) - \sigma_{\text{off}}(r))n_{\text{wv}}} \frac{1}{mk} \left[\frac{N_{\text{S.on}}(r) + N_{\text{B}}}{N_{\text{S.on}}(r)^2} + \frac{N_{\text{S.on}}(r + \Delta r) + N_{\text{B}}}{N_{\text{S.on}}(r + \Delta r)^2} + \frac{N_{\text{S.off}}(r) + N_{\text{B}}}{N_{\text{S.off}}(r)^2} + \frac{N_{\text{S.off}}(r + \Delta r) + N_{\text{B}}}{N_{\text{S.off}}(r + \Delta r)^2} \right]^{0.5} \quad (5)$$

where m is the number of range averages, k is the number of samples/profiles averaged for the online wavelength (assumes a 50 % duty cycle), σ_{on} is the online absorption cross section, σ_{off} is the offline absorption cross section, and Δr is the range bin size. It should be noted that the equation assumes the time transmitting and receiving the online and offline wavelengths are equal. However, asynchronous wavelength switching – spending more time transmitting and receiving the online wavelength – could provide an enhancement in performance.

This random error equation can be used to provide performance estimates for a diode-laser-based WV-DIAL. The performance estimate includes the instrument parameters given in Table 1, the atmospheric parameters summarized in Table 2, overlap functions shown in Fig. 4, and the backscatter coefficients and water vapor number density shown in Fig. 5.

The expected instrument performance for day and night conditions with a 10 min integration time and 150 m range resolution is shown in Fig. 6. Using 5 % error as a target, the maximum range of the instrument is expected to vary from about 4.5 to 5.5 km from day to night; respectively. At these spatial and temporal resolutions, the near channel would provide a redundant measurement extending to about 3 km range except during periods of bright clouds where the count rate in this channel would exceed the linear count rate of the photon counting module. The maximum range can be marginally increased by tuning the online wavelength to provide a lower column optical depth (OD) although this introduces more error close to the ground. A more effective method is to process the data above the boundary layer with a larger range bin size. As shown

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in Fig. 7, a two-way column OD of 0.6 and range bin of 600 m increases the maximum range of the instrument to about 7 km for a 5 % error.

A practical limit to the maximum range for the ground-based DIAL results from the small differential optical depth associated with the water vapor absorption in the free troposphere. The differential optical depth, $\Delta\tau$, needed to retrieve the water vapor number density (Wulfmeyer and Walther, 2001a) is $\Delta\tau = n\sigma_{\text{on}}\Delta R \approx 0.03\text{--}0.1$, where n is the water vapor number density, σ_{on} is the absorption cross section at the online wavelength, and R is the range bin size. For a maximum range bin size of 1 km, the maximum range at which the water vapor profile can be retrieved approaches 7 km.

Figure 8 shows the model results for a case with higher temporal and spatial resolution. For low level boundary layer studies, the instrument could be operated with a resolution of 75 m and 1 min as the near and far range channels could be combined to provide < 5 % error for the lowest 1.75 km. For a 75 m pulse length the duration of the TSOA current pulse would be reduced in half, from 1000 to 500 ns resulting in a pulse energy 2.6 μJ . It is possible that the pulse energy could be increased from the standpoint of eye-safety restrictions; however, a conservative TSOA pulse current of 10 A was assumed constant for this case. Any dataset can be processed to high temporal resolution a posteriori however reducing the pulse duration, and subsequently the power, to achieve higher spatial resolution needs to be considered more carefully.

4 Data examples and intercomparisons

The fourth generation diode-laser-based DIAL was constructed at the NCAR lab in Boulder, CO in four phases between October 2013 and June 2014, implementing (1) the shared telescope, (2) two channel receiver, (3) fast switching transmitter and receiver, and (4) the optimization of the background suppressing filters and etalon. During the 8 month period of development the instrument was run almost continuously with sonde comparisons done at each stage of the development. The completed instrument was moved to the Boulder Atmospheric Observatory (BAO) for operation

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during the Front Range Air Pollution and Photochemistry Experiment (FRAPPE) between 1 July 2014 and 19 August 2014. Data from this field campaign are presented to demonstrate the capability of the WV-DIAL in continual operation for an extended period of time in a variety of atmospheric conditions.

For the results in this paper, the Voigt differential absorption cross section of the water molecule was calculated from parameters contained in the 2008 High-Resolution Transmission (HITRAN) molecular spectroscopic database (Rothman et al., 2009). Spectral parameters for the H(16)OH molecule from 815 to 841 nm (1017 spectral lines in total) were used from the database to calculate the absorption cross section at the online and offline wavelengths. The numerically calculated Voigt absorption cross section is a convolution of the Lorentz and Doppler line shapes which are a function of temperature and pressure. A standard atmosphere with surface $T = 25^{\circ}\text{C}$ and $P = 0.83\text{ atm}$ was used to correct the temperature and pressure dependent terms as a function of range. The previous MSU WV-DIAL prototypes used the HITRAN 2000 database parameters. For those reported results (Nehrir et al., 2009, 2011, 2012; Repasky et al., 2013), only the main absorption line at 828.187 nm was corrected for the air pressure shift. The updated version of the database includes a parameter to correct for the air broadened pressure shift of each line. The pressure shift corrections and other updated line parameters included the 2008 database should provide more accurate results.

For the previous generations of MSU WV-DIAL prototypes, sonde comparisons were made for both day and night conditions as shown in Nehrir et al. (2009, 2011, 2012) and Repasky et al. (2013). However these instruments switched from online to offline at timescales of several seconds and could suffer from insufficient background suppression during daylight bright-cloudy sky conditions. This made it difficult to achieve continuous water vapor measurements. Therefore, an important goal of this research effort was to demonstrate a next generation instrument with the capability to make accurate continuous water vapor measurements during a broadened range of atmospheric conditions. Sondes were released at the BAO in close proximity to the WV-DIAL instrument

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4 km for the far-range channel. For this predominantly daytime set of comparisons, the near range channel provides a slightly lower error below 500 m range. The SD is $\approx 10\%$ about the mean at the surface and increases to $\approx 20\%$ at 1.5 km for the near-range channel and 4 km for the far-range channel. A small number of comparisons were greater than $3 \times$ SDs and were removed as outliers from the calculation of the mean. There are several potential reasons for discrepancies between the absolute humidity measured by the WV-DIAL and the radiosondes. The sondes inevitably drift with the wind as they rise and are generally not in close proximity to the lidar beam. Spatio-temporal matching was not employed at this phase in the analysis such as done in Vogelmann et al. (2011). Additionally, a strong wet-bias often occurs in the WV-DIAL at the cloud edges which is not filtered out in the current post-processing – as evidenced in the time vs. height profiles shown in Fig. 9. These spatially localized biases can dominate the statistics given the relatively small number of comparisons. More work will be done to remove these small regions of bias in the future. And finally, there may be systematic instrument bias or errors within the HITRAN 2008 molecular spectroscopic database parameters used to calculate the differential absorption cross section of the water molecule. To improve performance, detailed studies of the molecular spectroscopic parameters have been performed for other DIAL systems – such as those presented by Grossmann and Browell (1989), Lisak et al. (2009) and Ponsardin and Browell (1997) – and may be required to improve the accuracy of this system. With these caveats, it seems reasonable to claim that the measurements of water vapor provided by the WV-DIAL agree well (with less than 10 % mean error) with the radiosonde measurements of water vapor over a wide range of atmospheric conditions.

The instrument was operated unattended for 50 continuous days during the FRAPPE field campaign from a mobile laboratory container with approximately $\pm 5^\circ\text{C}$ temperature stability. The device was aligned once (at setup only) and there was no detectable degradation in performance during the project or evidence of temperature cycling in the data. The instrument operated reliably – providing $> 95\%$ data coverage. A subset – a two week period from 1–14 July 2014 – of near continuous data is shown as Fig. 11.

The top panel shows the relative backscatter at 1 min, 150 m vertical resolution from 0 to 14 km range. The image is a composite of the near and far range channels below 3 km and the far-range channel only above 3 km. The second panel from the top shows the measured absolute humidity in g m^{-3} at 10 min, 150 m vertical resolution from 0 to 7 km range (data from the near-range channel). This unique image of the water vapor distribution in the lower atmosphere is only possible with high vertical-resolution continuous profiling. The second panel from bottom shows the measured two-way column optical depth at 2.5 km (blue) and 5.0 km (black) range for the far range channel for this time period. The wavelength of the instrument was not adjusted for this time span so this is representative of the natural atmospheric variability and can be converted to a water vapor column content and used to compare with other instrumentation. The bottom panel shows the measured background in counts per second (C s^{-1}) for the near (red) and far (black) range channels. To measure water vapor accurately, the photon count rates need to be within the linear response range of the photon counting modules – below 5 MC s^{-1} for the modules used in this instrument. As seen in the plot, the far range channel has a maximum count rate of 1 MC s^{-1} during the brightest of atmospheric conditions. This is a significant improvement over the previous generation receivers where the count rate would be in excess of 10 MC s^{-1} under daytime cloudy conditions as shown in Fig. 9 of Repasky et al. (2013). The near range channel, with its wide field-of view and one less filtering stage, approaches 100 MC s^{-1} under these bright conditions and is not capable of accurately measuring water vapor during these time periods.

At FRAPPE the diode-laser-based WV-DIAL was co-located with several active and passive remote sensing instruments. A quantitative comparison between other instruments is beyond the scope of this instrument paper. However a detailed intercomparison study highlighting the different spatial and temporal resolutions between the WV-DIAL and the AERI using the FRAPPE dataset is planned for a separate paper. In the future, more effort is needed on improved algorithms to process the data (e.g., masking the data at cloud boundaries, improving low signal-to-noise thresholds,

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allowing for variable temporal and spatial resolution with range, etc.). Also, real-time algorithms are desired to adjust the online wavelength (and corresponding offline and etalon temperature) to maintain optimal optical depth and performance for extended autonomous field operations. Tests should be performed at shorter pulse duration to

investigate reducing the lowest usable gate a.g.l. to below 300 m. Currently the transmitter is capable of higher output power and is limited by eye-safety regulations – the shared transmit-receive path could be redesigned (albeit with some added complexity) to allow the beam to be expanded to the full telescope diameter which would allow higher output power and improved performance. Also asynchronous wavelength switching could be tested as a means to improve performance without increasing the transmitted power level. The near-range channel could be modified to have a slightly reduced field-of-view to avoid non-linear detector response at high count rates during bright cloud conditions. And finally, a more portable environmental enclosure should be designed and constructed to make fielding the instrument easier and less costly in the future.

5 Conclusions

A field-deployable, high-vertical-resolution water vapor profiling instrument has been constructed and tested. It was built on the success of previous diode-laser-based prototypes and advances the technology to provide measurements over a broadened range of atmospheric conditions. The opto-mechanically stable, eye-safe design provides improved temporal resolution, reduced errors at short range, improved daytime performance, and reduced errors when clouds are present. This next-generation water vapor profiler has been demonstrated to be capable of reliable operation in the field, and shown to provide data that compares favorably with sondes over a wide range of atmospheric conditions. The instrument has the potential to provide a priority observation needed for national mesoscale weather observation networks, the National Weather Service and other federal agencies. The demonstrated performance

and reliability suggest that this technology may be suitable for a future network of water vapor profiling instruments.

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Table 1. Instrument parameter list.

Seed lasers	2 DBR diode lasers at 140 mA
Amplifier	single stage TSOA
Pulse duration	1 μ s (10 A)
Transmitted pulse energy	5 μ J
Pulse repetition rate	9 kHz
Max range	16.5 km
Laser wavelength	830 nm
Transmitted beam M2	2 \times 6
Laser divergence	56 μ rad
Transmitted beam diameter	114 mm effective (axicon shaped to 180 mm with 70 mm hole)
Transmitted geometry	shared telescope
Telescope type	<i>f</i> /3 Newtonian
Telescope diameter	406 mm
Area of the receiver	935 cm ²
Field-of-view, FOV	115 μ rad (far channel), 451 μ rad (near channel)
Detector active area diameter	105 μ m diam. fiber coupled (far channel), 180 μ m diam. free space (near channel)
Photon detector module	20 ns dead time (< 5 Mcs ⁻¹), saturation at 40 Mcs ⁻¹
Quantum efficiency of detector	0.45
Efficiency of the receiver	0.23 (far channel), 0.04 (near channel)
Daylight blocking filters	750 pm two-cavity interference filter (far and near) 2.5 pm fringe etalon plus (far and near) 500 pm two-cavity interference filter (far only)
Combined filter width (FWHM)	20 pm (near), 14 pm (far)
Online-offline switch speed (type)	0.3 μ s (ElectroOptic)
Online-offline switching rate	100 Hz
Photon counting	multi-channel scaler card (four channel output)
Data collection duty cycle	100 %
Data collection rate	1.1 s
Water vapor averaging time	1–10 min (typical)
Online and offline wavelength locking	± 0.05 pm (absolute Accuracy ± 0.2 pm with ± 0.03 pm repeatability)

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Table 2. Model atmosphere parameters used to calculate the performance.

Daytime sky radiance	$1.15 \times 10^{-3} \text{ W cm}^{-2} \mu\text{m}^{-1} \text{ sr}^{-1}$
Aerosol lidar ratio	50 sr
Molecular lidar ratio	$8/3\pi$ sr
Molecular backscatter coefficient	Fig. 5 (left panel)
Aerosol backscatter coefficient	Fig. 5 (left panel) data from Vaughan et al. (1995)
Water vapor concentration profile	Fig. 5 (right panel) data from Wulfmeyer and Walther (2001b)

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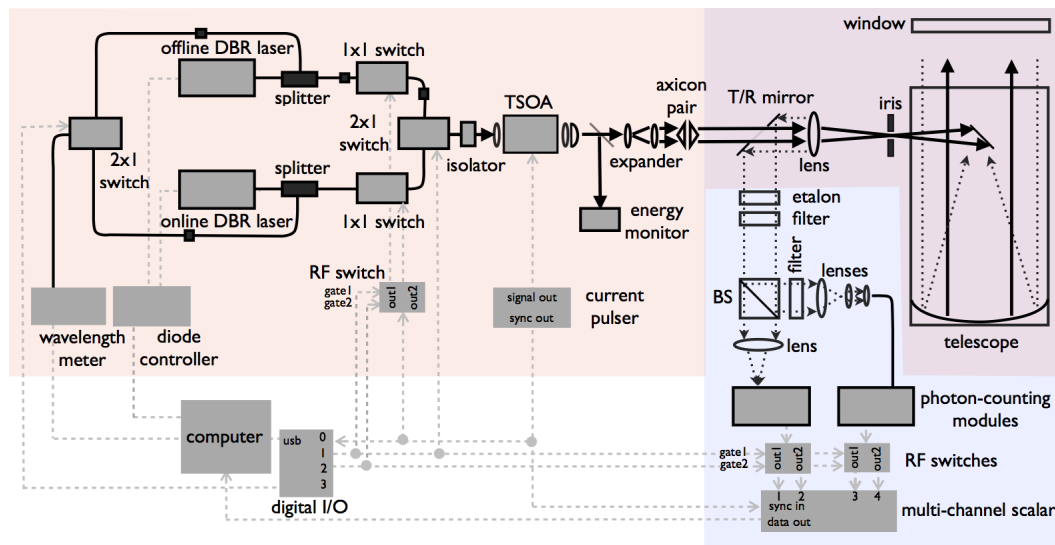


Figure 1. Schematic of the WV-DIAL system. BS = beam-splitter; T/R = transmit receive; I/O = input output.

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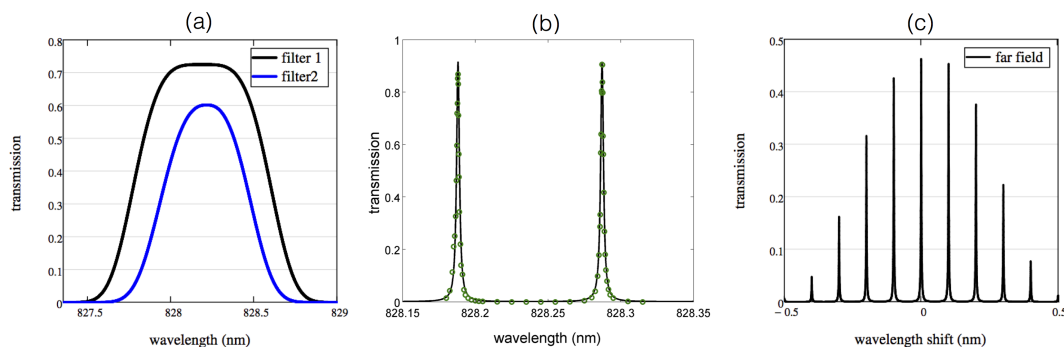


Figure 2. The multi-stage optical filtering enabling measurement of water vapor during daytime bright-cloud conditions. **(a)** shows the interference filter transmission as a function of wavelength. The solid black (blue) line is a fit to the measured filter transmission for the FWHM bandpass of 750 pm (500 pm). A double cavity design was used for both filters to provide a more flat passband. The wider filter is common to both the near and far range channels while the narrower filter is used only in the far range channel. **(b)** shows the etalon transmission as a function of wavelength. The green circles represent measured values while the solid black line represents a fit. **(c)** shows the combined passband for the far range channel including both interference filters and the etalon.

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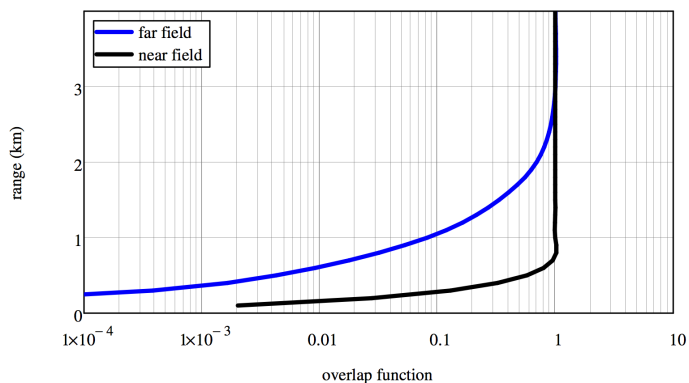


Figure 4. Overlap function for the far and near range receiver channels calculated from an optical model of the instrument.

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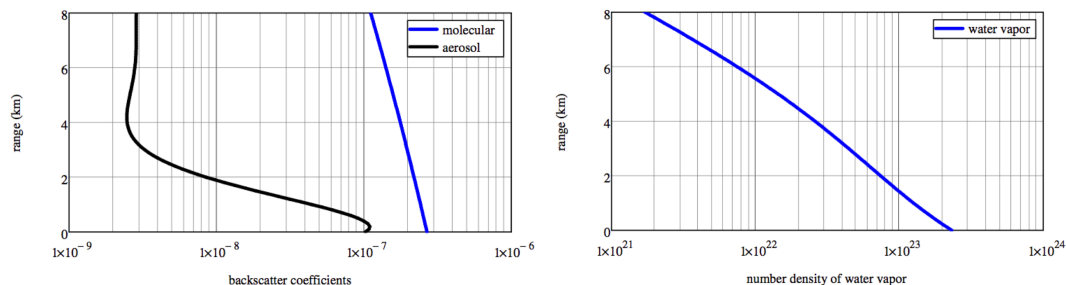


Figure 5. Backscatter coefficients (left panel) and water vapor number density (right panel) used in the performance model.

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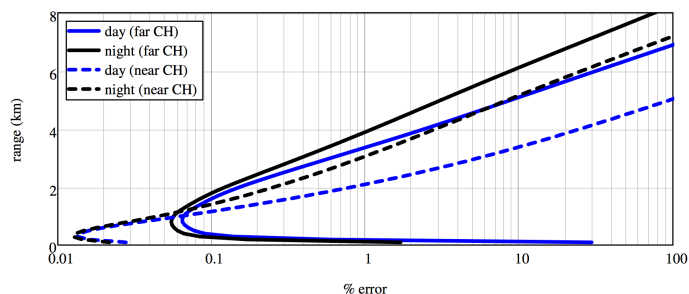


Figure 6. Performance estimate for day and night with 150 m range resolution for the near and far range channels for an online column OD of 1.5. For a 5 % error, the instrument has a maximum daytime range of ≈ 5 km.

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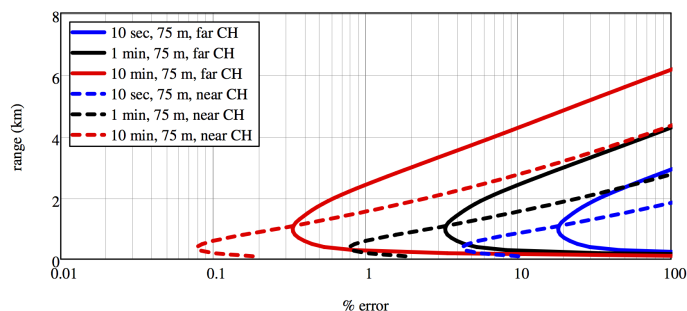


Figure 8. Daytime performance estimate in % error for temporal resolutions of 10 s, 1, and 10 min with a spatial resolution of 75 m for an online column OD of 1.5. The pulse energy is half – $2.6 \mu\text{J}$ – for this case because of the shorter pulse duration. These model results indicate that 1 min, 75 m resolution may be useful for boundary layer studies.

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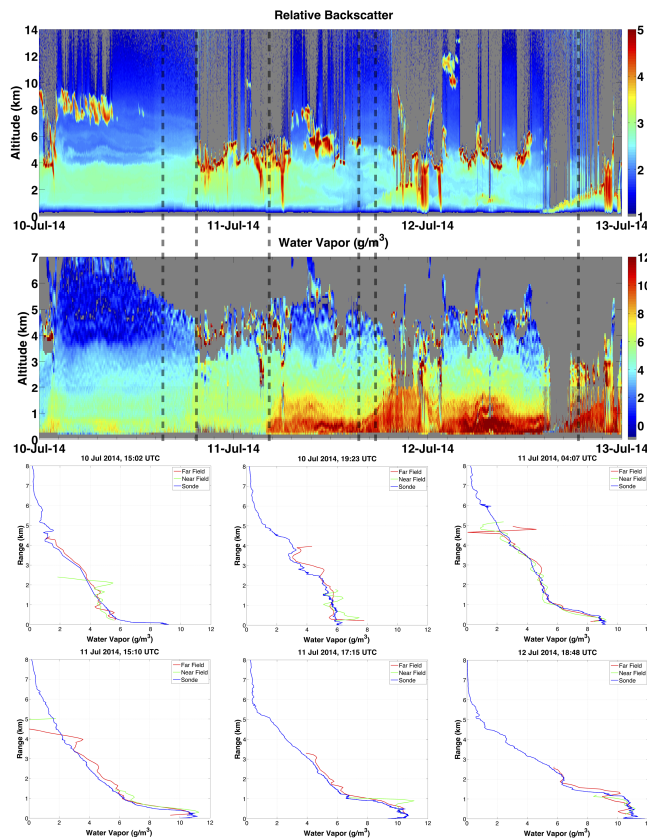


Figure 9. Top panels: 1 min, 150 m resolution relative backscatter from 0–14 km range; bottom panels: 1 min, 150 m resolution water vapor in g m^{-3} from 0–2 km range, and 10 min, 150 m resolution from 2–7 km. Far range channel. The dashed black lines indicate times when the sondes were launched. The individual water vapor concentration profiles are shown on the bottom for the sonde (blue), far range (red) and near range channel (green) in g m^{-3} .



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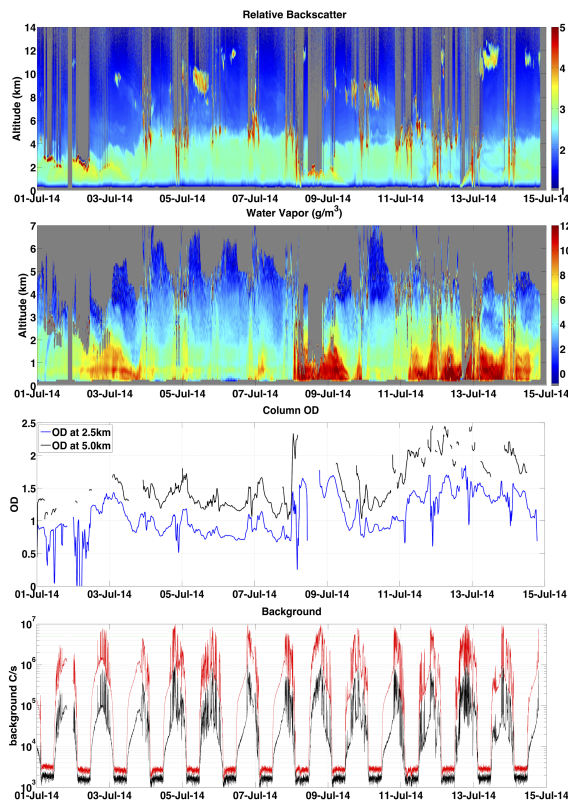


Figure 11. Two weeks of near continuous data collected 1–14 July 2014. Top panel: 1 min, 150 m resolution relative backscatter from 0 to 14 km range for the far range channel; second panel from top: 10 min, 150 m resolution water vapor in g m^{-3} from 0 to 7 km range for the far range channel, second panel from bottom: measured two-way optical depth at 2.5 km (blue) and 5.0 km (black) range for the far range channel; and bottom panel: background in counts per second (C s^{-1}) for the near (red) and far (black) range channels.