

DEVELOPMENT OF AN EYE-SAFE DIODE-LASER-BASED MICRO-PULSE
DIFFERENTIAL ABSORPTION LIDAR (MP-DIAL) FOR ATMOSPHERIC WATER-
VAPOR AND AEROSOL STUDIES

by

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of

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Amin Reza Nehrir

July, 2011

DEDICATION

To Grandma,

for being strong when nobody else could. You are my guiding light.

To my best friend Jamie,

for wonderful times together and more importantly for your constant support when the end was nowhere in sight.

To my family,

for your love and support over the many years it took to finish this long journey.

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ABSTRACT

This dissertation describes the design, construction, and testing of an all diode-laser-based water-vapor differential absorption lidar (DIAL) instrument through two distinct stages of development. A second generation low pulse energy, high pulse repetition frequency DIAL instrument was developed to overcome the power limitations of the first generation instrument which required unrealistic integration times approaching 1 hour. The second generation DIAL transmitter used a custom built external cavity diode laser (ECDL) as the seed source for an actively current pulsed tapered semiconductor optical amplifier (TSOA), yielding a maximum output transmitter pulse energy of 2 μJ over a 1 μs duration pulse width at a 20 kHz pulse repetition frequency, decreasing the required integration Period to approximately 20-30 minutes. Nighttime and daytime water-vapor profiles were collected with the second generation DIAL instrument which showed good agreement with collocated radiosonde measurements from near the surface up to the top of the planetary boundary layer. Aerosol optical properties were also measured using the calibrated offline channel returns using the iterative Fernald solution to the lidar equation.

Most recently, a third generation DIAL transmitter has been developed to further increase the output pulse energy and to also decrease the DIAL atmospheric spectral sampling time. Two custom built high power ECDL's and an electro-mechanical based fiber optic switch are used to sequentially seed a single stage actively current pulsed TSOA in order to minimize the systematic errors introduced in the DIAL retrievals resulting from air-mass miss-sampling between the two DIAL wavelengths. Peak output pulse energies of 7 μJ have been measured over 1 μs pulse durations at a 10 kHz pulse repetition frequency with a 1-6 second DIAL spectral switching time, further decreasing the total required integration period to 20 minutes for both nighttime and daytime operation. The increased performance of the third generation transmitter has allowed for nighttime and daytime water vapor profiling under varying atmospheric conditions that shows good agreement with collocated radiosonde measurements up to ~ 6 km and ~ 3 km, respectively. A detailed description of the second and third generation DIAL instrument performance as well as data retrievals are presented in this dissertation. Future work to improve the current third generation DIAL instrument for full-time autonomous measurements of atmospheric water-vapor and aerosols is also discussed.

INTRODUCTION

Atmospheric Composition

The Earth's atmosphere is divided into several distinct layers from the sea surface up to 600 km. Each layer plays a key role in supporting life on Earth, such as absorbing harmful incoming solar radiation, recycling water, and chemical transport. The complex blanket of gases comprising the layers has been characterized in terms of thermal trends, chemical composition, mass motions (convection, winds, and turbulence), and density. Figure 1 shows the four primary layers and the corresponding temperature profile. The troposphere is the bottom layer, beginning at the Earth's surface and extending up to approximately 15 km. This is the densest part of the atmosphere, where most of the weather takes place. The atmospheric boundary layer, more commonly referred to as the planetary boundary layer (PBL) is the bottommost part of the troposphere, coming in contact with the Earth's surface. The PBL height typically ranges from 100's of meters in stable conditions, typically at night, to greater than 2 km during the day where solar induced convection causes shear and turbulence in the air parcel near the surface. Most of the convective processes that drive the Earth's weather patterns initiate within the PBL, where most of the atmosphere's moisture and aerosols reside. A more detailed description of the PBL and diurnal process occurring within it will be presented in chapter 3. The troposphere above the PBL, (referred to as the free troposphere) is typically clear of aerosols, and the temperature decreases adiabatically up to the bottom

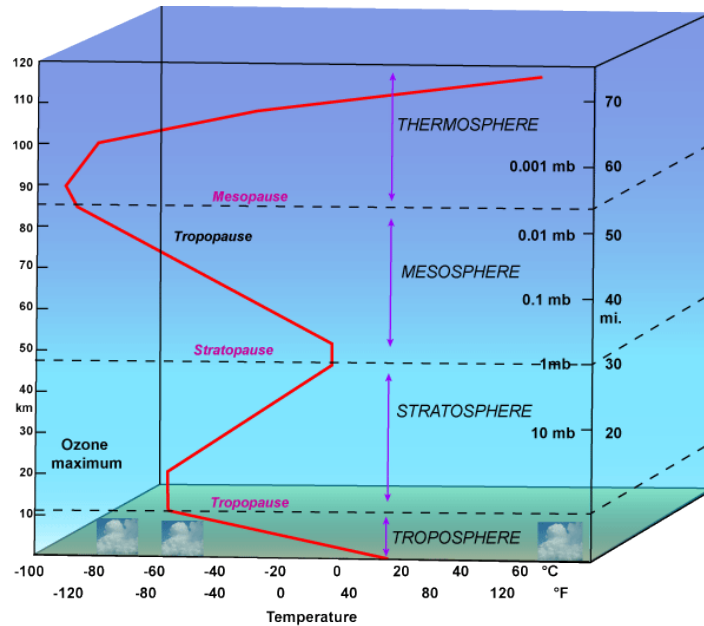


Figure 1 The primary layers in the Earth's atmosphere
(http://www2.sunysuffolk.edu/mandias/global_warming/greenhouse_gases.html).

of the stratosphere. The thin buffer zone between the troposphere and the next layer is called the "tropopause".

The stratosphere begins just above the tropopause and extends to approximately 50 km. The air flow within this layer is mostly horizontal, and is also considerably drier and less dense than the troposphere. The ozone layer in the stratosphere contains an abundance of O_3 , a reactive form of oxygen that absorbs harmful ultraviolet (UV) radiation. The temperature increases with height in the stratosphere due to the UV absorption. Above the stratosphere are the mesosphere and ionosphere (thermosphere), where many of the atoms are ionized due to the solar wind. In the ionosphere, the temperature increases with increasing height due to solar radiation. As stated earlier, each of the atmospheric layers described in this section plays an important role in maintaining Earth's habitable environment, but the majority of the short-term mesoscale

weather patterns that occur on the planet take place in the PBL and free troposphere, and these regions will be the primary targets for the instruments whose development is discussed in this dissertation.

Table 1 Earth's atmospheric concentrations of major gaseous constituents with respect to dry air (Wallace & Hobbs 2006).

Constituent	Molecular Weight	Fractional concentration by volume
Nitrogen (N ₂)	28.013	78.08%
Oxygen (O ₂)	32.000	20.9%
Argon (Ar)	39.95	0.93%
Water-vapor (H₂O)	18.02	0-5%
Carbon dioxide (CO₂)	44.01	0.038% (380 ppm)
Neon (Ne)	20.18	0.0018% (18 ppm)
Helium (He)	4.00	5 ppm
Methane (CH₄)	16.04	1.75 ppm
Krypton (Kr)	83.80	1 ppm
Hydrogen (H ₂)	2.02	0.5 ppm
Nitrous oxide (N₂O)	56.03	0.3 ppm
Ozone (O₃)	48.00	0-0.1 ppm

The Earth's atmosphere is composed of a mixture of both "constant" and "variable" gases shown in Table 1. Nitrogen, oxygen and argon are referred to as

constant gases because their relative fractional concentrations have not changed dramatically in recent history. The boldfaced constituents indicate greenhouse gases, and they are variable over space and/or time. Even though these greenhouse gases represent a small portion of the atmosphere by volume, they have a large impact on our environment through the greenhouse feedback effect and cannot be ignored when considering the Earth's atmospheric-biosphere radiative transfer budget. For all practical purposes, most of the greenhouse gases in the present atmosphere with the exception of water-vapor are well mixed spatially and temporally and can therefore be measured with relative ease. In contrast, water-vapor's concentration exhibits extreme spatial and temporal variability due to the evaporation and condensation of water between the land, oceans, and atmosphere. The geographical and temporal variability make water-vapor a key driver of the Earth's weather patterns and long-term climate shifts and is also the primary reason the concentration is inadequately measured, both in the lower and upper atmosphere.

Atmospheric Water-Vapor

Water-vapor is the most dominant greenhouse gas in the atmosphere (Trenberth et al. 2007). The radiative forcing for a clear sky due to water-vapor is 75 Wm^{-2} , while for carbon dioxide (CO_2) it is a factor of two weaker at 32 Wm^{-2} (Kiehl & Trenberth 1997). The sensitivity of radiative forcing due to changing water-vapor/ CO_2 concentrations in the equatorial regions is small due to the already large greenhouse effect and therefore such changes have only a small direct impact on the re-emitted downward infrared radiation. However, in the cold dry polar regions, the effect of a small increase in water-

vapor/ CO_2 caused by equatorial convective circulations is much greater (Trenberth et al. 2007).

As the temperatures of the Earth's surface and atmosphere increase as a result of the increase in anthropogenic greenhouse gases such as CO_2 , the concentrations of water-vapor also increase resulting from oceanic evaporation (Raval & Ramanathan 1998; Pierrehumbert 1995; Rind et al. 1991; Del Denio, Kovari & Mao-Sung 1994). Since water-vapor is a strong greenhouse gas, the higher levels of atmospheric water-vapor cause a further temperature increase, thus producing a positive feedback. Atmospheric water-vapor is directly related to the surface and atmospheric temperature and has been shown to have the largest positive feedback effect in the climate system (Trenberth et al. 2007). Water-vapor feedback, according to current climate models, approximately doubles the warming from what it would be for a fixed level of atmospheric water-vapor (Forster et al. 2007; Held & Soden 2000; Colman 2004; Wetherald & Manabe 1988). With the growing concern for understanding and predicting global climate, detailed data of water-vapor distribution and flux and related feedback mechanisms in the lowest 4 km of the troposphere are required to aid in climate models such as the simple climate models (SCMs) (Harvey et al. 1997; Wigley & Raper 1992; Wigley & Raper 2001), the Earth system models of intermediate complexity (EMICs) (Claussen et al. 2002; Randall et al. 2007), and the atmospheric and ocean general circulation models (AOGCM's) (Randall et al. 2007). The results of these models are used for developing climate initiatives and regulatory rules, and rely heavily on coupled components of the atmosphere including aerosols, water-vapor, and clouds.

Atmospheric Aerosols

Aerosols play an important role in the Earth's climate system. The increased aerosol loading of the atmosphere due to anthropogenic sources produces a negative radiative forcing similar in magnitude to the positive radiative forcing associated with the increase in anthropogenic greenhouse gases (Charlson et al. 1992). According to the Fourth Assessment Report (FAR) of the Intergovernmental Panel on Climate Change (IPCC), the radiative forcing due to aerosols currently has a "low level of scientific understanding" (Forster et al. 2007), resulting in the largest uncertainties in our understanding and modeling of the Earth's climate system. The radiative forcing of aerosols depends on three coupled components of the climate system; water-vapor, clouds, and the aerosols themselves. To better understand and model the role these atmospheric constituents play in the climate system, new instruments and observational techniques are needed to reduce these uncertainties (Forster et al. 2007). Aerosols affect the climate system both directly and indirectly. In their direct effect (Haywood & Boucher 2000; Penner et al. 2001), aerosols reflect incoming solar radiation back into space, causing a net negative radiative forcing of $-0.5 \pm 0.4 \text{ W/m}^2$ (Forster et al. 2007). This large relative uncertainty ($\pm 80\%$) associated with the negative radiative forcing due to the aerosol direct effect is an indication of the uncertainty in understanding how aerosols influence the climate system. The large uncertainty of the radiative forcing due to aerosols is in contrast to the "high level of scientific understanding" for radiative forcing due to the increase of greenhouse gases such as CO_2 , nitrous oxide (N_2O), and methane (CH_4) (Forster et al. 2007). For example, the radiative forcing due to carbon

dioxide has a value of $+1.66 \pm 0.17 \text{ W/m}^2$ (Forster et al. 2007). This smaller uncertainty ($\pm 10\%$) is considerably lower than the uncertainty associated with the aerosol direct effect ($\pm 80\%$) on the radiative forcing.

In the aerosol indirect effect, aerosols can influence cloud microphysical properties, which in turn indirectly affect the climate system. (Twomey 1974) suggests that an increased concentration of atmospheric aerosols will result in a higher concentration of cloud condensation nuclei (CCN). The increased concentration of CCN then leads to a higher cloud droplet concentration that will suppress drizzle formation (Albrecht 1989) and lead to more reflective clouds. However, as noted by (Eichel et al. 1996) and (Wulfmeyer & Feingold 2000), this chain of events is not a foregone conclusion but, instead depends on properties associated with the aerosols, including the aerosol composition and hygroscopicity. The changes in the cloud microphysical structure due to the interaction of aerosols and water-vapor produce more reflective clouds, resulting in more solar radiation being reflected back into space, leading to an overall negative radiative forcing that is estimated to be -1.8 W/m^2 to -0.3 W/m^2 (Forster et al. 2007). This large range for the radiative forcing by the aerosol indirect effect also reflects the uncertainty in the understanding of this effect. To better understand the aerosol indirect effect, (Wulfmeyer & Feingold 2000) noted that lidar measurements of aerosol properties and of water-vapor concentrations can provide important information to enhance our understanding of the role of aerosols in the climate system.

Current Status of Water-Vapor Remote-Sensing Technologies

Over the past 30 years, researchers have developed a wide range of remote sensing instruments for monitoring atmospheric physical processes for applications such as micro and macro-scale meteorology, climate modeling, hydrologic cycle monitoring, and studies of atmospheric transport and chemistry. *In situ* measurements such as radiosondes and chilled-mirror hygrometers have shown great utility for point-source measurements and verification but lack the spatial and temporal coverage needed for climate modeling and weather forecasting (Turner, Feltz & Ferrare 2000). Further, radiosonde measurements in the upper troposphere lower stratosphere (UTLS) region of the atmosphere have been shown to be dry biased, where high accuracy water-vapor concentrations are required for this portion of the atmosphere for global climate and chemical transport models (Turner et al. 2002). Space-based satellite platforms housing passive sensors such as the Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) (Milz et al. 2005), the Atmospheric Infrared Sounder (AIRS) (Divakarla et al. 2006), and the Halogen Occultation Experiment (HALOE) (Russell et al. 2005) have shown great utility for global coverage of water-vapor fluxes but are often limited in the atmospheric sampling region due to accessibility to various atmospheric windows and also suffer from coarse vertical resolutions of approximately 1-6 km.

Active remote sensors such as lidars (Light Detection And Ranging) have become an attractive alternative to passive sensors for monitoring atmospheric aerosols and water-vapor with high spatial and temporal resolution. Various research groups around the world have developed and deployed lidar systems, both ground-based and airborne, to

simultaneously monitor vertical distributions of aerosols and water-vapor. Such instruments include Raman lidars (Goldsmith et al. 1998; Eichinger et al. 1999; Whiteman, Melfi & Ferrare 1998) and differential absorption lidar (DIAL) (Browell, Ismail & Grant 1998; Rall et al. 1994; Wulfmeyer 1998; Wulfmeyer & Bosenberg 1998; Ehret et al. 1993; Ehret et al. 1998; Wirth et al. 2009; Machol et al. 2004; Nehrir et al. 2009; Nehrir, Repasky & Carlsten 2011). Raman lidar instruments provide high spatial resolution of atmospheric water-vapor by observing a characteristic Raman shift to longer wavelengths generated from inelastic backscattering in the atmosphere from high power laser transmitters. Raman lidar's have proven to be attractive for monitoring atmospheric processes because of their capabilities for detecting multiple gas constituents simultaneously, but they suffer from high operating costs due to periodic instrument calibration and the need for bulky powerful non eye-safe laser transmitters required to compensate for weak Raman-scattering cross sections. Alternatively, the DIAL technique reported here uses a tunable laser transmitter and the backscattered signal from molecules and aerosols to determine range-resolved water-vapor profiles. The ratio between a relatively un-attenuated backscattered return at an offline wavelength and an attenuated backscattered return at the online wavelength is proportional to the vertical range resolved water-vapor profile. Because the DIAL technique uses a ratio of the return signals from a closely-spaced pair of online and offline transmitter wavelengths, difficult calibration processes faced by Raman lidar instruments are avoided, making the DIAL technique a suitable method for ground-based and airborne mobile platform instruments used for long duration aerosol and water-vapor monitoring.

Large scale water-vapor transport processes are difficult to observe from a single ground based instrument, but can be easily monitored with high spatial and temporal resolution using airborne DIAL instruments, at the expense of high operating and maintenance costs. The high spatial and temporal variability of water-vapor can also be captured using an array of low-cost, eye-safe, automated DIAL instruments (Reagan, Cooley & Shaw 1993). Water-vapor transport processes used to enhance climate studies and weather forecasting capabilities can be measured using a network of commercial off the shelf (COTS) built water-vapor DIAL instruments which can also be supplemental to larger scale airborne and satellite based campaigns. Many high power, large scale water-vapor DIAL instruments have been successfully built, deployed, and used for a wide range of sounding measurements in various geographical locations (Wulfmeyer 1998; Ismail et al. 2000), but few eye-safe autonomous systems have been successfully demonstrated. Recently, (Nehrir et al. 2009; Nehrir, Repasky & Carlsten 2011) and (Machol et al. 2004) have demonstrated the utility of using semiconductor lasers as DIAL transmitters for water-vapor and aerosol profiling in the lower troposphere. Diode lasers are extremely compact and inexpensive and can be widely tuned to both access weak and strong water-vapor absorption bands near 830 nm and 940 nm, respectively. Recently, tapered semiconductor optical amplifiers (TSOA) have become commercially available, allowing for the development of actively pulsed eye-safe micro-pulse DIAL transmitters in the 830 nm spectral region.

Dissertation Organization

This dissertation will focus on the development and demonstration of the first all-diode-laser-based micro-pulse DIAL instrument capable of full time tropospheric water-vapor and aerosol profiling. Chapter 2 will present the theoretical frame work for the water-vapor DIAL technique including the requirements and selection process for a suitable water-vapor absorption line. A detailed description of the second generation DIAL instrument will be presented in Chapter 3 where comparisons with collocated radiosonde measurements will also be presented. Chapter 4 will focus on the calibration of the offline channel of the second generation DIAL instrument where the Fernald aerosol inversion technique and example aerosol retrieval data sets will be presented. Chapter 5 will focus on the development of a third generation DIAL instrument where a detailed description of the instrument components as well as initial data sets will be presented. Chapter 6 will then conclude the dissertation with final thoughts and comments and provide an insight towards future work.

THEORY

Background

Approximately 71% of the Earth's surface is covered in liquid water which has a very large heat capacity. The evaporation of liquid water at the Earth's surface, primarily over the oceans in the tropical regions, releases a large portion of this energy during the phase transition. This "hidden" energy, referred to as latent heat is released during condensation processes in the lower atmosphere such as cloud formation and precipitation. Latent heat is the most efficient feedback mechanism in controlling the surface-atmosphere energy balance. As depicted in Figure 2, a large percentage of atmospheric water-vapor absorption occurs around the 7 μm absorption band and the continuum starting around 12 μm , where a large part of the Earth's thermal radiation attempts to escape to space.

The absorption of light by water-vapor molecules strongly depends on the wavelength and must be very well characterized in order to accurately describe the atmospheric radiative transfer processes. Very accurate knowledge of the water-vapor absorption spectrum is needed for precise retrievals of atmospheric water-vapor density profiles using remote-sensing techniques. Characterization of this spectrum has been the subject of many studies and is an ongoing effort. In the late 1960's, The Air Force Cambridge Research Laboratories began a long running project known today as the High resolution TRANsmision (HITRAN) molecular absorption database in response to the need for detailed knowledge of the infrared properties of the atmosphere (Rothman et al.

2003). The HITRAN database consist of both measured and simulated spectroscopic properties of a variety of atmospheric gases from the shortwave visible out to the mid-infrared. For this study, the HITRAN database was used to provide absorption line parameters for the DIAL retrievals of water-vapor number-density profiles.

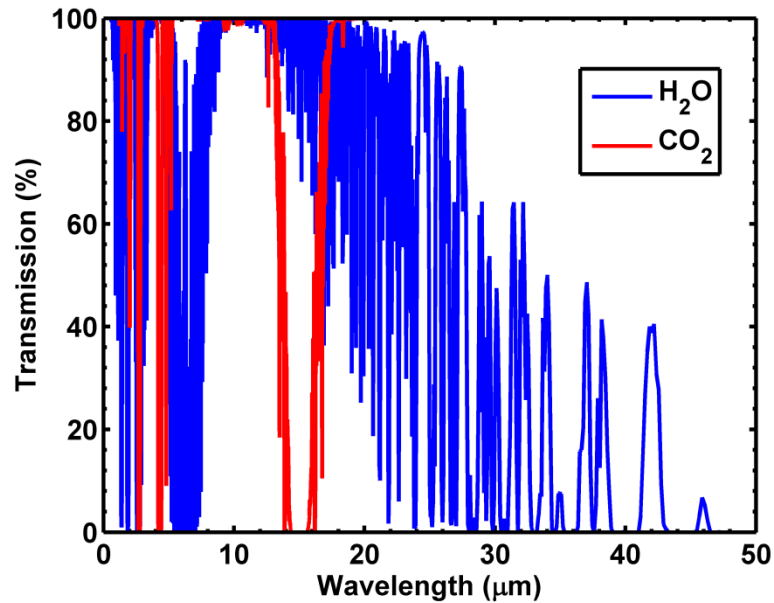


Figure 2 MODTRAN (MODerate resolution atmospheric TRANsmission) simulation of the Earth's atmospheric transmission spectrum from sea level up to 120 km for two major greenhouse gases, water-vapor and carbon dioxide. A standard atmosphere model was used for inputs to the simulation.

Water-Vapor Spectra

The water-vapor molecule is a tri-atomic bent molecule consisting of two hydrogen atoms that are bound to one oxygen atom with an angle of 104.36° between the O-H bonds (Darling & Dennison 1940). The water molecule has three fundamental oscillation modes as shown in Figure 3. The symmetric and asymmetric modes involve

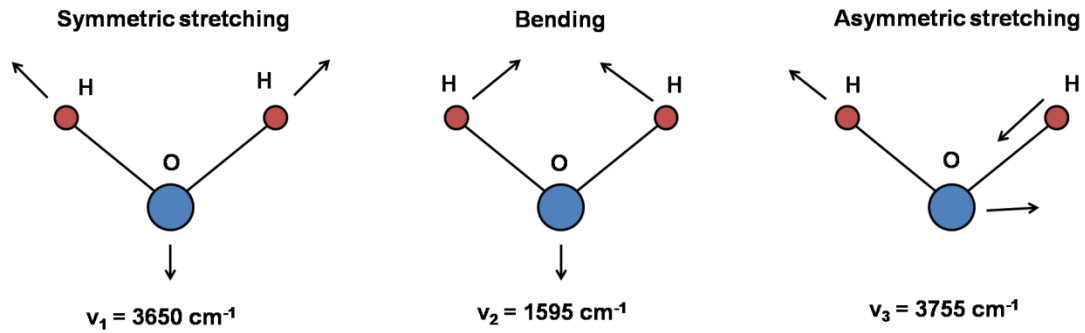


Figure 3 Vibration modes of the water molecule. The blue and red circles indicate oxygen and hydrogen atoms, respectively.

stretching of the O-H bonds. The bending mode involves the change of the angle between the O-H bonds and has a lower excitation energy than the stretching modes. ν_1 (2.74 μm), ν_2 (6.27 μm), and ν_3 (2.66 μm) represent the absorption transition energies from the ground state to the lowest excited state and are all in the near infrared (NIR) portion of the spectrum. The photon energy in an absorption or emission transition equals the energy difference ΔE between the two states involved in the transition, typically the ground state and the lowest excited state for the vibrational mode of interest. The photon's wavenumber [cm^{-1}] is given by

$$\Delta E = hc\nu, \quad (2.1)$$

where h is the Plank constant [J s]. The wavenumber is used as a unit of energy in spectroscopy and is related to the optical frequency or wavelength by $\nu = \frac{1}{\lambda} = \frac{f}{c}$, where λ [m] is the wavelength, f [Hz] is the frequency, and c [m/s] is the speed of light. The vibrational transitions are often accompanied by much weaker rotational transitions, giving way to an abundance of allowable transitions in the NIR. To fully describe the

complex spectrum of the water molecule, a full quantum mechanical representation is required, which is beyond the scope of this study.

In the NIR, the water-vapor absorption lines are separated into distinct bands where lines at wavelength longer than 1 μm are not well distinguished. A HITRAN (Rothman et al. 2003) simulation of the atmospheric transmission due to water-vapor absorption bands from 0.5-1.0 μm , given a standard atmosphere (U.S. Standard Atmosphere 1976), is shown in Figure 4. The various absorption bands shown have varying line strengths, allowing for a wide range of concentration soundings of atmospheric water-vapor needed for various geographical locations. The varying intensity absorption bands are attributed to the permanent dipole moment of the water

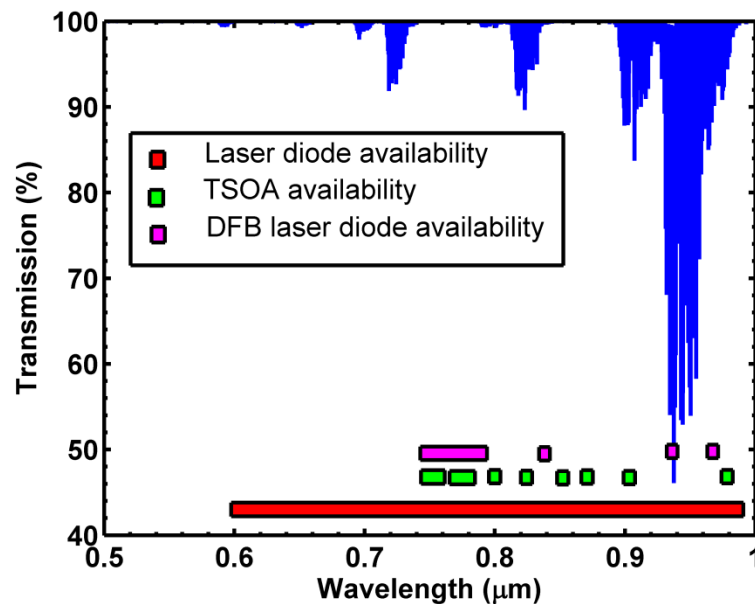


Figure 4 HITRAN simulation of the transmission due to water-vapor absorption bands in the NIR portion of the spectrum using a standard atmosphere. The spectral availability of laser-diode technology is also overlaid, showing the potential of the different operating regions for the proposed DIAL instrument.

molecule. This dipole moment is what allows for efficient coupling of external fields such as monochromatic laser sources to the water vapor molecular state.

For active remote-sensing of atmospheric gases using the DIAL technique, narrow-linewidth laser sources are used to probe the molecular resonances in order to arrive at molecular concentrations of the species of interest. Typically, injection-seeded solid-state lasers are used in DIAL measurements of atmospheric water-vapor, due to the high laser spectral purity and high pulse energies, yielding high signal to noise ratios (SNR) in relatively short integration periods (Browell, Ismail & Grant 1998; Ehret et al. 1998). Although robust, these types of laser transmitters are bulky, expensive, and require constant maintenance. As an alternative to solid-state lasers, diode lasers operating in the visible or NIR can be used as lidar or DIAL transmitters.

Laser diodes are cost effective, commercially available, and have broad spectral coverage. Laser diodes in a distributed feedback (DFB), distributed Bragg reflector (DBR), or external-cavity diode laser (ECDL) configuration can be used as the seed source in a DIAL transmitter. These types of seed sources have good spectral properties but exhibit low continuous-wave (cw) output powers. To overcome the power limitations, TSOA's can be used to increase the output power of the DIAL transmitter. In order to exploit the commercially-available laser-diode technology, there must be spectral overlap between the water-vapor absorption lines, and availability of the seed and amplifier sources. The spectral coverage of diode-laser-based technologies in the visible and NIR is shown in Figure 4. As seen from the figure, there is no spectral region with water-vapor absorption lines of appropriate strength for which both DFB laser diodes and

TSOA's are available. Because the 830 nm water-vapor absorption band is the only spectral region where overlap between all three requirements described above is achieved, the water-vapor DIAL transmitters were designed to operate near 830nm using custom a built ECDL's as the seed sources and TSOA's for profiling tropospheric water-vapor.

Principles of Lidar

Lidar is a useful method for retrieving range-resolved profiles of atmospheric gases and aerosols. A schematic of the typical components comprising a lidar instrument is shown in Figure 5. A coherent illumination source, typically a laser, ranging in wavelength from the UV to the NIR, repeatedly sends short, collimated pulses of light

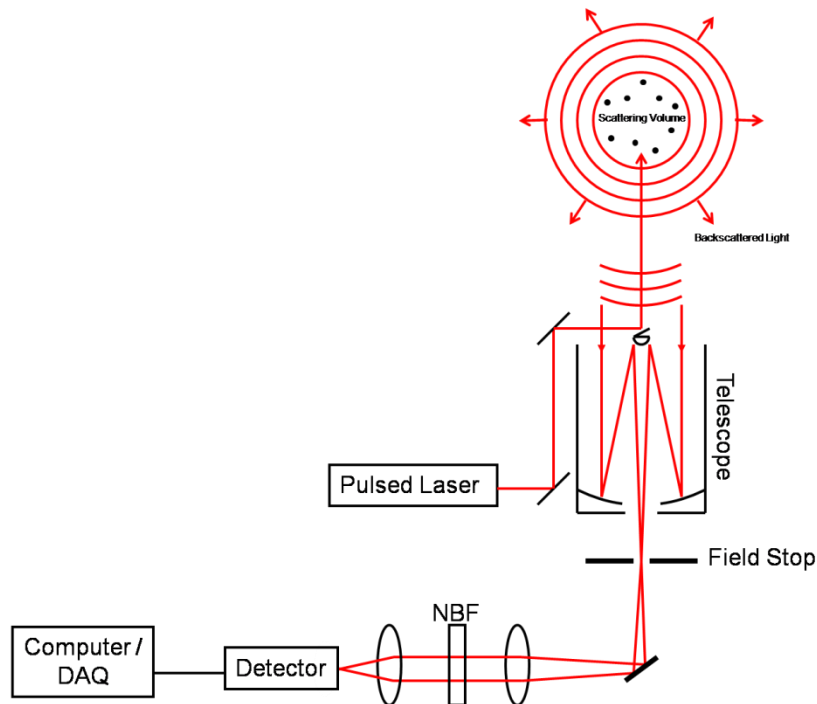


Figure 5 Schematic of a typical lidar instrument including basic principles and components.

into the atmosphere. Typical pulse widths, pulse repetition frequencies (PRF), and pulse energies range from 1-1000 ns, 0.001-50 kHz, and 0.001-100 mJ, respectively. As the laser pulse propagates through the atmosphere, some of the energy is absorbed or scattered by airborne molecules, cloud droplets, ice crystals and aerosols with a small fraction of the backscattered light collected by the lidar receiver.

Lidar instruments are configured in one of two layouts. The first layout, the bi-static configuration, uses a laser transmitter located a small distance away from the receiver, limiting the region where the laser transmitter and receiver field of view (FOV) are spatially overlapped. The second layout, which is a co-linear configuration such as the one depicted in Figure 5 utilizes a common axis between the laser transmitter and optical receiver, ensuring that the laser beam is within the field of view of the telescope during the entire time of flight. The backscattered light collected by the telescope then passes through a field stop placed at the focal plane of the telescope. The field stop limits the field of view of the telescope such that returns from multiple scattering events and stray background light are prevented from reaching the detector. The light is then collimated and passes through a narrowband optical filter (NBF) to ensure that only the backscattered light from the laser transmitter is measured by the detector. The filtered light is then focused on a detector where a data acquisition (DAQ) card digitizes the detector output. The time of flight of each scattering event from a single laser pulse is directly proportional to the distance to the scattering volume along the entire illuminated path, and the manner in which the light is scattered back to the receiver reveals information about the scattering volume's microphysical and spectroscopic properties.

DIAL Equation

The DIAL equation can be derived from the single scatter, monochromatic elastic lidar equation (Kovalev & Eichinger 2004; Measures 1984). The optical power, $P(\lambda, r)$, collected at a wavelength λ from a range r is schematically shown in Figure 6 and described by

$$P(\lambda, r) = P_t(\lambda) \frac{A}{r^2} \Delta r \beta(\lambda, r) T^2(\lambda, r) \epsilon_0(r) \epsilon_R(\lambda, r) \epsilon_D(\lambda, r). \quad (2.2)$$

$P_t(\lambda)$ is the transmitted optical power and has units of [W] and can also be written in terms of transmitted photons by using the conversion $P_t(\lambda) = \frac{n_t h c}{\lambda}$ where n_t is the number of transmitted photons over the pulse duration, $h = 6.626 \times 10^{-34}$ [J s] is Plank's constant, and $c = 2.998 \times 10^8$ m/s. $\frac{A}{r^2}$ [sr] is the solid angle subtended by the receiver where A [m²] is the entrance pupil area of the telescope receiver, r [m] is the range or distance from the

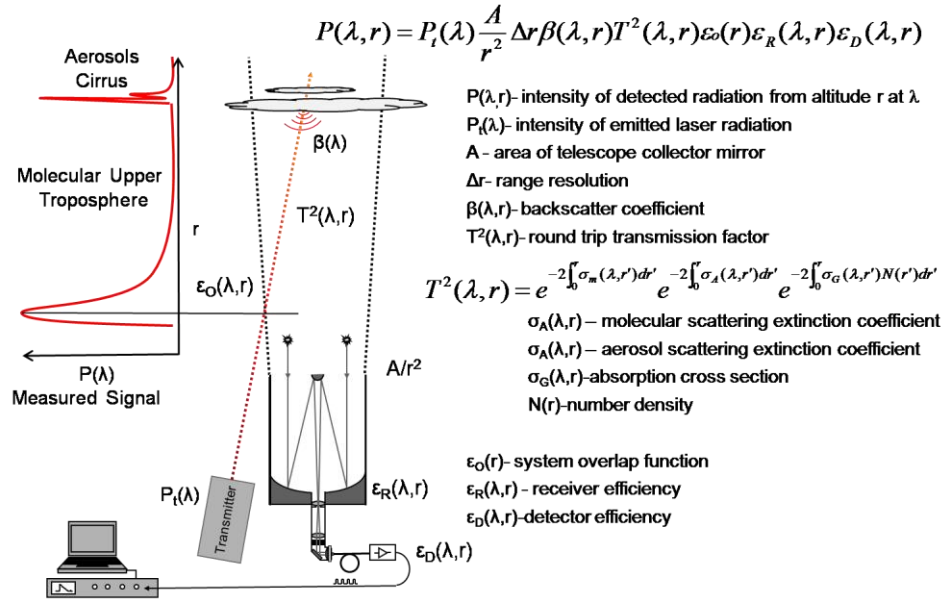


Figure 6 Schematic of lidar returns, depicting the various components that contribute to form the lidar equation.

receiver to the scattering volume, and $\Delta r = \frac{\tau c}{2}$ is the range bin size where τ [s] is the laser pulse duration. Given a two component atmosphere, $\beta(\lambda, r)$ is the total atmospheric backscatter coefficient (i.e. fraction of the input pulse per unit length and per unit solid angle into the backward direction) and can be expressed as

$\beta(\lambda, r) = \beta_m(\lambda, r) + \beta_a(\lambda, r)$ [$\text{km}^{-1}\text{sr}^{-1}$] where β_m and β_a are the molecular and aerosol backscatter coefficients, respectively. $T^2(\lambda, r)$ [dimensionless] is the round-trip atmospheric transmission factor, accounting for extinction of the light due to scattering and absorption by molecules and aerosols in the atmosphere. $\epsilon_0(r)$, $\epsilon_R(\lambda, r)$, and $\epsilon_D(\lambda, r)$ [all dimensionless] are the lidar geometric overlap function, the receiving optics transmission factor (Nehrir et al. 2009), and the optical detector efficiency, respectively.

To arrive at the number-density of the molecular species of interest, water-vapor in this case, the round-trip transmission factor must be broken into its various components. The round trip atmospheric transmission factor from equation (2.2) is described by the Beer-Lambert relationship and can be expressed as

$$T^2(\lambda, r) = \exp \left(-2 \int_0^r \alpha(\lambda, r') dr' \right), \quad (2.3)$$

where $\alpha(\lambda, r)$ [m^{-1}] is the total atmospheric extinction coefficient taking into account molecular and aerosol absorption and scattering. The atmospheric extinction coefficient can be expanded into two primary terms

$$\alpha(\lambda, r) = \kappa(\lambda, r) + \sigma_G(\lambda, r)N(r), \quad (2.4)$$

where $\kappa(\lambda, r)$ [m^{-1}] is the total atmospheric extinction due to molecular scattering and aerosol scattering and absorption. It can be expanded into its two primary terms

$\kappa(\lambda, r) = \sigma_m(\lambda, r) + \sigma_a(\lambda, r)$ where subscripts m and a denote molecular and aerosol, respectively. $\sigma_G(\lambda, r)N(r)$ [m^{-1}] is the atmospheric extinction due to molecular absorption, where $\sigma_G(\lambda, r)$ [m^2] is the absorption cross-section of the atmospheric constituent of interest and $N(r)$ [m^{-3}] is the number-density of the same absorbing constituent. Substituting equation (2.4) into equation (2.3) yields the expanded round-trip atmospheric transmission factor

$$T^2(\lambda, r) = \exp \left(-2 \int_0^r \kappa(\lambda, r') dr' \right) \exp \left(-2 \int_0^r \sigma_G(\lambda, r') N(r') dr' \right). \quad (2.5)$$

Lastly, the total receiver efficiency is defined as the product of the receiver overlap function and the receiver optics transmission factor and can be written as

$$\epsilon(\lambda, r) = \epsilon_0(\lambda, r) \epsilon_D(\lambda, r) \epsilon_R(\lambda, r). \quad (2.6)$$

These three terms are often lumped together and are a part of what is known as the calibration constant needed for aerosol retrievals, to be described in further detail in chapter four.

The DIAL technique utilizes the return signal from two different wavelengths that are closely spaced to determine a vertical profile of the number-density of a particular absorbing species. The first wavelength, λ_{on} , is the wavelength corresponding to the center of a molecular absorption line, while the second wavelength, λ_{off} , is a wavelength corresponding to significantly less molecular absorption. The DIAL equation can then be found by considering the ratio of the two spectrally separated lidar returns over adjacent

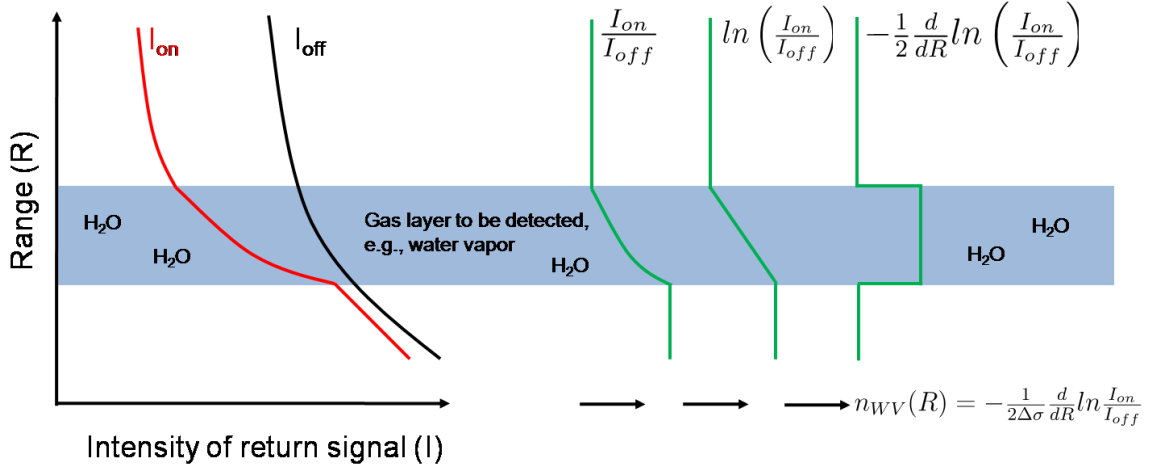


Figure 7 Methodology in DIAL technique to measure absolute humidity.

range bins as depicted schematically in Figure 7. Using equations (2.2)-(2.6) to solve for the number-density term, the expanded form of the differential between the two spectrally separated lidar returns over adjacent range bins can be written as

$$\begin{aligned}
 & [\ln P(\lambda_{on}, r) - \ln P(\lambda_{on}, r + \Delta r)] - [\ln P(\lambda_{off}, r) - \ln P(\lambda_{off}, r + \Delta r)] = \\
 & \left[\ln \frac{1}{r^2} - \ln \frac{1}{(r + \Delta r)^2} - 2 \int_0^r \kappa(\lambda_{on}, r') dr' - 2 \int_0^r \sigma_G(\lambda_{on}, r') N(r') dr' + 2 \int_0^{r+\Delta r} \kappa(\lambda_{on}, r') dr' \right. \\
 & \left. + 2 \int_0^{r+\Delta r} \sigma_G(\lambda_{on}, r') N(r') dr' + \ln \beta(\lambda_{on}, r) - \ln \beta(\lambda_{on}, r + \Delta r) + \ln \epsilon(\lambda_{on}, r) - \ln \epsilon(\lambda_{on}, r + \Delta r) \right. \\
 & \left. - \left[\ln \frac{1}{r^2} - \ln \frac{1}{(r + \Delta r)^2} - 2 \int_0^r \kappa(\lambda_{off}, r') dr' - 2 \int_0^r \sigma_G(\lambda_{off}, r') N(r') dr' + 2 \int_0^{r+\Delta r} \kappa(\lambda_{off}, r') dr' \right. \right. \\
 & \left. \left. + 2 \int_0^{r+\Delta r} \sigma_G(\lambda_{off}, r') N(r') dr' + \ln \beta(\lambda_{off}, r) - \ln \beta(\lambda_{off}, r + \Delta r) + \ln \epsilon(\lambda_{off}, r) - \ln \epsilon(\lambda_{off}, r + \Delta r) \right] \right] (2.7)
 \end{aligned}$$

For the DIAL technique, the wavelengths λ_{on} and λ_{off} are chosen to be spectrally close enough such that

$$\begin{aligned}
 \kappa(\lambda_{on}, r) &= \kappa(\lambda_{off}, r) = \kappa(r) \\
 \beta(\lambda_{on}, r) &= \beta(\lambda_{off}, r) = \beta(r) \\
 \epsilon(\lambda_{on}, r) &= \epsilon(\lambda_{off}, r) = \epsilon(r).
 \end{aligned} \tag{2.8}$$

These assumptions hold true if the time between atmospheric soundings for the two wavelengths is shorter than for which the atmospheric state changes significantly, typically on the order of 1-60 seconds. For λ_{on} and λ_{off} closely spaced in wavelength so that the atmospheric extinction, backscatter and overall instrument efficiencies are equal, equation (2.8) can be substituted into equation (2.7). Then many terms cancel out, yielding

$$[\ln P(\lambda_{on}, r) - \ln P(\lambda_{on}, r + \Delta r)] - [\ln P(\lambda_{off}, r) - \ln P(\lambda_{off}, r + \Delta r)] = 2 \int_r^{r+\Delta r} \sigma_G(\lambda_{on}, r) N(r) dr' - 2 \int_r^{r+\Delta r} \sigma_G(\lambda_{off}, r) N(r) dr'. \quad (2.9)$$

Given that the laser pulse width is small enough, corresponding to no more than ~ 300 m in range, the absorption cross-section of the molecule of interest can be assumed to be constant across a single range bin, leading the range dependence over this region (a single range bin) to fall out such that

$$\begin{aligned} \sigma_G(\lambda_{on}, r) &= \text{constant} = \sigma(\lambda_{on}) \\ \sigma_G(\lambda_{off}, r) &= \text{constant} = \sigma(\lambda_{off}). \end{aligned} \quad (2.10)$$

The molecular number-density in the Beer's law relationship is also assumed to be constant over a single range bin, allowing the integrals in equation (2.9) to be simplified as

$$\begin{aligned} 2 \int_r^{r+\Delta r} \sigma(\lambda_{on}, r) N(r) dr' &= 2\sigma(\lambda_{on}) N(r + \Delta r) \Delta r, \\ 2 \int_r^{r+\Delta r} \sigma(\lambda_{off}, r) N(r) dr' &= 2\sigma(\lambda_{off}) N(r + \Delta r) \Delta r. \end{aligned} \quad (2.11)$$

It is important to emphasize that the assumptions used in equations (2.10) and (2.11) are only valid for relatively small range bin sizes that can accurately capture the small scale features of the constituent of interest. The range-dependent absorption cross-section in equations (2.10) and (2.11) will be discussed in further detail in the next section. Given a constant differential absorption cross section and number-density over a finite range, equation (2.9) can be solved directly for the range dependent number-density of the constituent of interest. This is referred to as the DIAL equation and takes the common form

$$N(r + \Delta r) = \frac{1}{2(\sigma(\lambda_{on}, r) - \sigma(\lambda_{off}, r)) \Delta r} \left[\ln \left(\frac{P(\lambda_{on}, r)}{P(\lambda_{on}, r + \Delta r)} \frac{P(\lambda_{off}, r + \Delta r)}{P(\lambda_{off}, r)} \right) \right] .(2.12)$$

Water-Vapor Absorption Line Selection

Three main criteria must be considered when choosing a water-vapor absorption line in order to achieve accurate tropospheric water-vapor profiles: choosing an appropriate absorption-line strength for a given geographical location, minimizing the absorption cross-section sensitivity to temperature, and picking a line that is isolated from other nearby absorption features (Machol et al. 2004; Nehrir et al. 2009).

Absorption Line-Strength

The absorption line strengths associated with the different water-vapor absorption bands shown in Figure 4 are presented in Table 2. The optimal atmospheric measurement regions are also presented, giving insight towards choosing an appropriate absorption band for lower tropospheric water-vapor measurements. For tropospheric

water-vapor profiling, an absorption line must be chosen such that the optical depth (OD) due to water-vapor up to the maximum desired altitude is

$$OD = \tau = \int_0^{r_{max}} \sigma(r') N(r') dr' \approx 1 - 2 \text{ and also such that } \Delta\tau = N_{H_2O} \sigma_{on} \Delta r \approx 0.02 - 0.1$$

(Wulfmeyer & Bosenberg 1998; Bosenberg 1998). For a water-vapor OD of ~ 0.05 and for typical boundary layer water-vapor number-density and range resolution of $\sim 1 \times 10^{17} \text{ cm}^{-3}$ and 150 m, respectively, a line strength of $\sim 1 \times 10^{-23} [\text{cm}^{-1}/\text{molecule cm}^{-2}]$ is needed to achieve the lower limit on the SNR of 3-7 required for accurate measurements of lower tropospheric water-vapor number-density profiles. This approximate value of the line strength necessary for measuring mid-latitude tropospheric water-vapor profiles limits the suitable absorption bands to those between 690-740 nm and 780-860 nm. As depicted in Figure 4, TSOA's aren't available for the 690-740 nm spectral band, hence limiting the operation of the water-vapor DIAL instrument to the 830 nm spectral region, where TSOA's are commercially available.

Table 2 Spectral regions and line intensities of water-vapor absorption bands in the NIR. The most appropriate atmospheric target range for each absorption band is also given where UTLS is an acronym for the upper troposphere lower stratosphere.

$\nu \text{ (cm}^{-1}\text{)}$	$\lambda \text{ (nm)}$	$S \text{ (cm}^{-1}/\text{molecule cm}^{-2}\text{)}$	Target Range
9,700-11,000	900-1030	10^{-22}	UTLS
11,600-12,800	780-860	10^{-23}	Troposphere
13,500-15,000	690-740	10^{-23}	Troposphere
15,150-15,900	630-660	10^{-24}	NA
16,550-17,100	585-605	10^{-24}	NA

Temperature Sensitive Line Strength

To arrive at the temperature-sensitive line strength/absorption cross-section parameter of the water-vapor absorption line of interest, the Beer-Lambert relation is used to describe the transmission, T , through the atmosphere. The Beer-Lambert relationship can be written as

$$T = \frac{I}{I_o} = e^{-2\alpha L}, \quad (2.13)$$

where I is the attenuated optical intensity after traveling a path of length L . I_o is the initial transmitted optical intensity, and α [cm^{-1}] is the absorption per unit length which is referred to as the linear absorption coefficient. The factor of two in the exponential accounts for the round-trip transmission through the atmosphere and back to the receiving unit via molecular or aerosol scattering events. The water-vapor absorption feature is described by a unique linear absorption coefficient, α , and can also be represented as

$$\alpha = S g(\nu - \nu_o) N(T, P), \quad (2.14)$$

where S [$\text{cm}/\text{molecule}$] is the molecular line strength and includes information about both the partition function of the molecule and the Boltzmann population factor (Vidler & Tennyson 2000). Values of S for individual absorption lines are listed in the HITRAN database. N [$\text{molecule}/\text{cm}^3$], as described previously, is the number-density of the molecule of interest and is a function of both temperature and pressure. $g(\nu - \nu_o)$ [dimensionless] is the normalized line shape parameter that allows for the calculation of the absorption coefficient at any spectral position across the absorption feature and will be described in further detail in the next section. ν [cm^{-1}] is the wavenumber and ν_o is the wavenumber corresponding to the center of absorption line, (Rothman et al. 2003).

Accurate measurements of tropospheric water-vapor profiles require care in selecting appropriate strength absorption lines as well as lines that are insensitive to variations in the atmospheric temperature (Machol et al. 2004; Browell, Ismail & Grossman 1991). The evaluation of the temperature sensitivities of water-vapor absorption lines in the 820-840 nm spectral region were studied using the methods presented by (Browell, Ismail & Grossman 1991), leading to the selection of a suitable water-vapor absorption line for number-density profiling. The temperature dependence of the line strength S associated with a water-vapor absorption feature is given by (Browell, Ismail & Grossman 1991)

$$S(T) = S_0 \left(\frac{T_0}{T} \right)^{1.5} \left[\frac{1 - \exp(-hc\nu_0/kT)}{1 - \exp(-hc\nu_0/kT_0)} \right] \exp \left[\frac{hc}{k} \left(\frac{1}{T_0} - \frac{1}{T} \right) E'' \right], \quad (2.15)$$

where S_0 (HITRAN) is the reference line strength at temperature T_0 [K], T [K] is the temperature at which the line strength is being calculated, E'' [cm^{-1}] is the energy above the ground state of the absorption lines lower level, and k is the Boltzmann constant. In order to reduce systematic errors in the DIAL measurements, such as those caused by the sensitivity of the absorption line strength to the atmospheric temperature, to $< 0.4\% \text{ K}^{-1}$, an absorption line should be selected such that $200 \text{ cm}^{-1} \leq E'' \leq 300 \text{ cm}^{-1}$ (Wulfmeyer & Walther 2001; Bosenberg 1998).

This guideline is best depicted in Figure 8 where an optimal absorption line strength of $1.477 \times 10^{-23} [\text{cm}^{-1}/(\text{mol cm}^{-2})]$ in the 830 nm absorption band is plotted as a function of atmospheric temperature for varying E'' . It is clearly shown that the effects of temperature on the absorption line strength are minimized for E'' ranging between 200-300 cm^{-1} . In order to pick an appropriate strength temperature insensitive line, the water-

vapor optical depth of a given absorption line must be calculated by considering the absorption cross section and the normalized line shape.

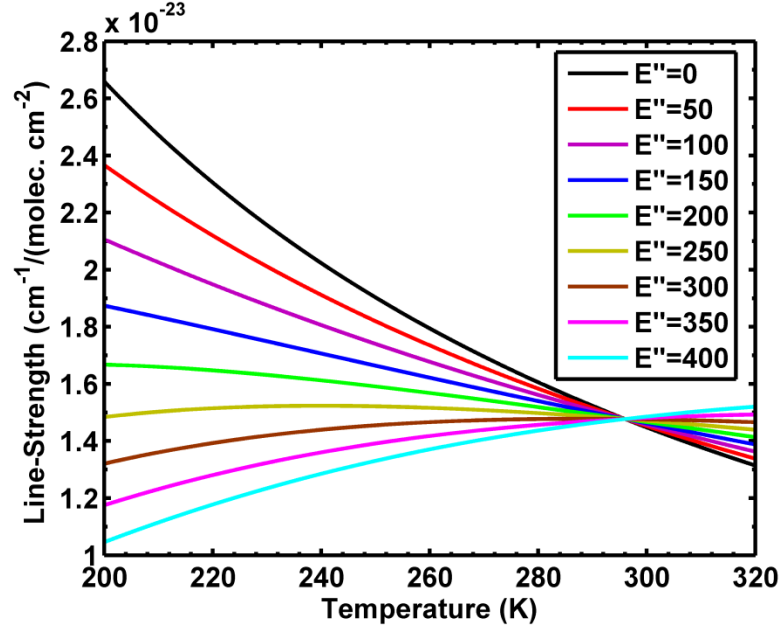


Figure 8 Temperature dependent absorption line strength as a function of typical tropospheric temperatures over varying E'' . S_0 and T_0 were set to 1.477×10^{-23} [$\text{cm}^{-1}/(\text{molecule cm}^{-2})$] and 296 K, respectively.

Pressure-Broadened Line Shape

Because the Earth's atmosphere is heterogeneous, different broadening processes dominate at different altitudes. For altitudes $\leq 2 \text{ km}$, pressure broadening is the dominant effect and yields a Lorentzian line shape. The Lorentzian half-width-at half-maximum (HWHM) value of the absorption line of interest is dependent on both atmospheric pressure and temperature and can be described by

$$\gamma_L = \gamma_0 \left(\frac{P}{P_0} \right) \left(\frac{T_0}{T} \right)^\alpha, \quad (2.16)$$

where α is the linewidth temperature-dependence parameter (Rothman et al. 2003), and γ_o is the HWHM of the line at standard temperature T_o and pressure P_o . To calculate $S(T)$ and γ_L , the reference value S_0 and γ_0 must first be obtained from the HITRAN database.

In the limiting case where pressure is the dominant broadening process, the line center cross section σ_0 is related to the line strength S and the line shape parameter g by

$$S = \int_{-\infty}^{\infty} \sigma_0 g_L(\nu - \nu_0) d\nu = \int_{-\infty}^{\infty} \sigma_0 \frac{\gamma_L^2}{(\nu - \nu_0)^2 + \gamma_L^2} d\nu. \quad (2.17)$$

Using a mathematical look up table (Beyer 1987) to evaluate the integral kernel yields

$$\int_{-\infty}^{\infty} \frac{a \, dx}{(x^2 + a^2)} = \pi, \quad (2.18)$$

where a substitution can be made from equation (2.18) into equation (2.17) such that $x = \nu - \nu_0$ and $dx = d\nu$. Using this substitution allows the water-vapor line strength to be written as

$$S = \sigma_0 \frac{\gamma_L^2}{\gamma_L} \int_{-\infty}^{\infty} \frac{\gamma_L}{(x)^2 + \gamma_L^2} dx = \sigma_0 \gamma_L \pi. \quad (2.19)$$

From equation (2.19) the line center absorption cross section σ_0 [cm^2] can be expressed as

$\sigma_0 = \frac{S_0}{\gamma_L \pi}$ and the pressure broadened absorption cross section as

$$\sigma_L(\nu) = \sigma_0 \frac{\gamma_L^2}{(\nu - \nu_0)^2 + \gamma_L^2}. \quad (2.20)$$

Doppler-Broadened Line Shape

In the other limiting case, where measurements are taken at altitudes ≥ 50 km, the pressure broadening is negligible, since the atmosphere is so tenuous, and Doppler broadening dominates. This can be described by a Gaussian function with HWHM linewidth given by

$$\gamma_D = \left(\frac{\nu_0}{c} \right) \left(\frac{2kT \ln 2}{m} \right)^{1/2}, \quad (2.21)$$

where m [kg/molecule] is the mass of a water-vapor molecule. Using a similar approach as with the Lorentzian line shape, the Doppler-broadened absorption cross section can be written as

$$\sigma_D(\nu) = \sigma_0 \exp \left[-\frac{\ln 2 (\nu - \nu_0)^2}{\gamma_D^2} \right], \quad (2.22)$$

where the line centered Doppler-broadened absorption cross section is expressed as

$\sigma_0 = \frac{S_0}{\gamma_D} \left(\frac{\ln 2}{\pi} \right)^{1/2}$. A simulation comparing the normalized pressure and Doppler broadened linewidths is presented in Figure 9. The pressure and Doppler broadened linewidths (FWHM) at standard temperature and pressure are ~ 6.2 GHz and ~ 0.6 GHz, respectively.

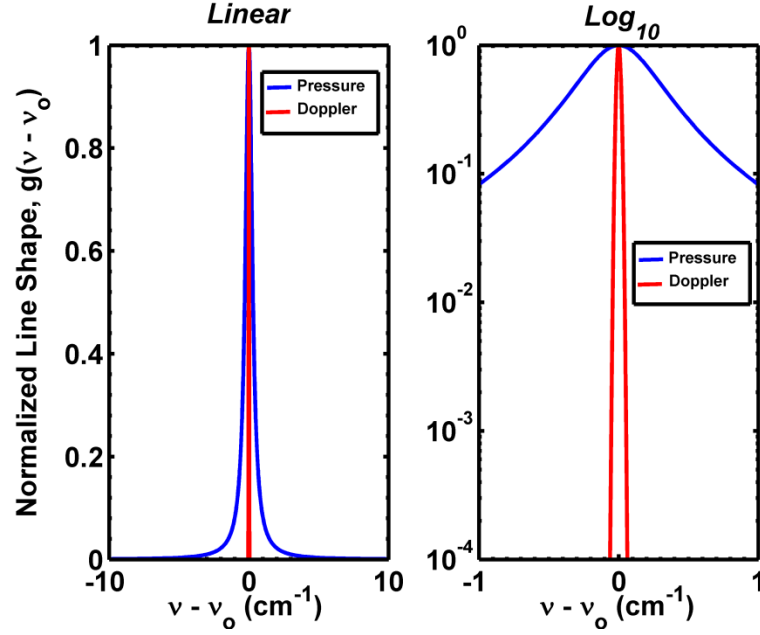


Figure 9 Normalized line shapes due to pressure and Doppler broadening in the atmosphere. The log scale on the right shows the Doppler broadened line shape to represent a delta function near the surface. $S_o = 1.477 \times 10^{-23} \text{ [cm}^{-1}/(\text{molecule cm}^{-2})]$, $\gamma_o = 0.0969 \text{ cm}^{-1}$, and standard temperature and pressure (296 K, 1-atm.) were used as inputs for the simulation.

Voigt Distribution

Although the DIAL instrument presented here focuses on the retrieval of the water-vapor density in the lower atmosphere, $\sim 0\text{-}6$ km above ground layer, where pressure broadening dominates, the effects of both broadening mechanisms must be accounted for in order to accurately describe the water line shape as a function of altitude. To do so, a convolution of the Lorentz and Gaussian line shapes must be calculated for a given water-vapor absorption line. The Voigt profile describing the range dependent water-vapor absorption cross section can be expressed as

$$V(x, y) = \frac{\sigma(x, y)}{K} = \frac{y}{\pi} \int_{-\infty}^{\infty} \frac{e^{-t^2}}{y^2 + (x - t)^2} dt, \quad (2.23)$$

where $\sigma(x, y)$ is the absorption cross section, $x = \left[\left(\frac{\nu - \nu_0}{\gamma_D} \right) \right] (\ln 2)^{1/2}$, $y = \left(\frac{\gamma_L}{\gamma_D} \right) (\ln 2)^{1/2}$, and $K = \left(\frac{S(T)}{\gamma_D} \right) \left(\frac{\ln 2}{\pi} \right)^{1/2}$. Once again, values of γ_0 , S_0 , and E'' are obtained from the HITRAN database.

The Voigt spectrum of the water-vapor absorption cross sections at two different altitudes for wavelengths near the center of the gain spectrum of the commercially available TSOA's are shown in Figure 10. Narrowing of the absorption lines is evident at higher altitudes as a result of Doppler broadening. Due to conservation of energy, the Doppler broadening at higher altitudes causes the absorption line shape to approach a delta function, resulting in an increase in the absorption cross section at the center of an absorption feature and a decrease in the cross section on the wings.

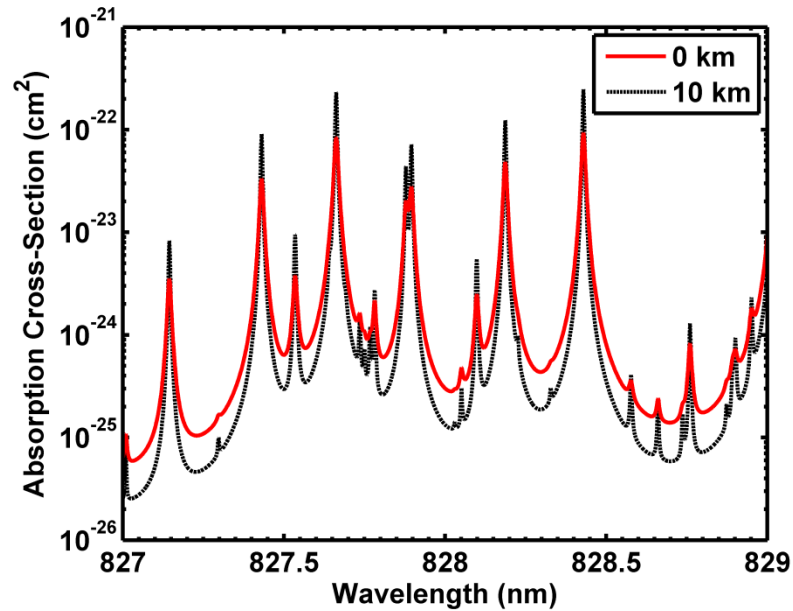


Figure 10 Water-vapor absorption cross section at 0 and 10 km calculated using a Voigt distribution. Narrowing and intensifying of the absorption lines is evident at higher altitudes due to the absence of pressure broadening.

Because of the broad wings of the pressure broadened lines at lower altitudes, contributions from the wings of neighboring lines are considered at all wavelengths when calculating the cross-section spectrum, resulting in a water-vapor continuum rather than discrete lines. In the absence of radiosonde measurements for the calculation of the cross sections, the temperature and pressure profiles in the troposphere can be estimated using a standard atmosphere model along with surface temperature, T_s , and surface pressure P_s . The temperature in the lower troposphere $T(r)$ is modeled using (Kovalev & Eichinger 2004)

$$T(r) = T_s + \gamma_a r, \quad (2.24)$$

where γ_a is the adiabatic lapse rate (i.e. temperature change per change in height) which ranges between -1 to -6 to -30 [K/km] for dry, average, and superadiabtic lapse rates, respectively. Typically, an adiabatic lapse rate of ~ -6.5 K/km is used to model the atmosphere between the surface and 10 km. Using the modeled temperature profile, the pressure profile can be modeled as (Kovalev & Eichinger 2004)

$$P(r) = P_s \left[\frac{T_s}{T(r)} \right]^{-5.2199}, \quad (2.25)$$

where $P(r)$ and P_s are in Pascal's.

Absorption-Cross-Section Temperature Sensitivity

Before moving forward with the selection of an appropriate-strength water absorption line, a temperature-sensitivity analysis must be carried out in order to estimate the errors induced in the number-density measurement resulting from changes in atmospheric temperature. The condition where the line center absorption cross section σ_0

is independent of temperature can be determined by differentiating σ_0 with respect to T and setting it equal to zero. The temperature sensitivity for the number-density measurement was calculated using methods presented by (Browell, Ismail & Grossman 1991) and can be expressed as

$$\frac{1}{dT} \frac{d\sigma_0}{\sigma_0} \approx \frac{1}{T - T'} \frac{\sigma_0(T) - \sigma_0(T')}{\left[\frac{\sigma_0(T) + \sigma_0(T')}{2} \right]}, \quad (2.26)$$

where $\sigma(T)$ is found using equation (2.23). The number-density error as a function of temperature at 1.0 atm. and 0.5 atm. for different values of E'' for a line similar to the 828.187 nm absorption line is shown in Figure 11. Details of the 828.187 nm line's parameters will be discussed in further detail throughout this chapter. Although not optimal, the systematic errors in the number-density measurements as a result of the sensitivity of the absorption cross section to changes in atmospheric temperature are far less than the random errors associated with noise sources such as background solar radiation, which can be ~ 5 -10% of the total measurement.

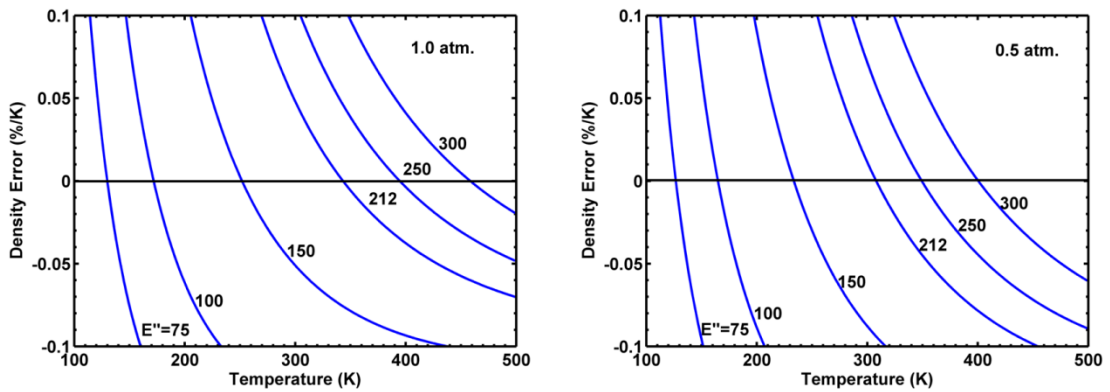


Figure 11 Temperature sensitivity calculations of water-vapor number-density errors at 1.0 and 0.5 atm. over varying E'' for the 828.187 nm absorption line. A shift in the temperature neutral point from ~ 360 K at 1.0 atm. to ~ 325 K at 0.5 atm. is observed.

Water-Vapor Optical Depth

In order to accurately measure tropospheric water-vapor profiles for a given geographic location, care must be taken in picking an optimal strength absorption line. Given that the absorption cross section spectrum has been calculated using methods described earlier, the range resolved increment in optical depth can be calculated using $\Delta\tau = N_{H_2O}\sigma_{on}\Delta r$ where the typical range resolution $\Delta r \sim 150$ m. As stated previously, the optimal OD per bin in order to achieve an acceptable SNR in the density determinations should range between 0.02-0.1. To calculate the range-resolved OD for a given absorption line, a modeled atmosphere consisting of temperature, pressure and water-vapor is required. For this section, the U.S. standard atmospheric model (U.S. Standard Atmosphere 1976) was used to calculate the OD, not to be confused with the modeled atmosphere derived from surface measurements and equations (2.24) and (2.25) used for day to day calculations in the DIAL measurements. The components of the modeled atmosphere used for the water-vapor OD calculations are shown in Figure 12.

An absorption line with $E'' = 212 \text{ cm}^{-1}$ that was generally clear of interference from other absorption features was identified as a potential candidate for the DIAL measurement. Its wavelength is 828.187 nm in vacuum, corresponding to $12074.5677 \text{ cm}^{-1}$. The OD calculations for this line are shown in Figure 13 and nominally fall within acceptable ranges. The water-vapor OD per 150 m range bin as well as the cumulative OD in the three scenarios for the 828.187 nm absorption line shown in Figure 13 are appropriate for the year round conditions observed over Bozeman, MT (U.S. mid-latitude summer/winter). Given prior experience in measuring water-vapor over Bozeman, a

per-bin OD ~ 0.02 near the surface due to water-vapor absorption is desired.

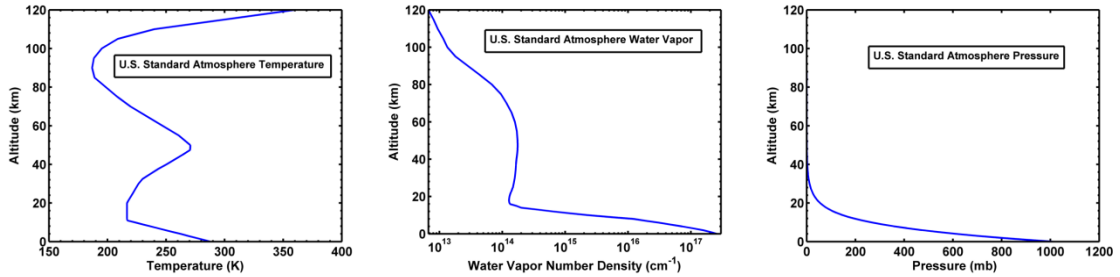


Figure 12 Modeled U.S. standard atmosphere parameters which are used as inputs for absorption-line calculations.

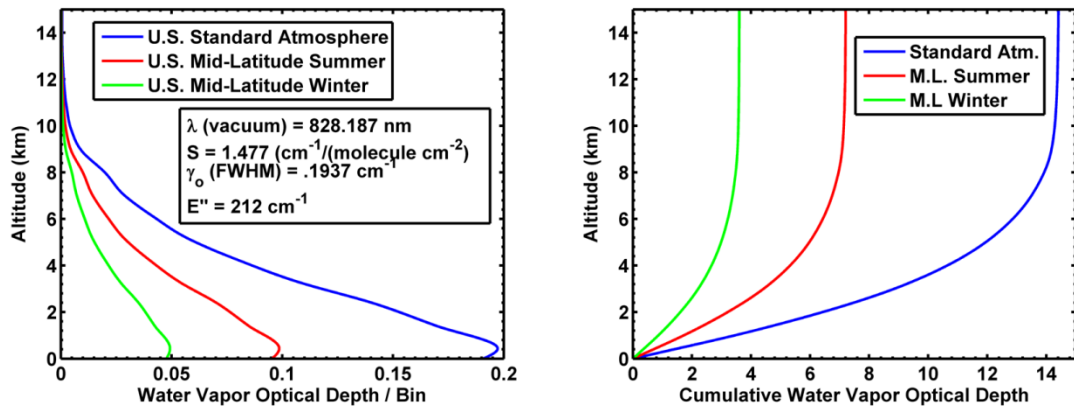


Figure 13 Left) Water-vapor optical depth profiles for the 828.187 nm absorption line for U.S. standard atmosphere, U.S. mid latitude summer and winter. Right) Cumulative OD for same input parameters as figure on the left.

Side-Line Tuning

Given the difficulty of finding temperature-insensitive water absorption lines of appropriate strength, side-line tuning of a desirable absorption line can be exploited to achieve varying OD's. As seen from the Voigt distribution of the water-vapor absorption

spectrum shown in Figure 10, the absorption cross section decreases rapidly away from the center of the absorption line. By tuning the probing frequency to the side of the water-vapor absorption line, smaller absorption cross sections, i.e. ODs, can be achieved, therefore resulting in higher SNRs of the collected backscatter signal. Examples of the sensitivity of the absorption cross section for the 828.187 nm absorption line to small offsets in frequency from the center of the line are shown in

Figure 14. Typically, for year-round operation, the probing frequency is detuned by ~ 3 -8 pm (~ 1.3 -2.0 GHz) to achieve optimal SNRs in the online backscattered returns.

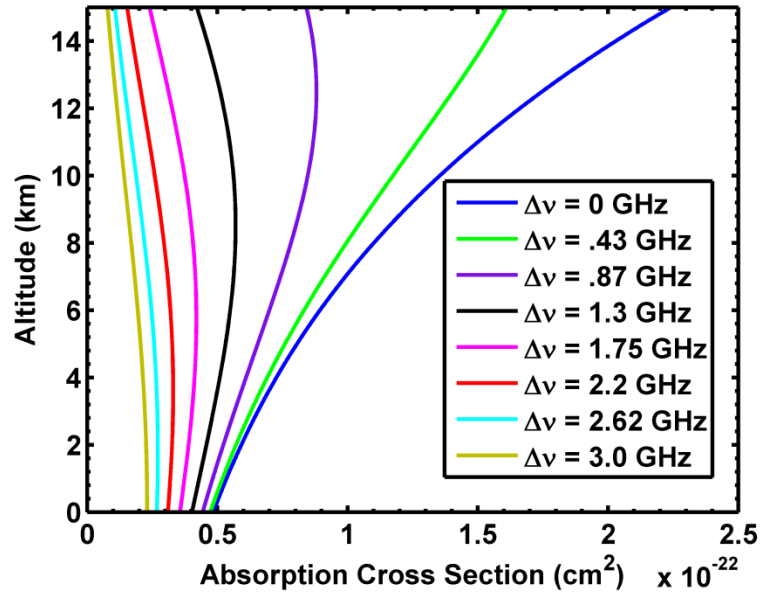


Figure 14 Water-vapor absorption cross section profiles for various detuning frequencies relative to the line center at 828.187 nm in vacuum as a function of altitude. A turn around point is visible around ~ 1 GHz where the absorption cross section begins to decrease as a function of altitude due to the decrease in the pressure broadening.

Pressure Shift

Accurate retrievals of atmospheric water-vapor using the DIAL technique requires detailed knowledge of the selected absorption line shape. A knowledge of the exact position of the line center of a given absorption line is also needed for accurate calculation of the absorption cross section spectrum. The shift of the absorption-line center with the pressure of the surrounding atmosphere can lead to large errors if not accurately accounted for. Air-induced pressure shifts have been measured in the 815 nm and 940 nm portion of the spectrum (Ponsardin & Browell 1997; Bosenberg 1985) where typical values ranged from 0.01-0.04 $\text{cm}^{-1}/\text{atm.}$.

The air-induced pressure-shift coefficient for the 828.187 nm line was calculated using horizontal-saturated-spectrum measurements through the lower atmosphere, which will be described in further detail in chapter five. A nominal air-induced pressure-shift coefficient of $-0.0428 \text{ cm}^{-1}/\text{atm.}$ was measured. The altitude dependent pressure-shift coefficient for the 828.187 nm absorption line, derived using surface temperature and pressure along with a modeled standard atmosphere as presented in equation (2.25) is shown in Figure 15. The effects of atmospheric density on both the line shape as well the location of the center of the water-vapor absorption line is depicted in Figure 16. A shift in the center of the absorption line as well as a broader line width resulting from pressure broadening is evident at the surface.

A decrease of the pressure broadening (along with some decrease in Doppler broadening) causes the line to shift back to the vacuum frequency line center at the top of the troposphere. Without accounting for the pressure-induced shift in the absorption line

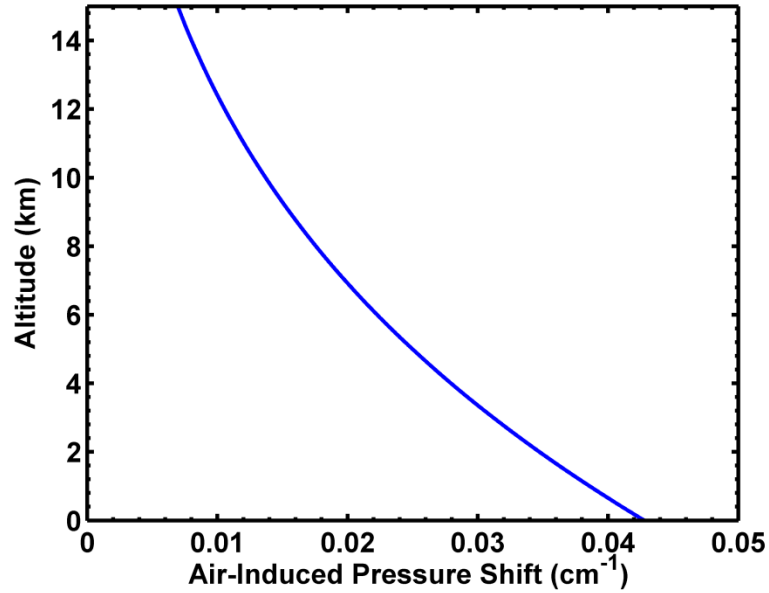


Figure 15 Magnitude of the air-induced pressure shift as a function of altitude for the 828.187 nm absorption line. Surface temperature and surface pressure values of 296 K and 1.0 atm were used to model the atmospheric pressure.

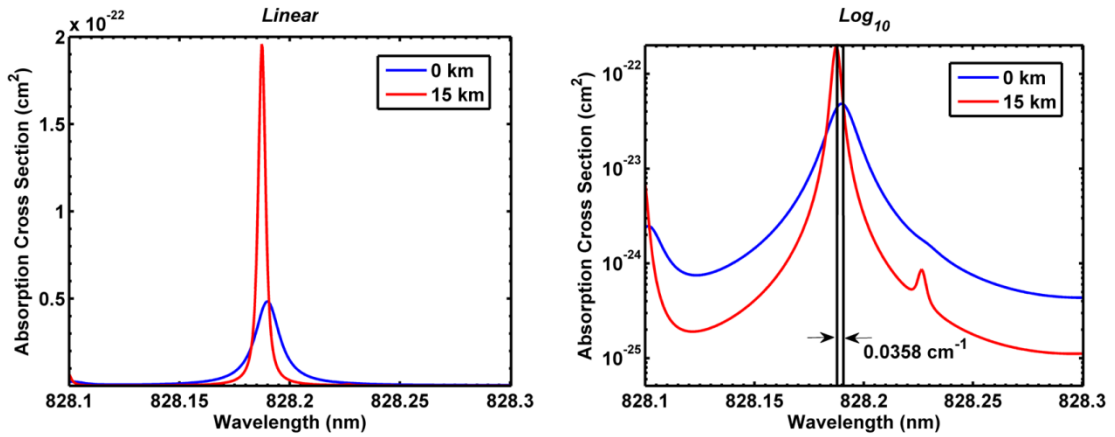


Figure 16 Left) Air-induced pressure shift on a linear scale depicting the shift of the line at lower altitudes as well as the Doppler narrowing and intensification of the line at higher altitudes. Right) Same as left figure except on a $\log_{10}$ vertical scale, further illustrating the effects of the pressure shift and line broadening at lower altitudes.

at lower altitudes, there will be significant positive or negative systematic errors in water-vapor-number-density retrievals, depending on the location of the probing frequency along the absorption feature. A simulation of the effects of the pressure-induced shift at two different probing frequencies is shown in Figure 17. For a probing frequency at the line center in vacuum, the absorption cross section is over estimated, hence causing an underestimation of the retrieved water-vapor profile. For side-line operation of the probing frequency, $\Delta\nu \sim 2.5$ GHz, underestimation of the cross section causes an over estimation of the water-vapor densities in the retrievals.

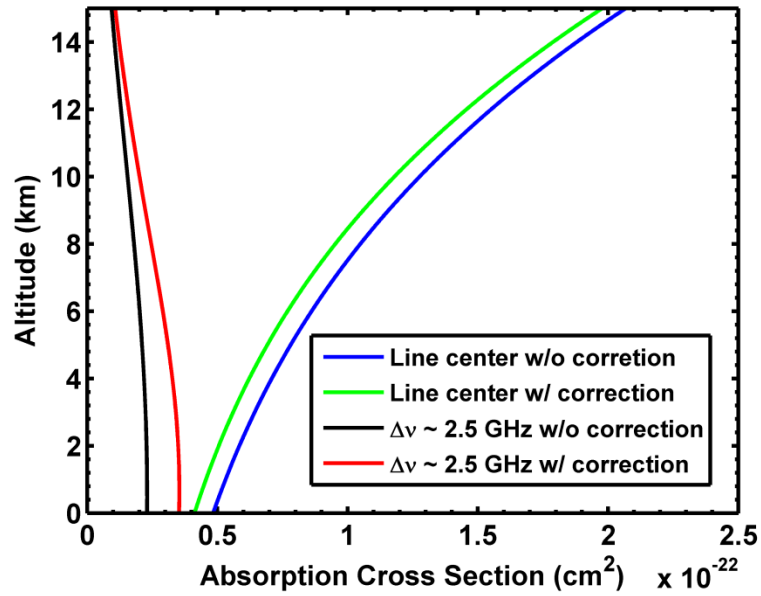


Figure 17 Voigt distributed absorption cross section as function of altitude resulting from the pressure-induced shift of the spectral position of the line for two probing frequencies along the absorption feature. $\Delta\nu \sim 2.5$ GHz implies a positive shift in the probing frequency to the side of the absorption feature.

Selected Water-Vapor Absorption Line

The three primary criteria used for the selection of a water-vapor absorption line for use in the DIAL technique include picking a temperature-insensitive line, choosing an absorption feature with appropriate line strength, and assuring the absence of interfering absorption lines nearby. Given this recipe, the most appropriate water-vapor absorption line that also overlapped with the gain spectrum of the TSOA that is used in the transmitter was at 828.187 nm in vacuum (828.0069 nm in air at 1.0 atm). The much less constrained offline wavelength was chosen to operate around 828.287 nm in vacuum (828.1069 nm in air), in order to avoid interference from the neighboring line. Side-line tuning of the water-vapor absorption line is operated between 828.19 nm-828.195 nm in vacuum depending on the moisture level and the time of year. Sideline tuning of the water-vapor absorption line is made possible by accurate knowledge of the line shape. The line parameters used to calculate the Voigt spectrum for the absorption line used in this dissertation are as follows: the line strength $S=1.477 \times 10^{-23} \text{ cm}^{-1}/(\text{molecule cm}^{-2})$, the pressured broadened linewidth (FWHM) $\gamma_0=0.1937 \text{ cm}^{-1}$ at sea level, the linewidth temperature dependence $\alpha=0.68$, and the ground state transitional energy $E''=212.2 \text{ cm}^{-1}$.

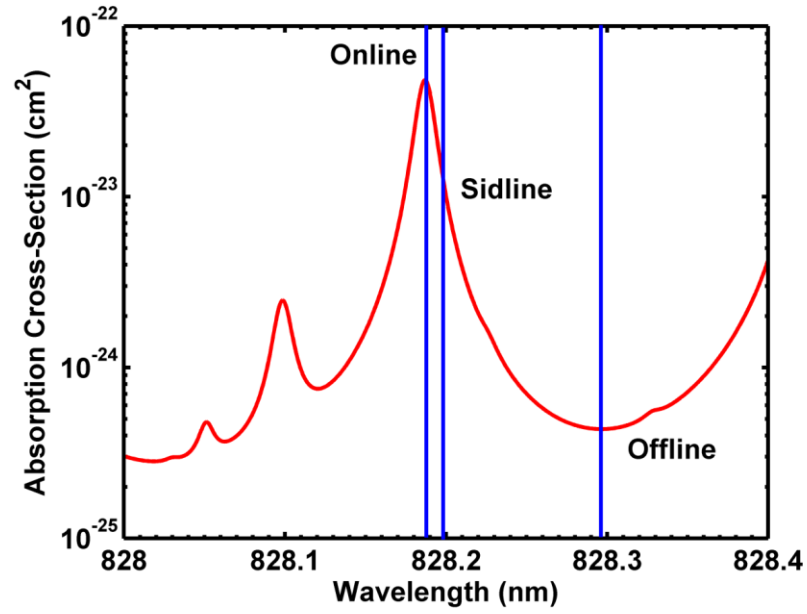


Figure 18 Voigt distribution (near surface) of the water-vapor absorption line used for the DIAL measurements in this dissertation. The indicated online, sideline, and offline wavelengths (in vacuum) used in this study are 828.187 nm, ~828.193 nm, and ~ 828.287 nm, respectively.

SECOND GENERATION DIAL INSTRUMENT AND PERFORMANCE

A first generation DIAL instrument was designed and built based on commercially purchased TSOA's. The passively pulsed transmitter yielded ~ 150 nJ pulses, requiring long integration periods to obtain nighttime water vapor profiles in the lower atmosphere. A detailed description of the first generation DIAL instrument is presented in (Nehrir 2008). A second generation water-vapor DIAL instrument has been developed based on pulsed semiconductor optical amplifiers to overcome the power limitations imposed by the first generation transmitter. The second generation DIAL transmitter makes use of the same diode-laser-based ECDL seed source as the first generation DIAL but incorporates actively pulsed TSOA's to achieve peak pulse energies ranging from 1-2 μ J, a factor of 10-20 greater in energy than the passively pulsed transmitter of the first generation DIAL. The second generation DIAL receiver was also redesigned to use an extremely compact light tight fiber coupling assembly, decreasing the ambient background noise of the DIAL instrument compared to the first generation instrument. This chapter will give a detailed description of the second generation DIAL transmitter and receiver components. Several data sets will also be presented, demonstrating the performance of the instrument under daytime and nighttime operating conditions.

Instrument Description

The first generation water-vapor DIAL instrument was developed in order to demonstrate the capabilities of diode laser based DIAL instruments (Nehrir 2008). Low

peak and average transmitted powers, limited by commercially purchased TSOA's modules, resulted in relatively long integration periods required for sufficient SNR's, yielding moderate temporal resolution (~ 1 hour) water-vapor profiles up to 2.5 km during nighttime only. A higher power DIAL laser transmitter was implemented in the second generation water-vapor DIAL to overcome the limitations set by the lower power first generation transmitter.

Master Oscillator

A schematic of the second generation water-vapor DIAL transmitter is shown in Figure 19. The entire second generation DIAL instrument is housed on a 24" x 48"

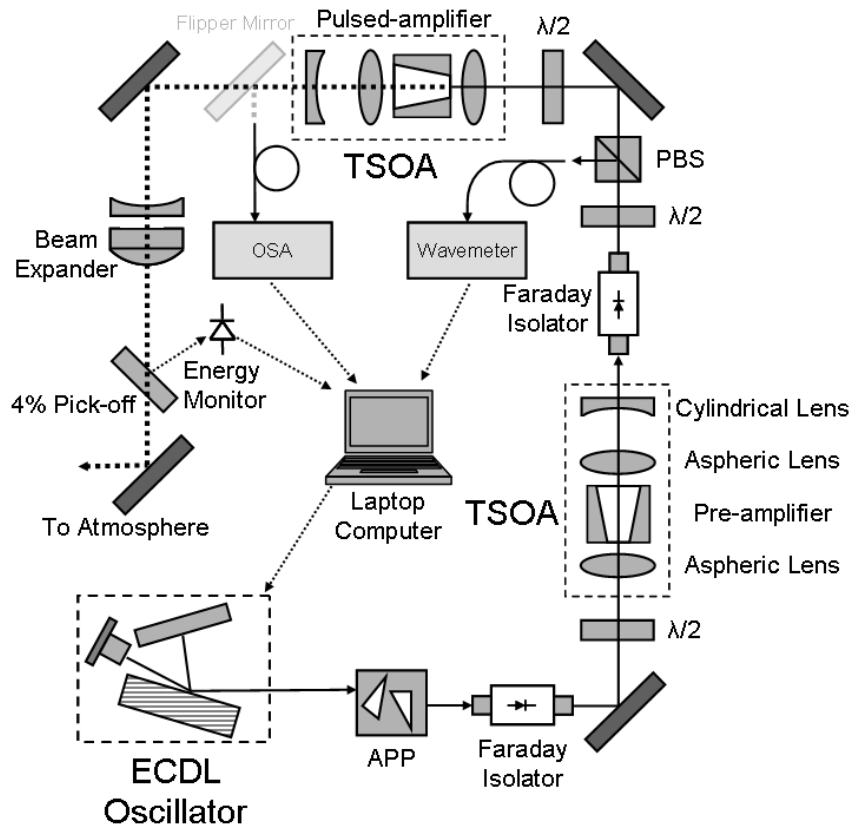


Figure 19 Schematic of the second generation DIAL transmitter.

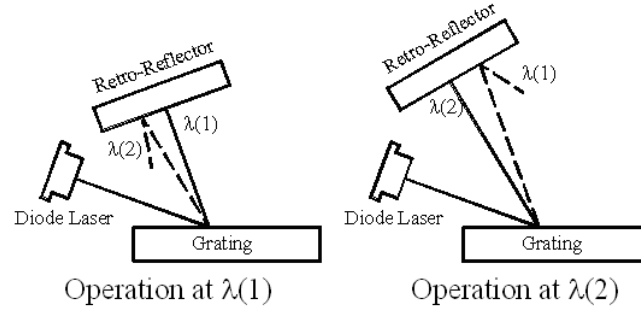


Figure 20 A schematic of the ECDL in the Littman-Metcalf configuration. The drawing on the left shows operation of the ECDL at $\lambda(1)$. Here, the first order reflection from the grating is directed back to the diode laser via a second reflection from the grating. This feedback forces the ECDL to operate at $\lambda(1)$. Continuous tuning of the ECDL is achieved by simultaneously rotating and moving the retro-reflecting roof prism so that $\lambda(2)$ is fed back into the laser diode while maintaining the cavity resonance condition at this new wavelength. This is shown schematically by the drawing on the right.

optical breadboard. A widely tunable ECDL based on a Littman-Metcalf configuration (Littman & Metcalf 1978; Switzer 1998) capable of accessing the water-vapor absorption band ranging from 824 nm to 841 nm is used as the master oscillator or seed source for the water-vapor DIAL instrument. The basic operating mechanisms in the Littman-Metcalf ECDL used is schematically shown in Figure 20. A 150 mW diode laser with a center wavelength of 830 nm (SDL-5421) is collimated using an aspheric lens with a focal length of 4.5 mm and a numerical aperture of 0.55 (Thor Labs 350230-B). The collimated light is incident on a 1600 line/mm holographic grating 15 mm wide by 60 mm long by 10 mm thick (Spectragon) at a grazing angle of three degrees which spatially separates the different spectral components. The first-order reflection from the diffraction grating is found from the grating equation $M\lambda = d(\sin\theta_i + \sin\theta_r)$ to be 71 degrees where $\theta_i(\theta_r)$ is the angle between the incoming (reflected) beam and the surface

normal of the diffraction grating, λ is the wavelength, and d is line spacing of the diffraction grating. The first-order reflection is next incident on a roof prism that directs the light back into the diode laser via a second reflection from the diffraction grating. The external cavity has a free spectral range $FSR = \frac{c}{2L}$ of 3.9 GHz, corresponding to a 3.8 cm long external cavity, where c and L are the speed of light and the length of the external cavity which is formed from the back facet of the diode laser, off of the diffraction grating, and to the roof prism. The roof prism rotates so that the resonant cavity length (integer number of half wavelengths) changes in concert with the wavelength of light fed back to the diode laser allowing for mode-hop free tuning. The roof prism can be rotated mechanically by a 3/16-100 screw for coarse tuning. The pivot point calculation to ensure continuous tuning over a finite range was chosen using methods presented by (McNicholl & Metcalf 1985). Fine rotation of the roof prism is achieved by applying a voltage to a piezoelectric transducer (PZT) stack (Thor Labs AE0505D16), giving mode-hop free tuning of over 20 GHz at a fixed diode temperature with a tuning rate of ~ 400 MHz/V.

The ECDL is placed on a thermo-electric cooler (TEC) for temperature stabilization. A 10 k Ω thermistor is used to monitor the temperature of the ECDL and a commercial temperature controller (ILX Lightwave LDD3722) is used to stabilize the temperature to within 0.1 C. A commercial current controller (ILX Lightwave LDD3722) is used to supply a drive current to the diode laser. The ECDL is operated in a cw mode and its performance is summarized as follows. The coarse tuning ranges from 824 nm to 841 nm with a mode-hop free tuning range greater than 20 GHz and the full

width half maximum line-width of less than 200 kHz. The laser linewidth was measured prior to this investigation using methods presented by (Switzer 1998). The maximum output power of the ECDL is ~ 10 mW, with a side-mode suppression of greater than 45 dB. A picture of the ECDL used in the DIAL transmitter is shown in Figure 21.

The output from a widely tunable ECDL in the Littman-Metcalf configuration has the narrow linewidth and broad tunability needed for the DIAL transmitter, but exhibits low cw output power. To increase the optical power while maintaining the good spectral properties of the master laser, the ECDL is used to injection seed two custom built cascaded TSOA's. To avoid vignetting on the input apertures of various optical components throughout the DIAL transmitter, the output from the ECDL is first circularized using an anamorphic prism pair (APP). The beam is then isolated using a 30 dB Faraday isolator to avoid unwanted feedback from the first stage tapered pre-amplifier from affecting the spectral properties of the master ECDL oscillator.

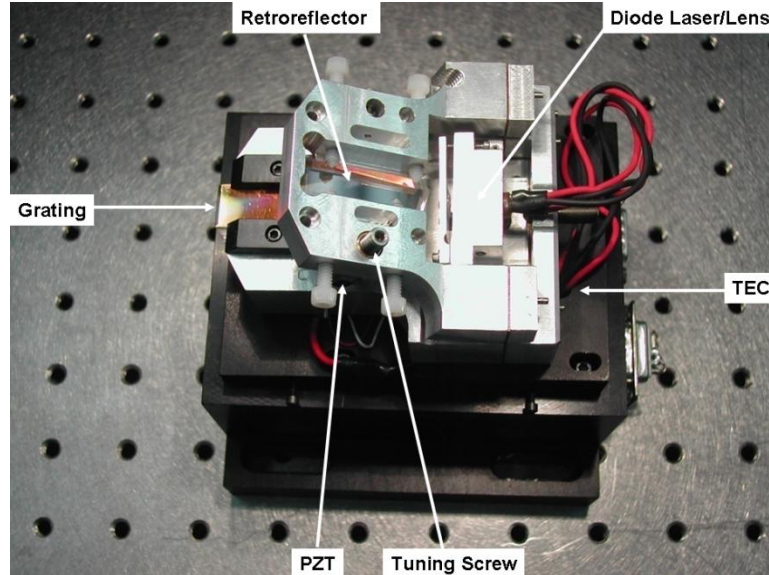


Figure 21 Photograph of the ECDL built in the Littman-Metcalf external-cavity configuration used to injection seed cascaded flared amplifiers used for the DIAL transmitter.

Power Amplifiers

To avoid large changes in the output power of the DIAL transmitter due to small fluctuations in the seed laser output power resulting from changes in the amplified spontaneous emission (ASE) spectrum as the ECDL tunes on and off the water-vapor absorption line (Repasky et al. 2006), a cascaded power-amplifier configuration is used. The output from the ECDL is used to injection seed a TSOA (EYP-TPA-830-01000) rated up to 1 watt cw. The TSOA is a two component device consisting of a ridge waveguide section for input coupling of the seed light and a tapered gain region where the amplification occurs. The amplifier is housed in a C-mount package. As shown in Figure 22, the anti-reflection (AR) coatings on both facets of the diode amplifier suppress lasing and provide an extremely large gain bandwidth approaching 30 nm around 830

nm. These types of amplifiers have high gains approaching 13 dB for cw seed input powers of 10-50 mW.

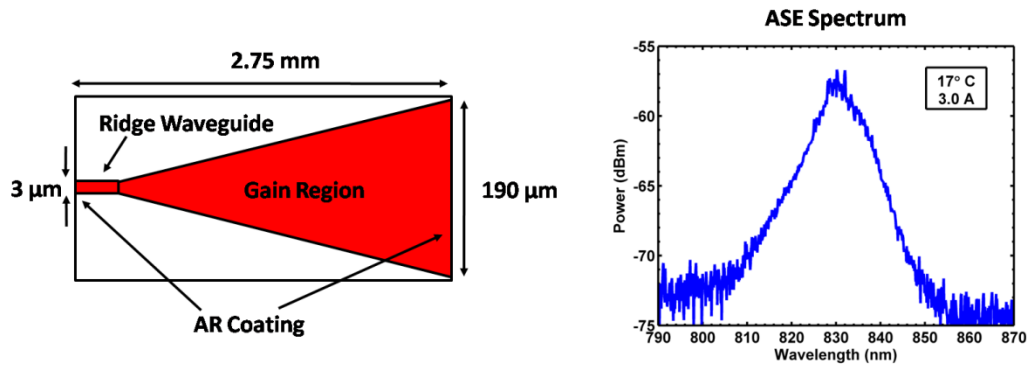


Figure 22 Left) TSOA chip structure (not to scale). Right) Unseeded cw ASE spectrum.

Typical laser diodes consist of a ridge waveguide gain medium which yields an increasing optical intensity along the length of the gain medium. This geometry limits the maximum practical gain because the chip's output facet would be destroyed by optical damage at the desired high intensities. In contrast, TSOA's permit extremely high gains because of the geometry of the gain medium. The tapered gain region provides an increasing area as the seeded traveling wave propagates down the chip. This increasing area results in a constant optical intensity that allows for high powers to be extracted from the device without optical damage to the output facet. This configuration is beneficial for amplifying weak signals in practice, but presents complications for an experimental setup.

Because the input aperture of the ridge guided section to the amplifier is 3 μm in width, care must be taken in designing a compact and stable housing for the diode in

order to assure stable and efficient coupling of the seed light into the TSOA. The custom built tapered amplifier housings consists of two main sets of components, a strain released and thermally compensated brass housing for the C-mount TSOA, and two modified commercially available 3-axis fiber chucks that house the input- and output-coupling optics. A schematic of the components of TSOA housing as well as an exploded view of a solidworks assembly are shown in Figure 23. A picture of the first and second stage amplifiers as well as the input and output coupling optics in the second generation DIAL transmitter is also shown in Figure 24. A detailed description of the design and characterization of the TSOA housings is presented in (Xiong et al. 2006; Xiong 2007).

In addition to the stability requirements, the geometry of the tapered gain region yields an extremely large output aperture width of 190 μm resulting in a highly anamorphic and astigmatic output beam which requires multiple beam-shaping optics to collimate. From the manufacturer's datasheet, the divergence angles parallel and perpendicular to the semiconductor junction are 15° and 28° , respectively. In order to collimate the output and achieve a circular beam profile, a two stage set up is required, consisting of an aspherical lens to collimate the fast axis (perpendicular to the junction) and a cylindrical lens for the slow axis (parallel to the junction). Figure 25 shows a functional schematic of the input and output coupling optics. A 4.5 mm (0.55 NA) focal length aspheric lens (Thorlabs C230TM-B) is used to provide sufficient mode matching into the TSOA. Because the TSOA junction height is constant over the length of the 2.75 mm laser chip, an identical aspheric lens was also used to collimate the fast

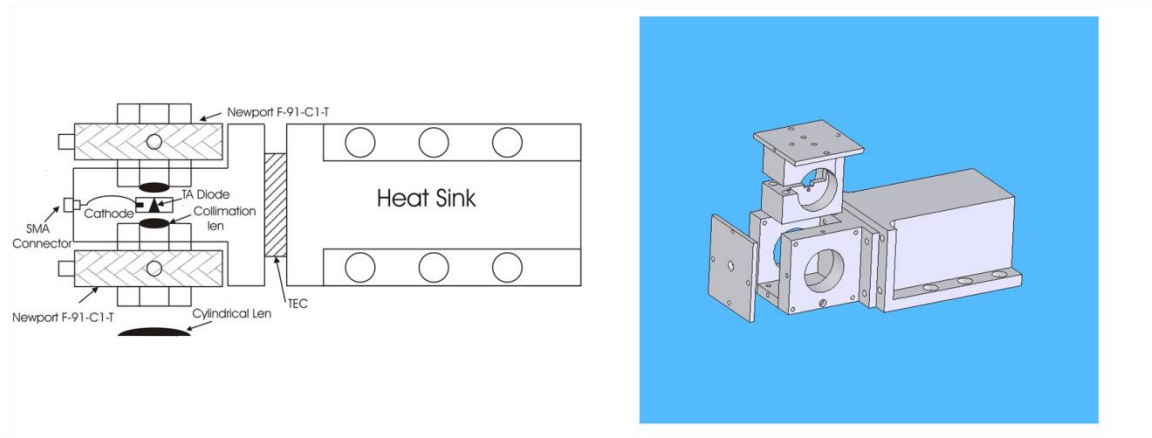


Figure 23 Left) Schematic of the TSOA housing. The two modified Newport F-91-C1-T components house the aspheric lenses that allow for the coupling of the seed light to the gain region as well for the collimation of the fast axis of the amplifier output. Right) Solidworks assembly of the TSOA housing. Schematic and assembly drawing courtesy of Yihan Xiong (Xiong et al. 2006; Xiong 2007).

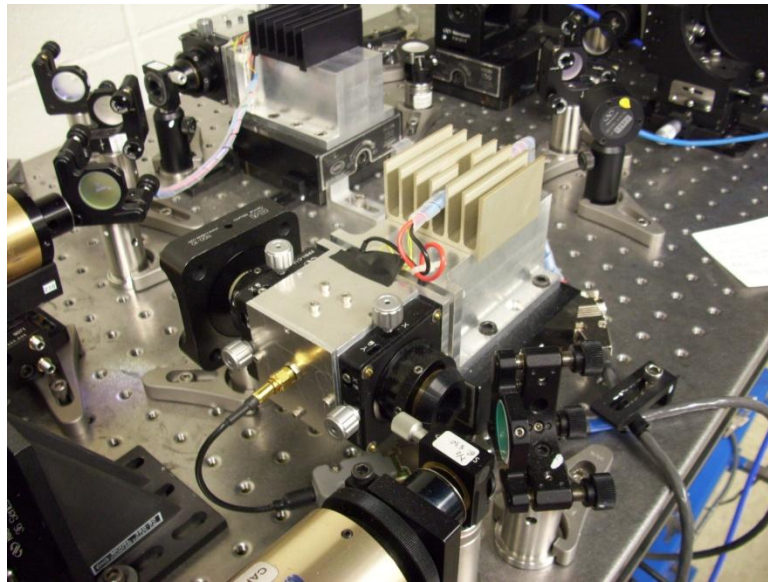


Figure 24 Picture of the first and second stage TSOA housing as well as accompanying optics in the second generation DIAL transmitter. The TSOA housings are approximately 6" L X 2" W X 2" H .

(perpendicular) axis of the TSOA output. Using geometrical ray tracing methods presented by (Xiong 2007), the slow(parallel) axis of the output beam was collimated by using a 50 mm focal length cylindrical lens, providing a nominally circular output beam profile (Appendix B). In order to efficiently extract the energy from the TSOA, the polarization of the input beam is aligned parallel to the junction plane (TM) of the first-stage amplifier using a zero order half wave plate (HWP).

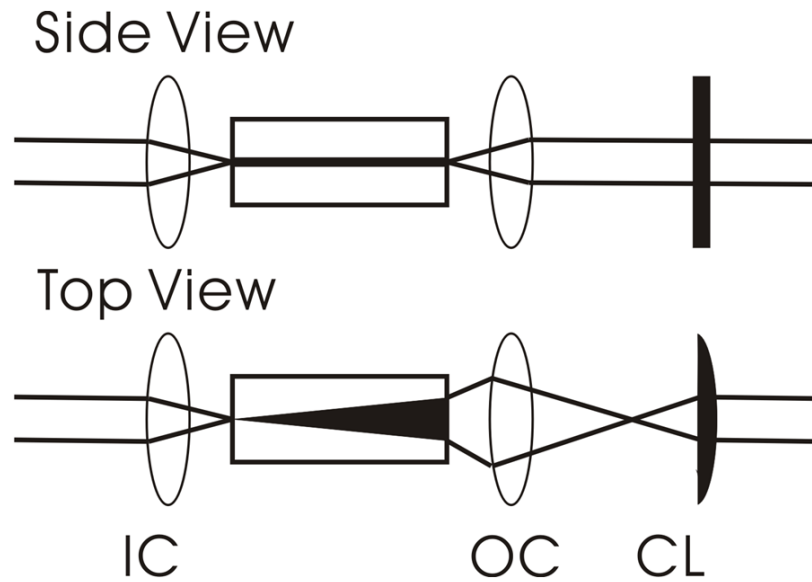


Figure 25 Side and top views of the optical setup used to collimate both axes of the TSOA. Because the input aperture is a ridge waveguide which is more so symmetric than the output, a single stage aspherical optic suffices for efficient mode matching into the TSOA. IC, OC and CL are acronyms for the input coupler, output coupler, and cylindrical lens, respectively.

Alignment of the ECDL seed source to the input aperture of the TSOA is achieved using a three step process. First, under low operating current currents, ~ 1.5 A cw, the ASE output from the input aperture of the TSOA is collimated by using the focusing motion of the input coupling lens. The collimated ASE from the input aperture

is then nominally aligned to the seed beam, and vice-versa, by using a two-iris dog-leg configured bore-sight system. Once the two beams are aligned to each other, the current driving the TSOA is turned off and its leads are connected in series with an ammeter so the TSOA functions as a photodetector. The alignment is optimized by maximizing the photocurrent resulting from the absorption of the coupled seed light with the adjustment of the bore sighting mirrors as well as making very minute changes to the focal point of the input coupling lens. Typical photocurrents measured for an optimal alignment setup ranges between 6-7 mA for seed powers > 50 mW. Once the photocurrent is maximized, the TSOA power supply is again connected, and the cw output signal is maximized by making very small adjustments to the bore sighting mirrors. Once maximized in the cw regime, the desired pulsed current is supplied to the TSOA and final adjustments are made to the bore sighting mirrors keeping in mind that the amplifier is much more prone to being electrically and optically damaged in the overdriven pulsed regime.

Injection Seeded Transmitter

The low cw output power of the seed laser is not sufficient to saturate the gain of the TSOA, hence a pre-amplification stage is required to ensure optimal power stability in the second stage pulsed TSOA. The pre-amplifier is operated with a cw forward bias current of 1.2 A, resulting in an amplification of the ~ 15 mW cw output of the ECDL up to 50 mW, a gain of ~ 5.2 dB. The output from the preamplifier is isolated using a 30 dB Faraday isolator to prevent feedback from the ASE of the second stage pulsed TSOA. The beam transmitted by the isolator is incident on a second half-wave plate followed by a polarizing beam splitter (PBS), so the fraction of light transmitted by the PBS is

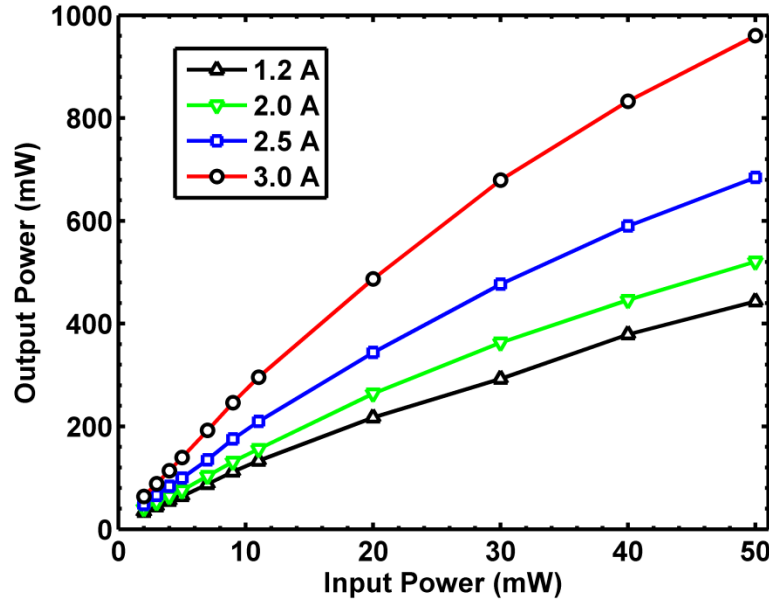


Figure 26 Continuous wave second stage TSOA output power as a function of available injection seeding power from for varying bias currents.

controlled by the orientation of the wave plate. Light rejected by the PBS ($\sim 1\%$) is sent to a wavemeter (Burleigh -1500) used to measure the seed laser's frequency (with precision of 88 MHz) for locking to the on-line, side-line, or off-line wavelength of a water-vapor absorption feature (Nehrir et al. 2009; Nehrir, Repasky & Carlsten 2011).

The light passed by the PBS is used to injection seed a second TSOA that is operated in saturation. A plot of the cw amplification of the second stage TSOA for various drive currents is shown in Figure 26. The temperatures of both amplifiers were stabilized to 15 °C. The input power to the second stage TSOA was varied from 1-50 mW using a half waveplate and a PBS for cw drive currents ranging from 1.2 A to 3.0 A. The small signal gain for cw seeding powers below 10 mW was measured to range from 12.43 dB to 14.66 dB for drive currents ranging from 1.2-3.0 A, respectively. A

saturated cw gain of 12.90 dB was measured for a 3.0 A drive current, yielding approximately a 1 W output for a 50 mw cw input seed power. The seeding efficiency has not yet been calculated but should be attainable with estimations of the intrinsic properties of the gain medium as well as the photocurrent measurements described in the alignment section.

Pulsing of the DIAL transmitter is achieved by directly modulating the forward current to the second stage TSOA. To evaluate the feasibility of an actively pulsed diode based DIAL transmitter, a time domain study of the output pulse train was performed. A nanosecond rise time silicon photodiode was used to measure the peak output power of the DIAL transmitter over 1 μ s pulse durations. The photo-detector was calibrated by measuring and fitting the small signal cw responsivity of the photodiode to that of a NIST traceable power meter. The temporal characteristics of the DIAL transmitter were studied by attenuating the output of the second stage TSOA using an OD 3.0 neutral density filter to avoid saturation affects and damage to the photodiode.

The performance of the DIAL transmitter was measured by applying 1.0 μ s square pulses of current to the second stage TSOA at a 20 KHz repetition rate with a 50mW cw seeding power. The current source used to drive the second stage TSOA (Directed Energy Incorporated PCX-7410) is rated to deliver current pulses ranging from 2-10 A, pulse widths variable from 50 ns to 500 ms with rise times <30 ns, and pulse repetition frequencies variable from single shot to 100 kHz. In order to reduce the parasitic inductance below that associated with standard current controller cables, a flat, low inductance cable is used to connect the current source to the TSOA. Furthermore,

experimental studies were carried out to address the impedance mismatch (due primarily to the small capacitance of the TSOA) between the current source and the TSOA which produced under-damped oscillations in the drive current actually reaching the amplifier, resulting in ringing in the output of the DIAL transmitter. A high power $4.8\ \Omega$ resistor was placed in series with the TSOA to reduce the drive current oscillations.

The absolute maximum rating for the cw operating current of the TSOA as specified by the manufacturer is 3.0 A, yielding up to 1 watt of output power with proper seeding. Higher peak powers have been obtained by overdriving the forward current to the TSOA in the pulsed regime. Low duty cycles and efficient conductive cooling to the large heat sink allows for the excess heat generated by the overdriven TSOA to be dissipated between laser shots. If the TSOA is not properly cooled, this technique of current pulsing can cause irreversible damage to the diode chip. A modulated forward current ranging from 3.0 A to 5.5 A was supplied to the TSOA to study the peak power as well as the shape of its output pulses. A small cw bias current of 100 mA was also supplied to the TSOA to alleviate thermal straining of the gain medium when modulating the TSOA with high current pulses. The cw bias current was chosen to provide an extinction ratio of greater than 1000 between the cw leakage light and the amplified pulsed output. A plot of the peak output power of the DIAL transmitter as a function of time for two values of the pulsed forward current is shown in Figure 27. A peak output power of 0.95 W and 1.78 W was achieved with a 50 mW input seed power over 1 μ s pulse widths for 3.0 A and 5.5 A forward currents supplied to the TSOA, respectively. High frequency impedance matching described above yields distinct square shaped

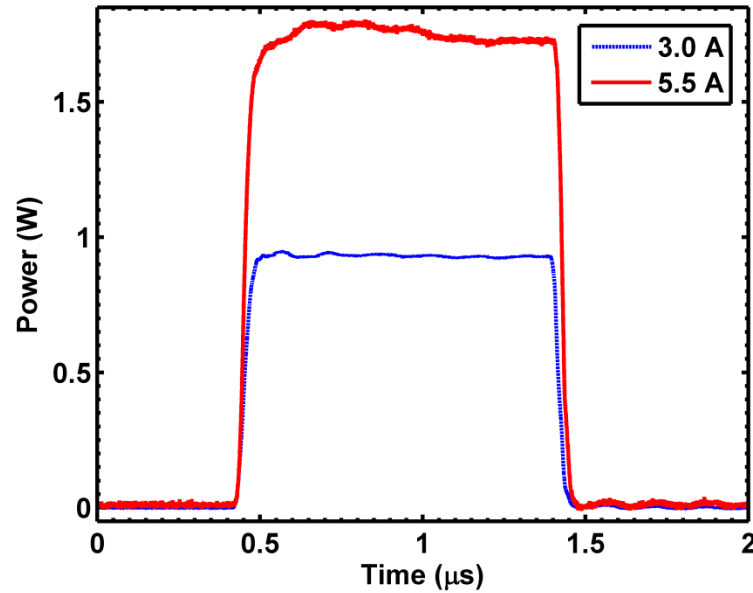


Figure 27 Time dependence of the output power of the injection seeded DIAL transmitter for a 3.0 A and 5.5 A current pulse. An increase in the output power of the DIAL transmitter is observed when the forward current to the second stage amplifier is overdriven above the manufacturers maximum specified 3.0 Amps.

pulses, with under damped oscillations suppressed to less than 1.5 % of the peak output power.

Higher peak powers achieved using larger pulsed forward currents have been observed in similar TSOA's at the increased risk of permanent damage to the input facet of the amplifier (Takase, Stockton & Kasevich 2007). For pulsed forward currents exceeding 6.5 A, back reflections from the collimation optics as well as from the input polarizer of the optical isolator behind the second stage amplifier resulted in significant reverse amplification through the gain medium causing irreversible damage to the input facet of the TSOA. Similar results were observed by Takase et al. (2007). The increased damage thresholds presented here over the damage thresholds presented by Takase et al.

(2007) are thought to be a result of the AR coatings of the collimation and isolation optics as well as a more efficient decoupling method of the back reflected light achieved by slight misalignment of the DIAL transmitter optics. As a result, the optical isolator after the second stage TSOA was removed to reduce the probability of reverse amplification and a careful misalignment technique of the subsequent transmitter optics was used. This technique resulted in a 15 % increase in the peak output power of the DIAL transmitter.

Stability and Spectral Purity

The cascaded master oscillator/power amplifier (MOPA) configured DIAL transmitter has been shown to produce up to 2.0 μJ of energy over a 1 μs pulse duration with a pulse repetition frequency of 20 kHz, yielding an average output power of approximately 40 mW. The long term pulse energy fluctuations were measured to be $\sim \pm 1.4\%$ of the mean value over a two day period. Figure 28 shows the long and short term

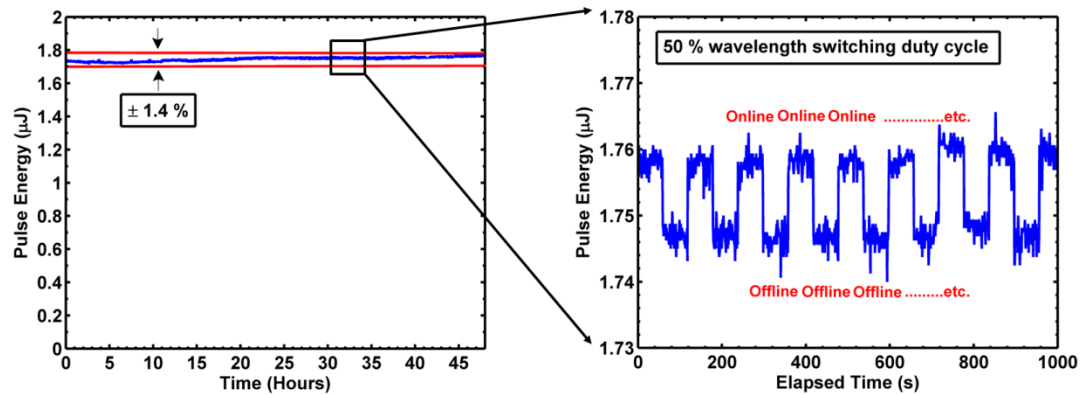


Figure 28 Left) DIAL transmitter pulse energy stability over a 2 day period. Excellent pulse energy stability of approximately $\pm 1.4\%$ is observed over the 48 hour measurement duration. Right) Zoomed in view of a segment of the 48 hour measurement, revealing the short term stability of the interleaved wavelength switching of the DIAL transmitter. 60 second dwell times were used for the online and offline wavelengths.

laser pulse energy stability over a 48 hour period. An expanded segment of the long duration measurement shown on the right reveals the interleaved wavelength switching every 60 seconds between the online and offline wavelengths used for the DIAL retrievals.

Although the relatively high pulse energies measured allow for lidar measurements to be retrieved at greater ranges, optimal seeding to ensure good spectral purity must also be a priority in order to make accurate measurements of atmospheric water-vapor. The spectral purity is typically defined as the ratio of the energy within a given acceptable spectral band around the absorption line center (~ 0.01 - 0.1%) to the total energy transmitted to the atmosphere (Ismail & Browell 1989). Typically this type of measurement is conducted with a multipath absorption cell containing a high partial pressure of the constituent of interest. The saturated spectrum measurement yields the spectral purity by taking the ratio of the light transmitted through the cell at the online and offline wavelengths. The light that leaks through to the detector when the transmitter is nominally tuned to the online wavelength is proportional to the spectral purity. Because of the long path lengths required to achieve a rigorous saturated spectrum measurement for the DIAL transmitter, the spectral purity of the second generation laser transmitter, instead, was estimated by integrating the transmitted spectrum captured from a moderate resolution optical spectrum analyzer. A typical transmitter spectrum used to infer the spectral purity as well as to assess the broad tunability of the transmitter is shown in Figure 29. The DIAL laser transmitter can be tuned from 824 nm to 841 nm, a

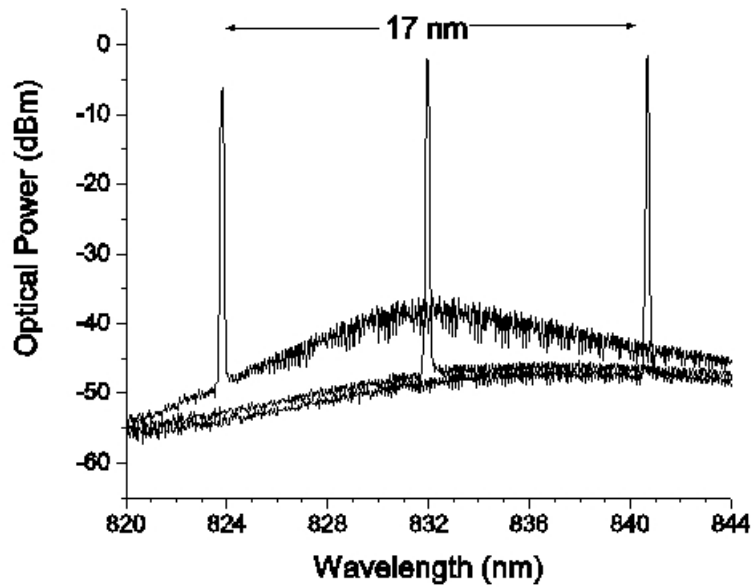


Figure 29 Continuous wave output power spectrum for the injection seeded DIAL transmitter. Good side mode suppression ratio and high optical power are maintained through the cascaded amplifier while still maintaining the spectral properties of the seed laser.

17 nm tuning range that allows for the probing of numerous water-vapor absorption lines with a wide range of line strengths, for operation in various geographic locations. The requirements for DIAL measurements with an error due to individual laser properties of less than 3% are shown in Table 3 (Bosenberg 1998). These properties arise from the fact that the absorption cross section of water-vapor absorption lines are highly dependent on the laser wavelength. If the laser linewidth, frequency stability, and spectral purity are not well known, systematic errors will arise in the water-vapor retrievals owing to uncertainty in the absorption cross section of water-vapor at the actual laser wavelength. The requirements on the laser transmitter for an error of less than 3% from individual laser properties include a linewidth of less than 390 MHz, a spectral purity of greater than

0.995, and a frequency stability of better than ± 210 MHz. The measured laser transmitter properties include a linewidth of less than 0.3 MHz, a spectral purity of greater than 0.995, and a frequency stability of ± 88 MHz (Obland 2007; Obland et al. 2007; Obland et al. 2010) .

Table 3 Required laser transmitter performance for tropospheric water-vapor profiling with a laser induced error of < 3.0 % (Bosenberg 1998).

Parameter	Requirement	Measured
Laser Linewidth (FWHM; MHz)	< 390	0.300
Frequency stability (MHz)	± 210	± 88
Spectral purity	> 0.995	> 0.995
Pulse length	< 200 ns	1 μ s
Beam divergence	< 1 mrad	~ 100 μ rad
Pulse energy	> 50 mJ	1-2 μ J
Repetition rate	> 10 Hz	20 kHz
$t_{on} - t_{off}$	< 1 ms	~ 60 s

Because the same ECDL seed laser was used in the second generation DIAL transmitter, the spectral purity measurement was assumed to be similar to that of the first generation DIAL, which was measured by (Obland 2007). The measurement was carried out by integrating and comparing the power spectral density measured across the full gain bandwidth of the semiconductor optical amplifier (~ 30 nm) to that of the power spectral density measured across the bandwidth of the narrowband optical filter 0.25 nm. A spectrometer with a 26 GHz resolution was used to make this measurement. It is understood that this technique for measuring the spectral purity of the DIAL transmitter is not optimum but it was the only method available at that time. The need for an improved laser transmitter led to the development of the third generation DIAL

transmitter with full-sky-scanning capabilities presented in chapter five. The new laser allowed for a more accurate measurement of the spectral purity using horizontal path saturated spectrum returns off of hard targets.

After the second stage TSOA, a fraction ($\sim 3\text{-}4\%$) of the light is split off via a 7 degree wedged window and sent to a detector for energy monitoring. The ~ 4 mm diameter collimated beam is incident on a commercial Thorlabs 5 X beam expander, yielding a ~ 20 mm diameter output beam that is transmitted coaxially to the atmosphere via a 45° turning mirror mounted to the outside of the secondary mirror of the telescope. The full angle divergence of the output of the DIAL transmitter was calculated to be approximately 0.05 mrad using Gaussian beam optics calculations. Because of this slow beam expansion, the divergence was not accurately measurable with standard techniques applicable over the scale of the laboratory, but, anyway, atmospheric turbulence such as scintillation has the potential to increase the divergence significantly as the beam propagates through the atmosphere.

Eye-Safety Calculations

The ocular hazard imposed by most operational lidar instruments using high power low pulse repetition frequency (PRF) laser transmitters limits the surroundings in which it can operate. An important aspect of operating a full-time autonomous lidar instrument is to ensure eye-safety at all ranges. A plot of the maximum permissible

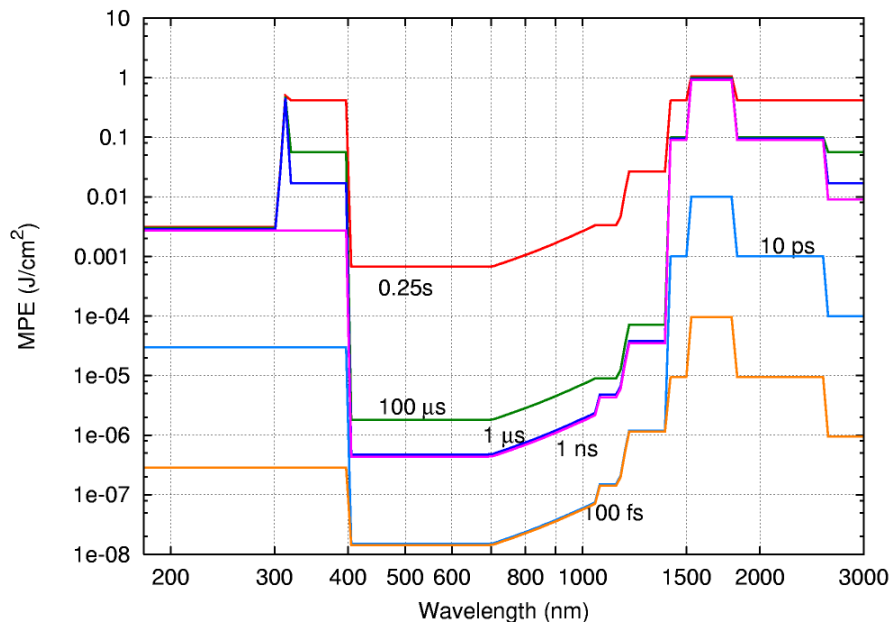


Figure 30 Maximum permissible exposure as a function of wavelength for different exposure times. The calculations are based off of the American National Standard Z136.1-1993.

exposure (MPE) as a function of wavelength for varying exposure times is shown in Figure 30 (Z136.1-1993 1993; Wikipedia 2011).

There are typically three techniques that can be used to minimize the ocular hazard resulting from either specular reflections or direct exposure to laser energy:

1) operate at wavelengths below 0.4 μm , 2) use a beam-expanded, high PRF micro-pulse transmitter in the visible or NIR, or 3) operate at wavelengths greater than 1.4 μm . As seen from Figure 30, the MPE for wavelengths below 0.4 μm and greater than 1.4 μm are significantly higher than for wavelengths in the visible part of the spectrum. This is primarily due to the fact that the majority of the laser energy for wavelengths below 0.4 μm and greater than 1.4 μm is absorbed in the lens and cornea of the eye, leaving little possibility of damaging the retina at energy densities sufficient for lidar applications.

The MPE for visible wavelength lidar transmitters is much lower because the scattered energy passes through lens and cornea and is focused directly onto the retina. NIR beams are especially dangerous due to the lack of the natural aversion response that occurs with visible wavelengths. To satisfy the lower MPE requirements in the visible-NIR part of the spectrum, the beam was expanded to reduce its power density (Spinhirne 1993).

The MPE for a 0.7-1.050 μm laser beam for exposure times ranging between 1 ns-18 μs can be expressed as

$$MPE = 5C_A \cdot 10^{-7} [\text{J}/\text{cm}^2], \quad (3.1)$$

where C_A is the wavelength correction factor (Z136.1-1993 1993). For the same wavelength range, C_A is given by

$$C_A = 10^{2(\lambda-0.7)} [\text{dimensionless}], \quad (3.2)$$

where the operating wavelength is expressed in μm . Given a nominal operating wavelength of 0.828 μm , the MPE for the DIAL transmitter is calculated using equations (3.1) and (3.2) to be $0.9 \mu\text{J}/\text{cm}^2$. For a maximum transmitted pulse energy of 2 μJ and an exit beam diameter of $\sim 2 \text{ cm}$, the calculated energy per unit area is $0.636 \mu\text{J}/\text{cm}^2$ over a 1 μs exposure time, which is well below the MPE at 828 nm for the same exposure time.

For a repetitively pulsed laser, the average MPE must be considered which is a function of the MPE/pulse over a given exposure time. The MPE/pulse for the 0.7-1.050 μm spectral range is expressed as

$$\frac{MPE}{Pulse} = n^{-0.25} MPE, \quad (3.3)$$

where $n = PRF \cdot \tau_{exp}$ (Z136.1-1993 1993). The PRF and τ_{exp} are the pulse repetition frequency of the laser transmitter and the exposure time, respectively. Since the 830 nm

wavelength does not provide a natural aversion response such as a visible wavelength laser would, a 10 s exposure time is assumed, with a PRF of 20 kHz. The corresponding MPE/pulse is calculated to be 42.6 nJ/cm^2 , a factor of 1.4 greater than the calculated value of 30 nJ/cm^2 for the DIAL. The average MPE over the 10 pulse train is then the product of the MPE/pulse and the number of pulses incurred during the full exposure period. As expected, the average MPE of 8.52 mW/cm^2 is again a factor of 1.4 greater than the measured average irradiance of 6 mW/cm^2 calculated for the DIAL. Given that the measured/calculated energy values for the DIAL are below that of the ANSI MPE standard for both single shot and average irradiance values, the second generation DIAL transmitter is considered to be eye-safe at the transmitter exit aperture. A summary of the second generation water-vapor DIAL transmitter specifications is shown in Table 4.

Table 4 Second generation DIAL laser transmitter specifications.

Parameter	Measured
Laser oscillator	Littman-Metcalf ECDL
Laser amplifier	Cascaded TSOA
Transmitted wavelengths (vacuum)	3: 828.187 nm (online), 828.193-828.195 nm (sideline), 828.287 nm (offline)
Pulse repetition frequency	20.0 kHz
Pulse length	1 μ s
Pulse energy	1-2 μ J
Short-term bandwidth	≤ 0.3 MHz
Long-term bandwidth	± 88 MHz
Spectral purity	$\geq .995$
Beam divergence	50-100 μ rad
Beam diameter	~ 20.0 mm
Eye-safe region	0 m
$t_{on} - t_{off}$	~ 60 s

DIAL Receiver

In addition to precise frequency control and high spectral purity required for the laser transmitters, low power DIAL instruments used for tropospheric water vapor measurements must also have highly efficient optical receivers to optimize the SNR of the weak backscattered returns. For lidar instruments targeted towards retrieving both near field and far field backscattered returns with a single receiving unit, a coaxial

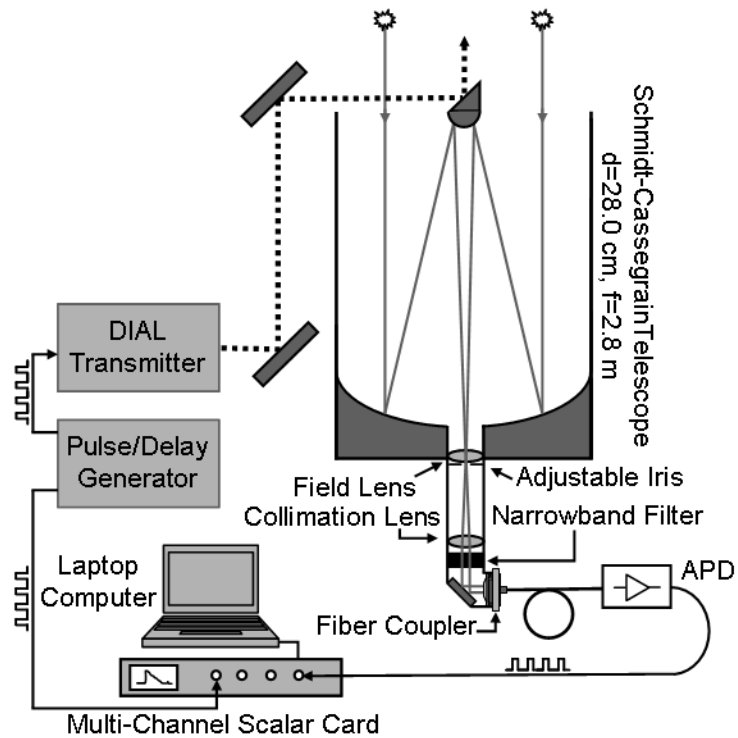


Figure 31 Schematic of the DIAL receiver layout. The back end optics are housed in a 1" light tight tube assembly.

transmitter-receiver geometry is optimal (Harms, Lahmann & Weitkamp 1978). The schematic of the DIAL receiver is shown in Figure 31. A 28-cm $f/10$ Schmidt-Cassegrain telescope (Celestron CGE 1100) is used to collect the backscattered returns from the DIAL transmitter. The commercially available Celestron telescope utilizes a StarBright XLT image-enhancement coating optimized for the visible band. Although not optimal for use in the 830 nm absorption band, the telescope assembly yields a system transmission of 74%.

To reduce the extraneous light reaching the detector, the background light collected by the telescope is baffled using an adjustable 1 mm diameter iris at the focal plane of the telescope. In order to reduce the initial instrument overlap range as well as

to reduce the needed detector size (fiber optic core diameter in this case) a field lens is used. A 60 mm (Thorlabs LB1596-B) focal length lens placed at the focal plane of the telescope is used to re-image the near field (< 0.5 km) off axis backscattered light on to the detector plane. Although potentially increasing the solar background noise at the detector, the field lens allows for the single channel DIAL receiver to more efficiently collect returns from the near field, where important water-vapor concentrations are present. The effects of the increase in the skylight background noise in the far field due to the field lens is corrected by subtracting off a pre-pulse background noise measurement on a second-to-second basis.

The design of the receiver conforms with two primary constraints, 1) to have a sufficiently narrow FOV to suppress background light (Spinhirne 1993), and 2) to ensure the delivery of the collected returns onto a sufficiently fast detector with high efficiency at the 830 nm operating wavelength. With an extensive technology search, it was concluded that, for an operating wavelength in the NIR, a photon-counting avalanche photodiode (APD) detector would provide superior performance to that of a photomultiplier tube (PMT), since PMT's typically have quantum efficiencies < 2 % in the NIR. A fiber-coupled Geiger-mode Perkin Elmer APD (SPCM-AQRH-13-FC) was chosen as the detector in the receiver unit for all three generation DIAL's. A picture of the APD module and its internal electrical layout are shown in Figure 32. The output of the APD provides > 1.0 V 15 ns wide TTL logic pulses for every photoelectron created at the detector junction plane. A specified APD dark count rate of less than 250 counts/second and a relatively high quantum efficiency of 45% at 830 nm yield high

SNRs for both daytime and nighttime operation. The APD module has a dynamic range spanning 4 orders of magnitude, where saturation is observed at ~ 15 M samples/second. Furthermore, due to a short APD dead time of 32 ns (below 5 Mc/s) and an extremely low after-pulsing probability of 0.5%, gating of the APD is not necessary, so it is operated in a free running mode. The full set of specifications for the Perkin Elmer APD can be found in Appendix C.

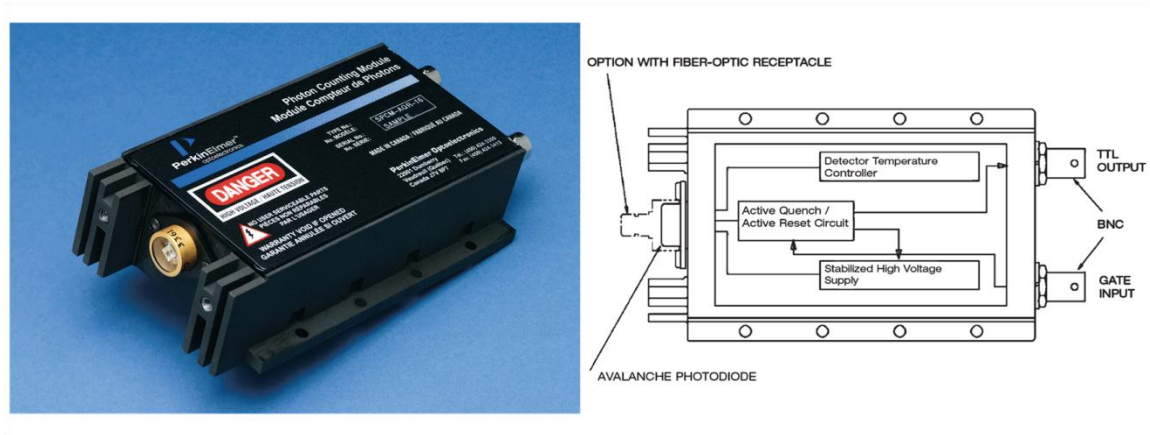


Figure 32 Left) Picture of the Perkin Elmer single photon counting APD module without the fiber connector. Right) Schematic of the internal layout of the APD module.

Although this APD module is self contained, highly efficient at 830 nm, and is very easy to use, the small active area diameter of $\sim 180 \mu\text{m}$ makes for critical alignment of the receiver unit. The fiber coupled APD module uses a 0.30 numerical aperture (NA) gradient index lens (GRIN) to reimage the input fiber on the detector plane with a magnification of 1.4. To minimize the non linear affects associated with spatial impurities around the edges of the APD chip (discussion with Perkin Elmer tech.), only the center 85 % of the APD chip was utilized for detection of the backscattered signal.

This was achieved by using a 105 μm core 0.22 NA fiber optic cable in the DIAL receiver which also acts as the system field stop.

The FOV of the receiving system can be estimated (Appendix D) by considering the effective focal length of the receiving telescope and the diameter of the field stop and is given by

$$FOV = \frac{D_f}{f}, \quad (3.4)$$

where D_f is the core diameter of the fiber and f is the focal length of the telescope (Chourdakis, Papayannis & Porteneuve 2002). For a core fiber diameter of 105 μm placed at the focal plane of an F/10, 28 cm diameter Schmidt-Cassegrain telescope, the full angle FOV of the receiver is 37.5 μrad . Ideally, the smaller the FOV that can be implemented for a lidar receiver, the higher the daytime SNR of the backscattered signal. Because of the angular angle sensitivity of the narrowband optical filter used to suppress out-of-band scattered sunlight and the relatively large divergence angle of the transmitted laser beam (compared to 37.5 μrad), the aperture stop was not placed at the focal plane of the telescope. Instead the focal plane of the telescope is reimaged with collimation and fiber coupling optics to yield a more suitable FOV which is approximately 2-3 times that of the transmitter divergence.

A 1" diameter 250 pm (FWHM) narrowband optical interference filter (Barr Associates) was used to suppress the background radiation at the APD detector. The transmission curve provided by Barr associates and the online and offline DIAL

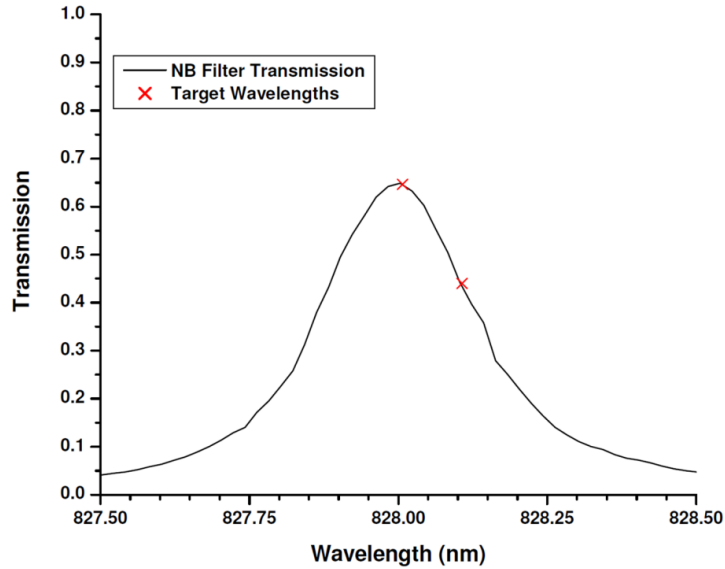


Figure 33 Transmission curve measured in vacuum for the narrowband optical filter at normal incidence provided by Barr associates as well as the target DIAL wavelengths denoted by the red x's (Obland 2007). Cauchy's theorem was used to calculate the equivalent online and offline wavelengths of 828.187 nm (828.0069 nm) and 828.287 nm (828.1069 nm), respectively, in vacuum (air) due to changes in the index of refraction resulting from varying atmospheric conditions (Obland 2007).

target vacuum wavelengths are shown in Figure 33. Filter transmissions measured in vacuum at normal incidence for the online and offline wavelengths are ~ 61% and 45%, although care must be taken to minimize the angle dependence of the transmission respectively where the filter transmission drops several orders of magnitude within ± 0.5 nm of the central peak. A transmission curve of the narrowband filter demonstrating excellent out of band rejection ranging over entire wavelength sensitivity span of the APD detector is shown in Figure 34. The inclusion this type of narrowband optical filter is critical for lidar measurements in the atmosphere using low-pulse-energy transmitters, function through the optical receiver.

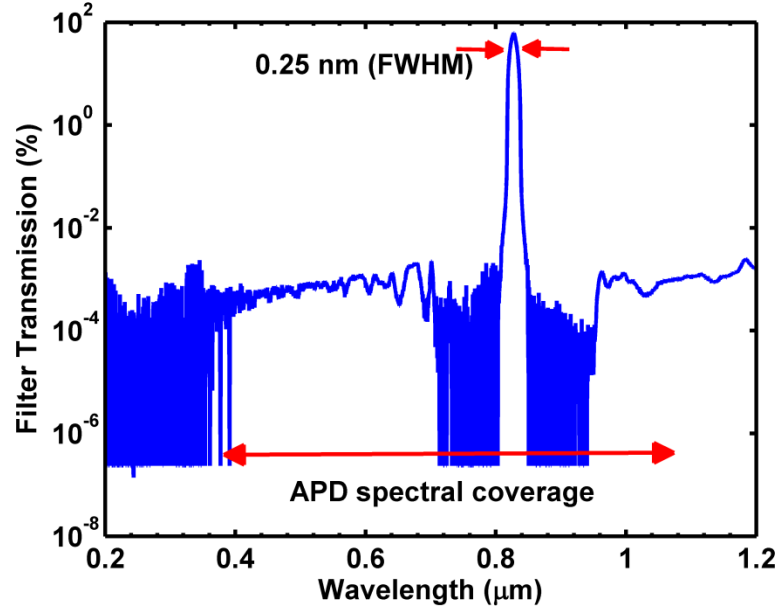


Figure 34 The narrowband optical filter broadband transmission spectrum for normal incidence (Barr Associates). Excellent out of band rejection across the $\sim 0.7 \mu\text{m}$ APD sensitivity range is observed, allowing for daytime lidar measurements in the presence of high solar background radiation.

The center wavelength λ for an optical interference filter shifts to shorter wavelengths as the angle of incidence θ of the incoming light increases relative to normal incidence. The center wavelength λ' can be expressed as (Hansch 1972)

$$\lambda' = \lambda_o \cos \frac{\theta}{n}, \quad (3.5)$$

where λ_o is the center wavelength of the filter at $\theta = 0$ and n is the effective index of refraction of the narrowband filter's spacer material. The spectral dependence of the 250 pm interference filter used in the DIAL receiver is shown in Figure 35. Due to the extremely narrow spectral pass-band of the filter, care must be taken to ensure that a well collimated beam is transmitted at normal incidence through the filter so that systematic errors are not introduced into the DIAL retrievals. A detailed characterization of the

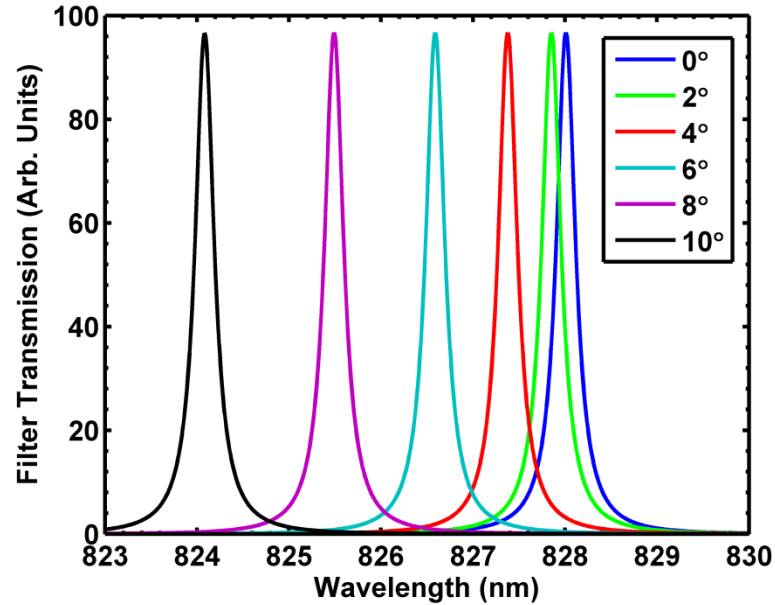


Figure 35 Spectral dependence of the narrowband filter transmission as a function of incidence angle (Barr Associates).

angle dependence of the narrowband optical filter and the resulting effects imposed on the DIAL retrievals is presented in (Nehrir 2008; Nehrir et al. 2009).

To minimize the effects of angle tuning through the filter and to ensure that the online wavelength sits at the manufactured peak of the filter transmission, the receiver optical train was back-illuminated with a collimated source at 633 nm and the telescope output was collimated using a shearing interferometer. An AR coated 1" diameter, 50.0 mm focal length achromatic doublet (Thorlabs AC254-050-B) was used to collimate the backscattered returns to a diameter of 4.25 mm. After the narrowband filter, an AR coated 4.5 mm diameter, 11 mm focal length (0.2 NA) aspheric lens as a part of a fiber coupling unit (Thorlabs PAF-X-11-PC-B) was used to image the backscattered light onto the core of a 0.22 NA, 105 μm core fiber optic cable that was optimized for transmission

at 830 nm. A picture of the six axis micro-positioning fiber coupler and the major components are shown in Figure 36. While holding the fiber connector (FC) and fiber stationary, the built-in lens can be aligned with six degrees of freedom: linear alignment of the lens on the x, y, and z-axes and angular alignment for tip, and tilt using the socket head screws.

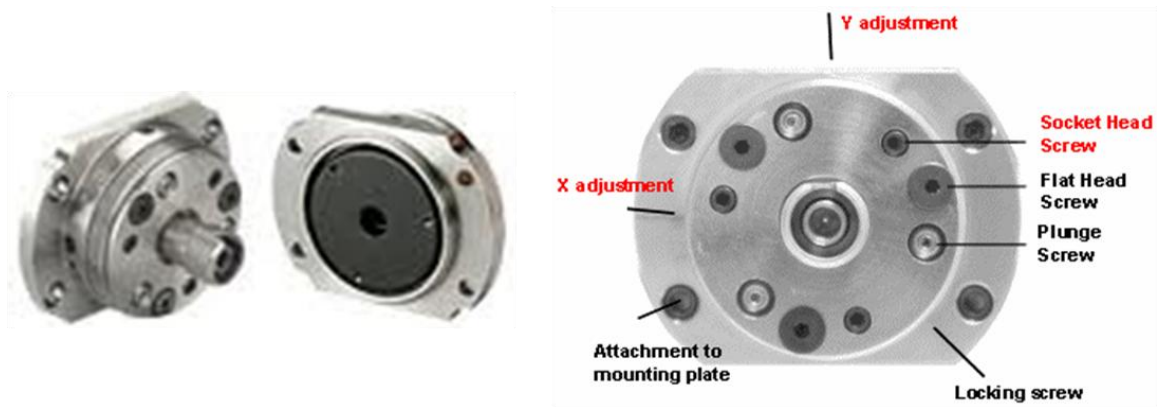


Figure 36 Picture of the six axis micro-positioning fiber coupling module used in the DIAL receiver to deliver light to the APD detector.

In the imaging case, the ratio of the focal lengths of the fiber coupling and collimation optics yields a magnification of the telescope focal plane image onto the fiber optic core at the back end of the receiver of $11/50 = 0.22x$. Using the etendue (optical invariant) principle, this decrease in the image size by $0.22x$ increases the NA of the incident beam by a factor of 4.5, hence increasing the field of view of the DIAL receiver from $37.5 \mu\text{rad}$ for an aperture stop placed at the focal plane of the telescope to $\sim 170 \mu\text{rad}$ for the fiber or aperture stop placed at the back end of the receiving optics. This principle was verified by modeling the DIAL receiver using the ZEMAX optical ray tracing program.

The DIAL receiver was modeled using sequential ZEMAX ray tracing to verify the first order FOV calculations presented above. Because the telescope used in the DIAL receiver was commercially purchased, the parameters required to design an accurate working model, such as the mirror curvatures and spacing, were not available. The model used for the Schmidt-Cassegrain telescope was originally developed by Anthony Notari at NASA Langley Research Center, with slight changes made to the telescope prescription to optimize the throughput. The model is for an F/11, 35 cm diameter Celestron Schmidt-Cassegrain, the same telescope which is used in the third generation DIAL, which will be discussed in chapter five. This telescope was also used in the zenith channel receiver of the NASA Langley Lidar Atmospheric Sensing Experiment (LASE) system, which was designed for high-altitude measurement of tropospheric water-vapor. Because the F/#'s for the modeled 35 cm (F/11) telescope and the 28 cm (F/10) telescope used in the second generation DIAL receiver are very similar, the 35 cm telescope's parameters were used in the DIAL receiver ZEMAX model, with the input aperture limited to 28 cm. Although this introduces errors in the FOV analysis, the model was used to provide rough estimates of the receiver parameters to validate the first order calculations presented above.

A ZEMAX schematic of the modeled DIAL receiver depicting the major optical components is shown in Figure 37. It should be noted that the ZEMAX model presented here is slightly different from the schematic shown in Figure 31 in that the collimating achromatic doublet lens and the narrowband optical filter are before the tertiary mirror

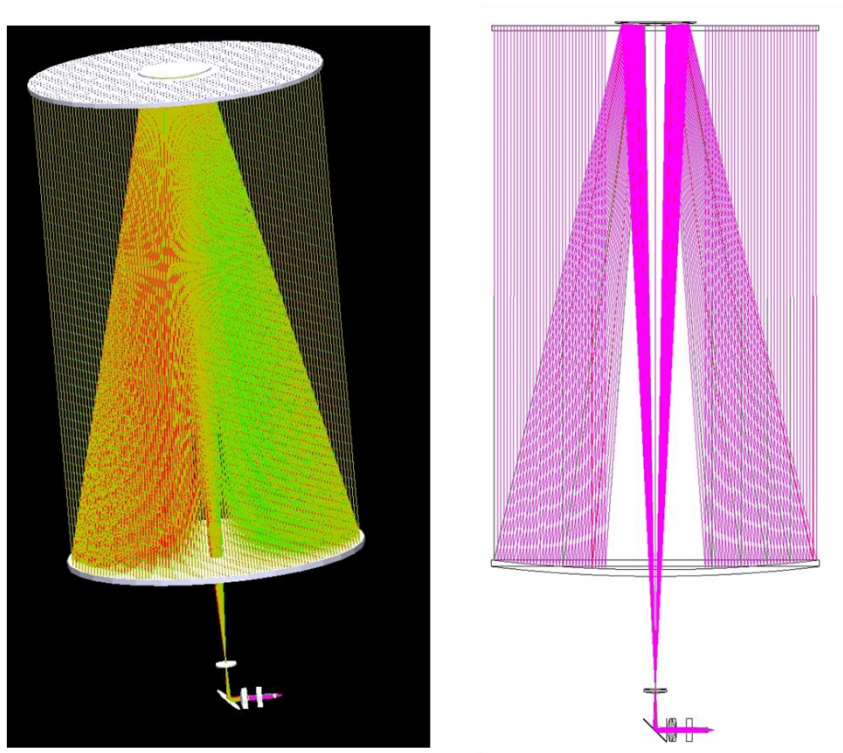


Figure 37 ZEMAX solid model and 2-D ray trace of the DIAL receiver shown in the left and right figures, respectively.

in Figure 31. It was experimentally verified that the small angles introduced by the tertiary mirror tune the narrowband filter's peak transmission to slightly shorter wavelengths, introducing systematic errors in the DIAL retrievals. Although optically no different than the ZEMAX model presented in Figure 37, the final design for the second generation DIAL receiver is as presented in Figure 31. A zoomed in picture of the back end optics on the receiver is shown in Figure 38. An iris before the field lens and another after the tertiary mirror allow for easier bore sight alignment when fiber coupling the backscattered returns. Once again, it should be noted that, even though the collimation doublet and the filter were moved ahead of the tertiary mirror in the final design, the two irises were placed in the same functional locations as shown in Figure 38.

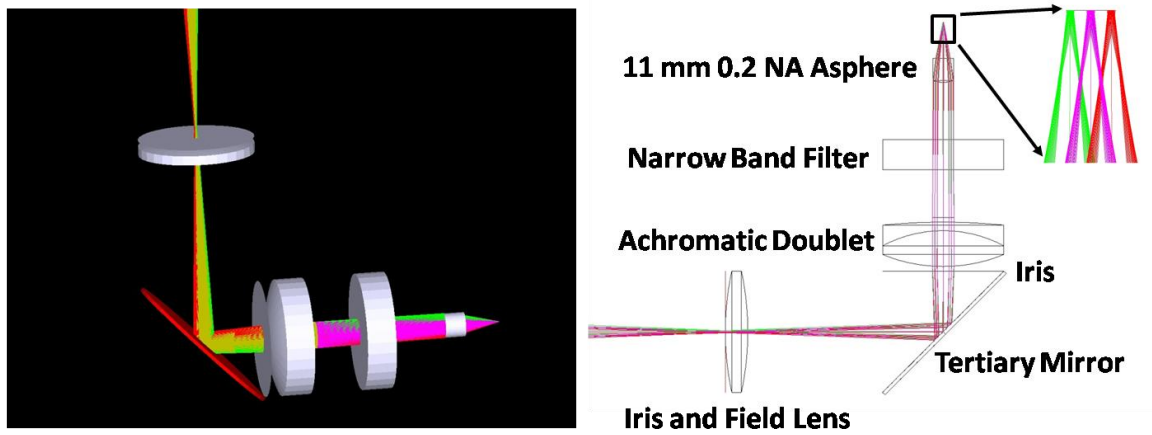


Figure 38 ZEMAX solid model and 2-D ray tracing model showing the major components of the collimation and fiber coupling optics. The different colors represent the different field of views.

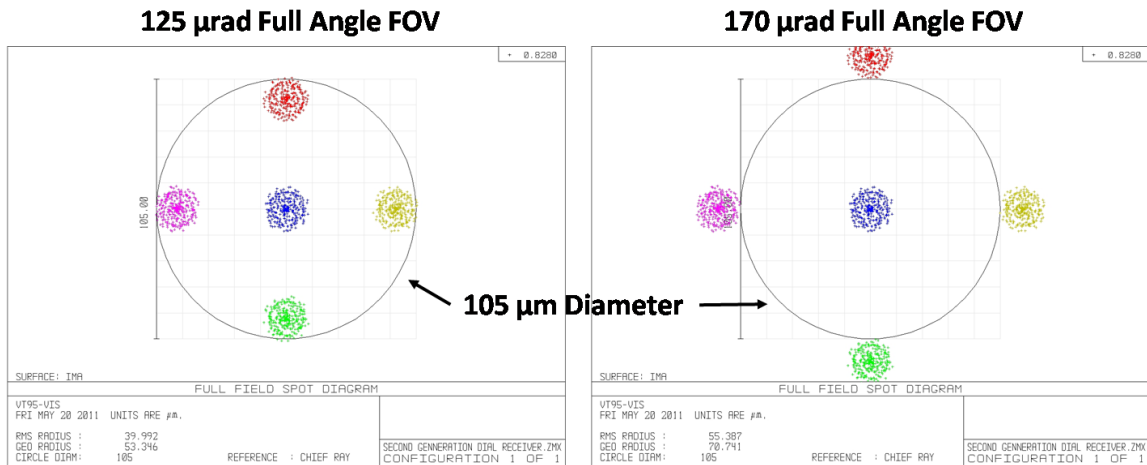


Figure 39 Left) ZEMAX full field spot diagram of the DIAL receiver for a 125μrad full angle FOV, where the on axis returns are shown in blue in the center of the image. The 105 μm fiber core diameter is superimposed to show the extent of vignetting of off-axis beams at the field stop. Right) Same as figure on the left except with 170 μrad full angle FOV, exhibiting the maximum FOV for detectable off-axis signals through the DIAL receiver.

The inset figure on the ZEMAX ray trace model in Figure 38 shows the imaged focal plane of the DIAL receiver (fiber coupling aspheric lens) for the on axis and ~ 170 μrad max FOV rays calculated above. Figure 39 shows the full field spot diagram at the fiber for on-axis and off axis beams through the DIAL receiver. The figure on the left shows that a full angle FOV of 125 μrad allows for complete imaging of the backscattered returns onto the 105 μm fiber core diameter. The figure on the right shows that off-axis returns exceeding a 125 μrad FOV are spatially filtered (vignetted) at the fiber, which acts as the field stop. A full angle FOV of 170 μrad was simulated in ZEMAX to be the maximum FOV for detectable off-axis signals through the DIAL receiver. This is in excellent agreement with the 170 μrad maximum full angle FOV calculated above. A summary of the second generation water-vapor DIAL receiver parameters and a picture of the DIAL instrument including the transmitter, receiver, and associated electronics are shown in Table 5 and Figure 40, respectively .

Table 5 Second generation DIAL receiver specifications.

Parameter	Measured
Telescope	Schmidt-Cassegrain
Primary mirror diameter	28.0 cm
Full angle field of view	170 μrad
Detector	Si Photon Counting APD
APD quantum efficiency	45 %
Optical filter bandwidth	0.25 nm
Receiver efficiency	≈ 10 %
Digitizer (MCSC) bandwidth	20.0 MHz
Range resolution	150 m
Total integration period	10-30 minutes



Figure 40 Picture of the second generation DIAL instrument. The transmitter is on the 2'x4' optical breadboard and the receiver is attached to a vertical breadboard where the output beam is transmitted coaxially with the telescope via two 45 degree turning mirrors. All of the instrument electronics are on the shelf below the instrument.

Data Acquisition and Post-Processing

Automated control and data acquisition for the second generation DIAL instrument is achieved using the Labview programming environment on a portable laptop computer. The data acquisition process is shown schematically in the flow chart in Figure 41. The laser transmitter is first tuned to the peak absorption of the water-vapor line at 828.0069 nm (828.187 nm) in air (vacuum) (side-line tuning on the water-vapor absorption line is also employed using same technique). The wavelength of the amplified cw seed laser is measured using the fiber coupled light rejected from the first PBS shown in Figure 19 with a Burleigh Wavemeter (WA-1500), which has a frequency resolution of ± 88 MHz.

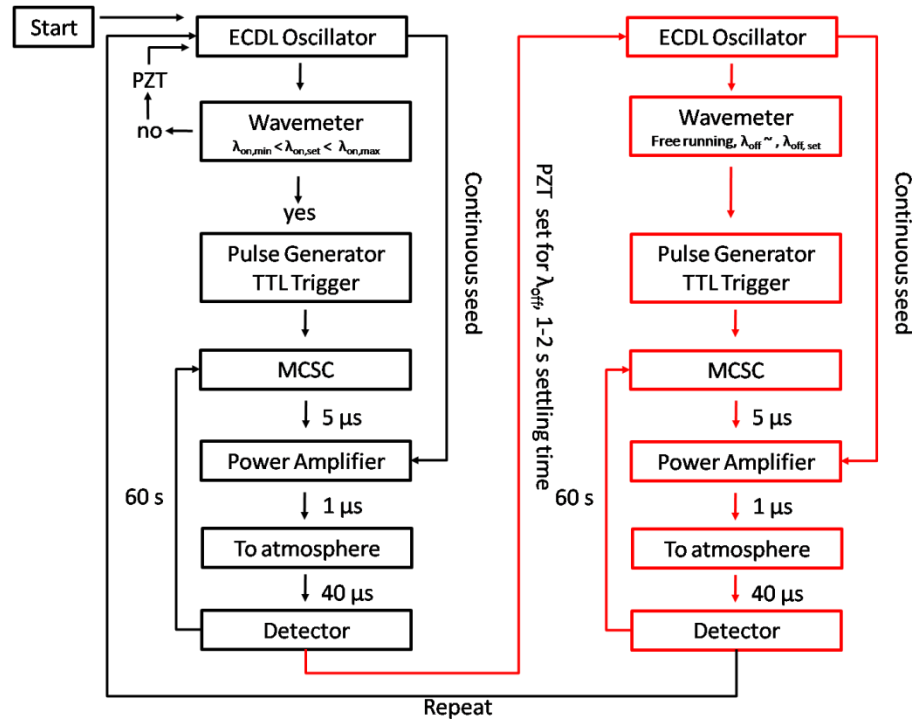
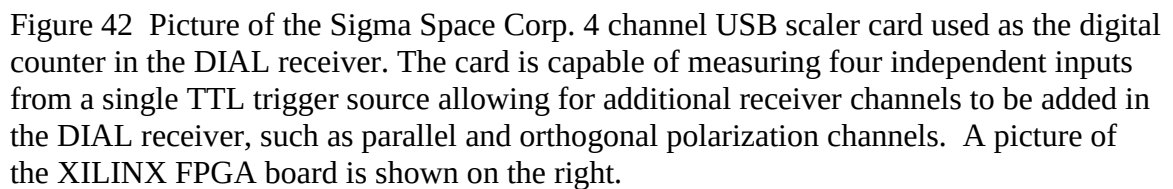


Figure 41 Flow diagram showing the basic steps in the second generation DIAL's data acquisition process.

The wavelength reading from the wavemeter is polled every half second over a general purpose interface bus (GPIB) and an appropriate voltage correction is made to the ECDL's piezo electric transducer using a programmable voltage source until the laser transmitter achieves a steady state wavelength to within ± 88 MHz (0.2 pm) of the selected wavelength. Next, a 4 channel digital delay/pulse generator (Stanford Research Systems DG 645) is used to trigger the data collection from the free running APD using a 4- channel Sigma Space Corp. multi channel scaler card (MCSC). A picture of the MCSC is shown in Figure 42. The reconfigurable MCSC is based on a 20 MHz 16-bit XILINX field programmable gate array (FPGA) board that sums 35 ns wide input TTL pulses from the APD into 50 ns bins, corresponding to a minimum range resolution of 7.5



Once triggered to begin data collection and prior to the firing of the laser transmitter, the MCSC acquires 5 μ s of APD background measurements to be used for background subtraction during post processing. After this 5 μ s delay, a second channel from the digital delay/pulse generator triggers the 1 μ s current pulse delivered to the second stage TSOA. During the 5 μ s delay between the initial trigger and the beginning of the laser pulse, the MCSC samples the APD data into the first 100 bins, each of width 50 ns. The subsequent return signal resulting from the laser interaction with the atmosphere accounts for the remaining 800 bins sampled by the MCSC, correspond to 40 μ s of return data. This sequence, lasting 50 μ s, is repeated and summed bin-by-bin

20,000 times over one second, yielding 800 range resolved range bins, each 7.5 m in depth, and corresponding to a total range of 6.0 km. The data collection process is repeated for the on-line (or sideline) wavelength of 828.0069nm (828.187 nm) in air (vacuum) for a user-defined period of time, normally 60 s. The software then tunes the laser to the off-line wavelength of 828.1069 nm (828.287 nm) in air (vacuum) via a predetermined PZT voltage, and a ~ 1 s settling time is provided for the laser wavelength to stabilize before data is once again collected for 60 s. No active feedback is provided for the offline wavelength, as small drifts in the wavelength do not significantly affect the water-vapor absorption cross section in the trough between two absorption lines. This entire interleaved switching process is repeated for a user defined duration.

Once the raw data are obtained, MATLAB is used to analyze the data. A flow diagram depicting the basic steps used to calculate water-vapor profiles is shown in Figure 43. First, spectral digital filtering is achieved by analyzing the polled wavelength from the wavemeter such that only the data that meets the selected wavelength requirement within ± 88 MHz (for online and sideline cases) are considered. Next, 1 s of data which is stored in an $m \times 900$ bin matrix is parsed out and normalized by the outgoing pulse energy to prevent any laser-induced systematic errors, although the shot-to-shot pulse energy fluctuations were found to be negligible. The normalized online and offline data are then background subtracted using the first 100 bins measured prior to the firing of the laser pulse. The data are then range averaged into 150 m bins by summing 20 successive 7.5 m bins, compressing the data array size down to 1×40 . This process is repeated until ~ 5 -15 minutes of data are temporally averaged at each wavelength. It is

important to note that the averaging time greatly depends on the atmospheric conditions. The range resolved water-vapor absorption coefficients at each wavelength are then calculated using surface temperature and pressure measurements as starting points for atmospheric temperature and pressure models. Using the calculated range resolved water-vapor absorption cross sections as well as the spatially and temporally averaged backscattered returns, a water-vapor profile is calculated using the DIAL equation presented in equation (2.12).

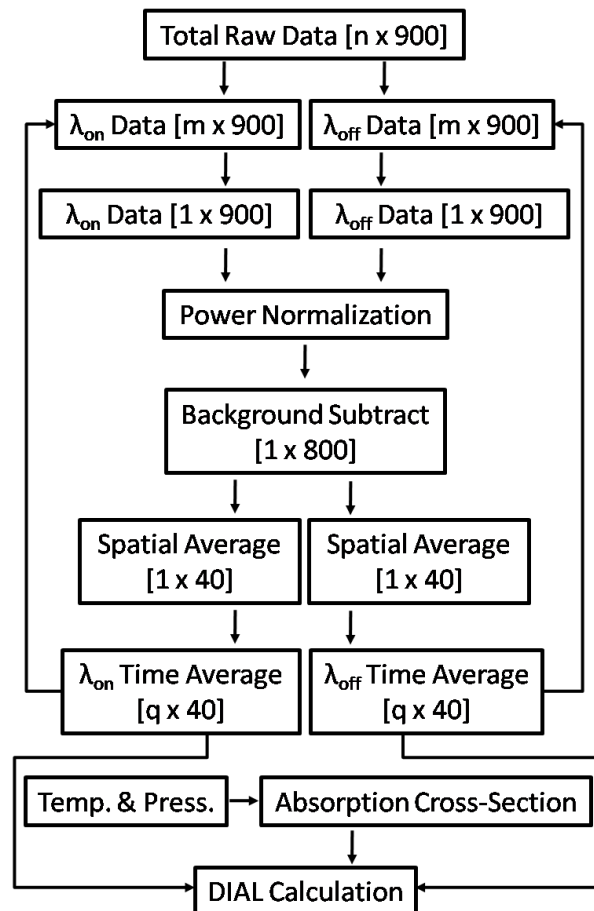


Figure 43 Flow diagram showing the basic steps in calculating a water-vapor number-density profile. The numbers represent the vertical (range) size of the matrices in number of bins.

Experimental Results

Nighttime Measurements

Initial testing of the second generation ground based DIAL instrument was performed during a small nighttime campaign in order to optimize the instrument performance, which would otherwise be limited by the daytime scattered solar radiation. Initial measurements with the DIAL instrument were conducted from 10 August 2009 to 11 August 2009 where the evolution of a stable nocturnal boundary layer was observed over approximately an eight hour period. To begin assessing the nighttime performance of the instrument, the water-vapor DIAL was operated for a twenty minute period centered at 06:15 UTC (00:15 MDT) on 11 August 2009 where ten minutes of side-line tuned backscattered data and ten minutes of off-line tuned backscattered data were recorded in 60 s interleaved increments as discussed in the data acquisition section earlier.

Plots of the background subtracted photoelectron counts as a function of altitude for a twenty minute total integration period for the side-line and off-line wavelengths are shown in Figure 44. A large dynamic range of $\sim 10^4$ from initial overlap at ~ 0.5 km up to 6.0 km can be seen in the backscattered returns for both the side-line and off-line wavelengths, where the additional attenuation at the side-line wavelength is attributed to absorption by water-vapor. An abrupt decrease in the backscattered returns at approximately 3.0 km can be seen at both DIAL wavelengths due to confinement of the aerosols trapped below the PBL. Rapid degradation of the backscattered signal above the PBL into the free troposphere has two main causes. First, a significant fraction of the

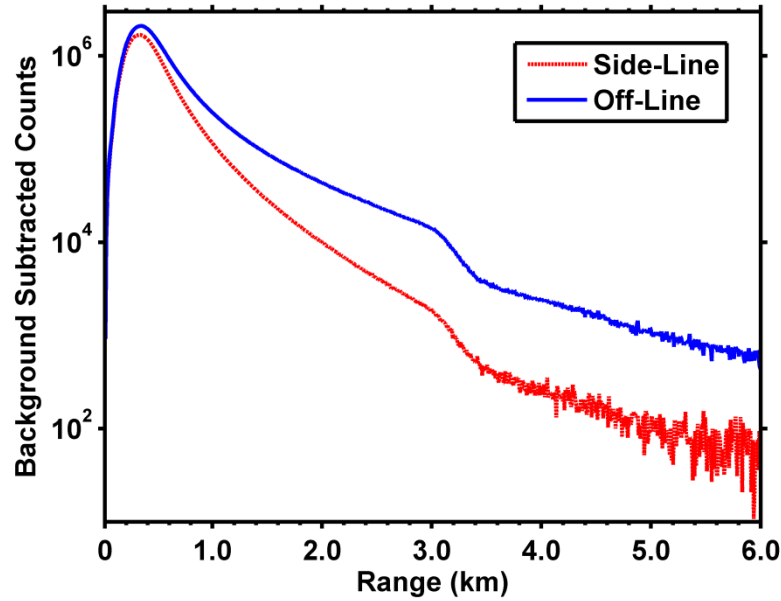


Figure 44 Log-Linear plot of the background subtracted side-line and off-line atmospheric backscattered returns for a 20 minute (10 minutes side-line and 10 minutes off-line) total integration period centered around 06:15 UTC (00:15 MDT) on 11 August 2009. A 7.5 m vertical range resolution yields appreciable backscattered returns at the side-line wavelength up to the top of the planetary boundary layer and up to 6.0 km for the off-line wavelength, well into the free troposphere.

transmitted light through the PBL has been attenuated as a result of forward and backward scattering due to high levels of aerosol loading from regional biomass burning, resulting in low laser energies reaching the free troposphere. Second, the backscattered signals at both DIAL wavelengths begin to degrade rapidly beyond the PBL due to the lack of aerosol scattering in the free troposphere, causing the SNR of the instrument to decrease exponentially beyond the PBL, hence limiting the detectable altitude for water-vapor profiles to ~ 3.8 km, where the SNR of the side-line returns drops below an acceptable level of ~ 3 -8 (Wulfmeyer and Walther 2001).

The nighttime collected backscattered returns shown in Figure 44 are used with radiosonde derived temperature and pressure profiles to arrive at a water-vapor number-density profile using the DIAL equation (Measures 1984; Kovalev & Eichinger 2004). Although a temperature insensitive water-vapor absorption line was chosen using methods presented in chapter 2, the differential absorption cross section of water-vapor is still calculated as a function of altitude using radiosonde derived temperature and pressure profiles to reduce the error in the water-vapor number-density measurement. In the absence of radiosonde measurements, modeled temperature and pressure profiles are calculated up through the lower troposphere using equations (2.24) and (2.25), starting with the surface-temperature and surface-pressure measurements (Measures 1984; Kovalev & Eichinger 2004; Machol et al. 2004). (Measures 1984; Kovalev & Eichinger 2004; Machol et al. 2004). Using the range-dependent side-line and off-line absorption cross-sections together with the background subtracted atmospheric returns from

Figure 44, the DIAL equation can be used to arrive at a water-vapor density profile vs. altitude shown in Figure 45. Using 150-m spatially averaged range bins and a 20 minute (10 minutes side-line, 10 minutes off-line) integration period, the density profile retrieved using the DIAL instrument (solid black line) shows good agreement with the corresponding in situ radiosonde measurement (dashed grey line) from near the surface up to the top of the boundary layer. Full overlap between the DIAL transmitter and receiver is achieved at approximately 500-m above the ground.

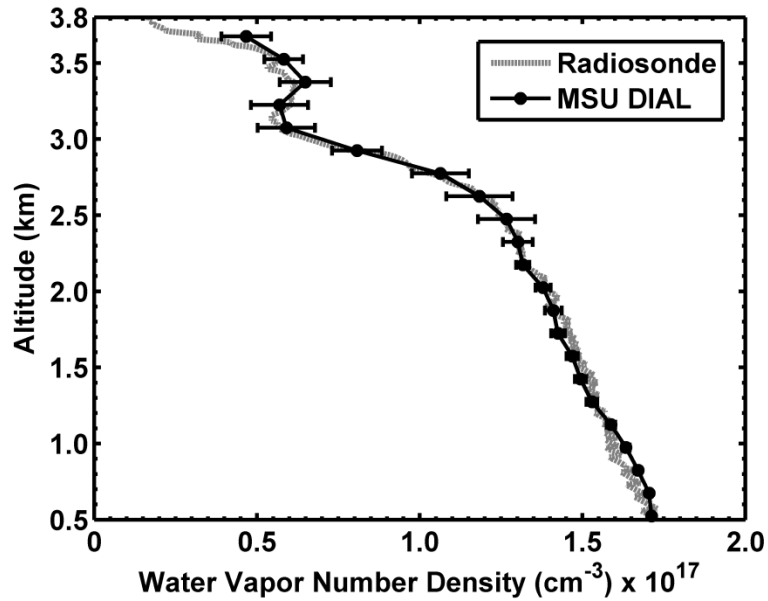


Figure 45 Vertical water-vapor number-density profile calculated starting at 06:05 UTC (00:05 MDT) on 11 August 2009 using the atmospheric returns from Figure 44. A 20 minute total integration period and 150 m down sampled vertical range resolution are displayed.

Below ~ 500 m, three dominant effects introduce systematic errors into the DIAL measurements. First, because of the coaxial configuration between the laser transmitter and receiver, the central obscuration of the telescope shields the telescope from the strong near-field returns. Given a 4" center obscuration and a $170 \mu\text{rad}$ full angle FOV, the shadow from the secondary mirror obscuration becomes infinitesimally small at ~ 590 m above the ground. Second, because of the finite "object" distance of the near-field scatterers, their image plane at the fiber is behind that of the "in focus" far field returns, hence reducing the collection efficiency of the near field returns. Last, because the two previous effects are equal for both the on-line and off-line wavelengths and cancel out in the DIAL equation, the deviations of the DIAL instruments measurements from those of the radiosonde below ~ 500 m are best accounted for by the angle-dependent wavelength

tuning of the narrowband filter's peak transmission. A correction factor for this effect is presented in detail in Nehrir et al. (2008,2009).

The nighttime measurements exhibit approximately 5 % error relative to the radiosonde measurement from 0.5 km above the ground based instrument up to ~ 3.7 km. The error bars in Figure 45 resulting from random uncorrelated errors in the return signals were calculated using Poisson photon statistics in methods presented by (Wulfmeyer & Walther 2001) and is described in further detail in Appendix E. The error resulting from atmospheric variability due to the slow spectral switching time is difficult to separate from the data but is assumed to be negligible in most of the data sets presented here where a homogenous aerosol layer was present. An increase in the overall measurement errors can be seen above the boundary layer at ~ 2.5 km, at altitudes where significantly fewer aerosol scattering events occur.

The utility of the second generation narrow FOV high PRF DIAL instrument lies in its ability to measure range- and time-resolved water-vapor densities up through the lower troposphere with relatively short integration periods, given clear atmospheric conditions. Nighttime false color plots of the atmospheric backscatter and the associated water-vapor number-density cross sections over an eight hour period on 10 August 2009 are shown in Figure 46. Figure 46-a represents a time-height cross section of the range corrected backscattered returns using the off-line data collected with the DIAL instrument. Although not calibrated, the off-line returns provide an insight to the atmospheric aerosol backscatter. A 1 s integration period and 7.5 m vertical range resolution provides high temporal and spatial resolution for monitoring a stable nocturnal

boundary layer. Although the operation of the MCSC at 20 MHz sets a nominal range resolution of 7.5 m, the $\sim 1 \mu\text{s}$ duration of the laser pulses yields a $\sim 150 \text{ m}$ ambiguity in the height at which any particular backscattered photon originated.

A well defined boundary layer at 3.0 km is visible throughout the evening due to aerosol loading from regional biomass burning. A discontinuity in the atmospheric backscattered returns at approximately 5:20 UTC (23:20 MDT) was caused by an accidental collision with another lidar instrument that was being repositioned. Although they're clearly visible in the backscattered returns, the differential use of the data collected at the online and offline wavelengths prevents such instantaneous disturbances from affecting the number density measurements. Water-vapor number-density cross sections associated with the atmospheric backscatter presented in Figure 46-a from 10 August 2009 are shown in Figure 46-b. Ten minute averaging times for both the on-line and off-line wavelengths were utilized to create one range resolved water-vapor number-density profile calculated using the DIAL equation (Measures 1984). Water-vapor number-density time series are then derived by using a twenty minute running average window (10 minutes of on-line and 10 minutes of off-line data) of the backscattered returns through the DIAL equation across the full data set. A nearest neighbor interpolation is then used to smooth the data in space and time to increase the viewing resolution of the water-vapor time series to 25-m in the vertical direction and 3.33-minutes in the horizontal direction. This method will be referred to as a "profile interpolation". With 20-minute total averaging times and an up-sampled range and temporal resolution, micro-scale convective features that agree well with in situ

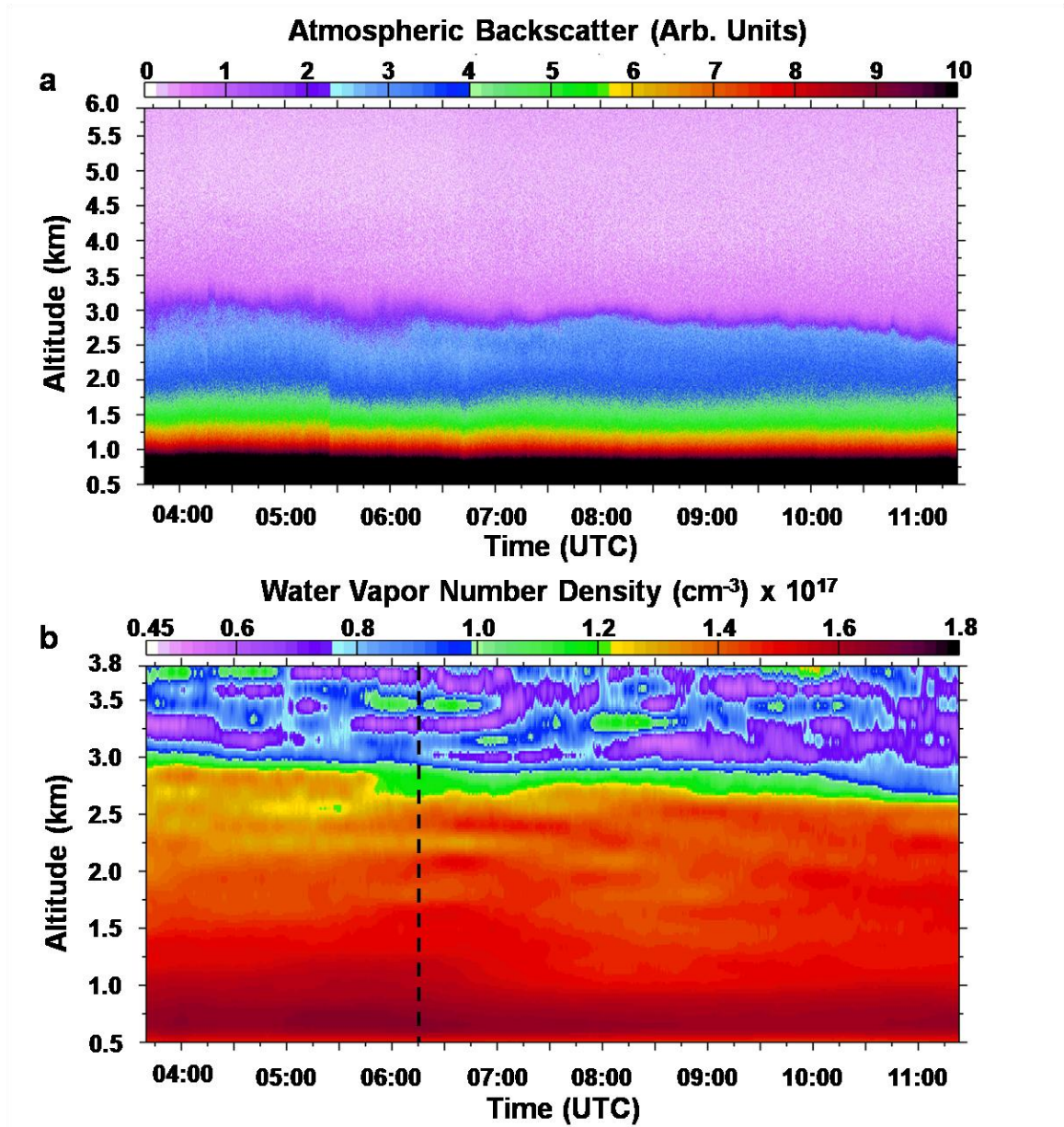


Figure 46 a) Vertical time series of the nighttime off-line range corrected backscattered returns for August 10-11 2009. A 7.5 m vertical range resolution and 1 s temporal resolution are displayed. b) Vertical time series of nighttime water-vapor number densities measured during August 10-11 2009. A 25 m vertical range resolution and 3.33-minute temporal resolution are displayed. A co-located radiosonde measurement shown in Figure 45 is indicated by the black dotted line at 06:15 UTC.

measurements can be seen up through the boundary layer to the free troposphere. A co-located radiosonde measurement taken starting at 06:15 UTC (00:15 MDT), as indicated by the black dotted line in Figure 46, is shown in Figure 45.

The high vertical and temporal resolutions shown in Figure 46 depict weak remnants of a mixed layer resulting from the residual convective heating of the surface during the prior day, which is evident by the presence of aerosols and warm moist air at the top of the boundary layer early in the evening. Then under clear skies, the convective thermals ebb as the radiation into the atmosphere cools the surface, which results in the cooling of the neighboring air mass through molecular conduction, hence allowing the turbulence to decay into the mixed layer from the previous day. This settled mixed layer, which contains the remaining moisture, convected heat, and aerosols from surrounding biomass burning, is known as the "residual layer" and can be seen, on average, at heights from ~1.0-2.6 km in Figure 46-b. By the end of the evening, the residual layer is largely trapped between a stratified shallow nocturnal boundary layer near the ground and a capping inversion at the top of the previous day's entrainment zone.

The statically stable nocturnal boundary layer seen in the lowest 1.2 km of the troposphere is formed as the cold nighttime surface cools the air mass near the ground, converting the bottom of the residual layer into a growing stable nocturnal layer. The capping inversion depicted by the green stratified layer at approximately 2.75-3.0 km in Figure 46-b is formed by warm air convecting to the top of the boundary layer in the early evening which is trapped between the cooler free tropospheric air and the cooling

residual mixed layer. The temperature inversion and subsequent decrease of the relative humidity (RH) that caused the capping inversion at the top of the boundary layer can be seen from radiosonde measurements shown in Figure 47. As the evening progresses into the following morning, the capping inversion gradually falls and diminishes as the surface cools off and the nocturnal boundary layer grows.

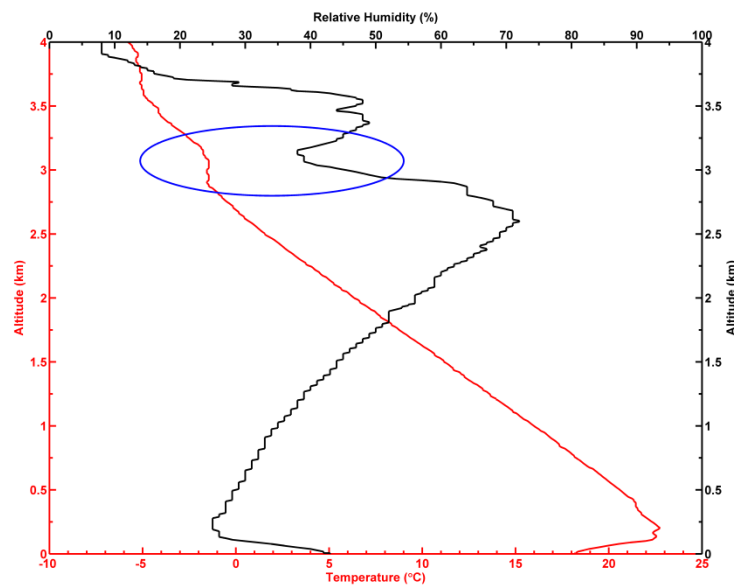


Figure 47 Radiosonde derived temperature (red) and relative humidity (black) profiles over Bozeman, Montana recorded at 06:15 UTC (00:15 MDT) on 11 August 2009.

Daytime Measurements

Monitoring the micro-scale dynamics of an evolving planetary boundary layer from a stable, stratified nocturnal boundary layer at night into an unstable, convective mixing state during the daytime provides useful insight towards gaining a better understanding of fundamental atmospheric transport processes (Wallace & Hobbs 2006). To assess the daytime performance as well as the long term operating functionality of the

MSU DIAL instrument, it was operated continuously over the course of three days during which atmospheric backscatter and water-vapor profiles were monitored and compared against in situ co-located radiosonde measurements. The DIAL instrument was operated continuously starting from 14:35 UTC (08:35 MDT) on 11 September 2009 until 02:45 UTC (20:45 MDT) on 13 September 2009.

Plots of the daytime, background subtracted photon counts as a function of altitude for a 30 minute total integration period starting at 14:20 UTC, for both side-line and off-line wavelengths, are shown in Figure 48. 15-minute side-line and 15-minute off-line integration periods yield relatively good SNR up to the top of the planetary boundary layer at approximately 2.3 km where the side-line returns then become dominated by background noise resulting from the attenuation of the signal due water-vapor absorption. Spatial averaging of the backscattered returns into 150-m range bins increases the SNR and permits for daytime water-vapor density profiles to be retrieved up to the free troposphere.

Plots of a daytime water-vapor profiles using a 30 minute total integration period centered at 14:35 UTC (08:35 MDT) and the associated water-vapor time-height cross sections for a one hour period are shown in Figure 49-a and Figure 49-b, respectively. Good agreement between the 150-m spatially averaged DIAL measurements and the data collected with the radiosonde measurement can be seen from 0.5 km to 2.5 km. in Figure 49-a. Drag at the ground causing near surface resistance of strong positive (westerly)

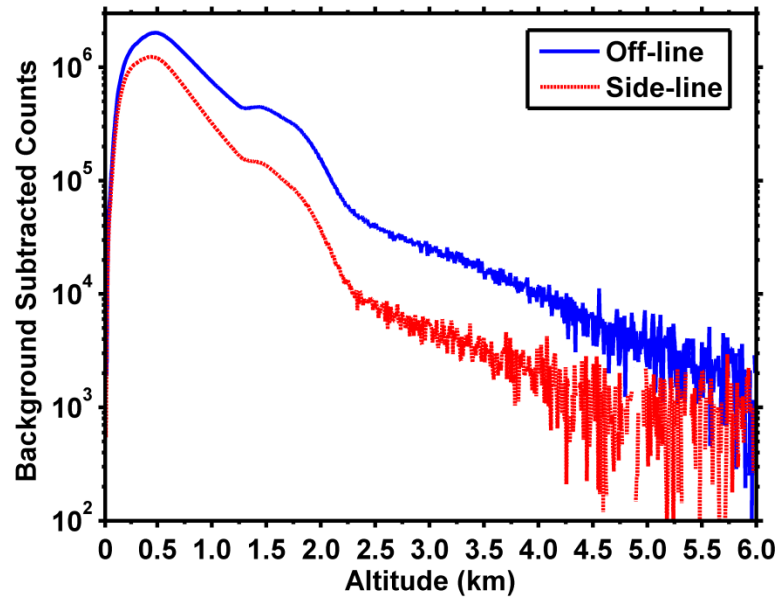


Figure 48 Log-Linear plot of the daytime background subtracted side-line and off-line atmospheric backscattered returns for a 30 minute (15 minutes side-line and 15 minutes off-line) total integration period centered around 14:35 UTC (08:35 MDT) on 11 September 2009.

zonal winds resulting in a distinct wind shear layer can be seen at approximately 2.25 km. A strong negative gradient in the water-vapor density at the shearing layer can be seen where the relative humidity calculated from the radiosonde measurements (Switzer 1998; Obland 2007) shown in Figure 50 dropped from approximately 55 % at 2.0 km to less than 4.0 % at 2.3 km. A capping inversion as a result of the temperature inversion at the top of the boundary layer (~ 2.25 km) is also visible. An overall error of less than 14% in the daytime water-vapor profile from the DIAL instrument compared with the radiosonde results was measured from 0.5 km up to approximately 2.0 km. Deviations between the two measurements up to the top of the boundary layer are attributed to the differences in the sampled air masses between the DIAL and radiosonde measurements due to the strong westerly winds; which carried the radiosonde away from the vertical air column

sampled by the DIAL instrument and, presumably, caused the time variations in the water vapor profile for any fixed column. Due to significantly lower concentration of aerosols in the atmosphere compared to the 10 August 2009 measurements, as well as the lower measured relative humidity above 2 km, and relatively large solar induced background noise, the errors between the in situ measurements and the DIAL measurements above the boundary layer increases to approximately 50%. The average daytime aerosol optical depth (AOD) measured using a CIMEL solar radiometer at 870 nm for 10 August 2009 and 11 September 2009 were 0.68 and 0.36, respectively.

Although the maximum altitude for an acceptable uncertainty of less than 10-15% for the DIAL measurement is limited to the top of the boundary layer for daytime measurements, qualitative information can be gathered about the spatial and temporal distributions of water-vapor up through the planetary boundary layer into the free troposphere. Water-vapor number-density cross sections associated with the water-vapor profile presented in Figure 49-a from 11 September 2009 are shown in Figure 49-b. 30-minute (15 minute side-line, 15 minute off-line) integration periods and up-sampled range and temporal resolution using profile interpolation reveals the evolution of a short term daytime inversion as well as a sustained shearing layer that agrees well with in situ measurements. A co-located radiosonde measurement taken starting at 14:35 UTC (08:35 MDT) shown in Figure 49-a is indicated by the black dotted line in Figure 49-b. The prominent inversion layer up around 2.25 km that trapped the boundary layer moisture and caused a capping inversion at the start of the data set begins to mix with the boundary layer and diminishes at approximately 15:00 UTC (09:00 MDT) as solar

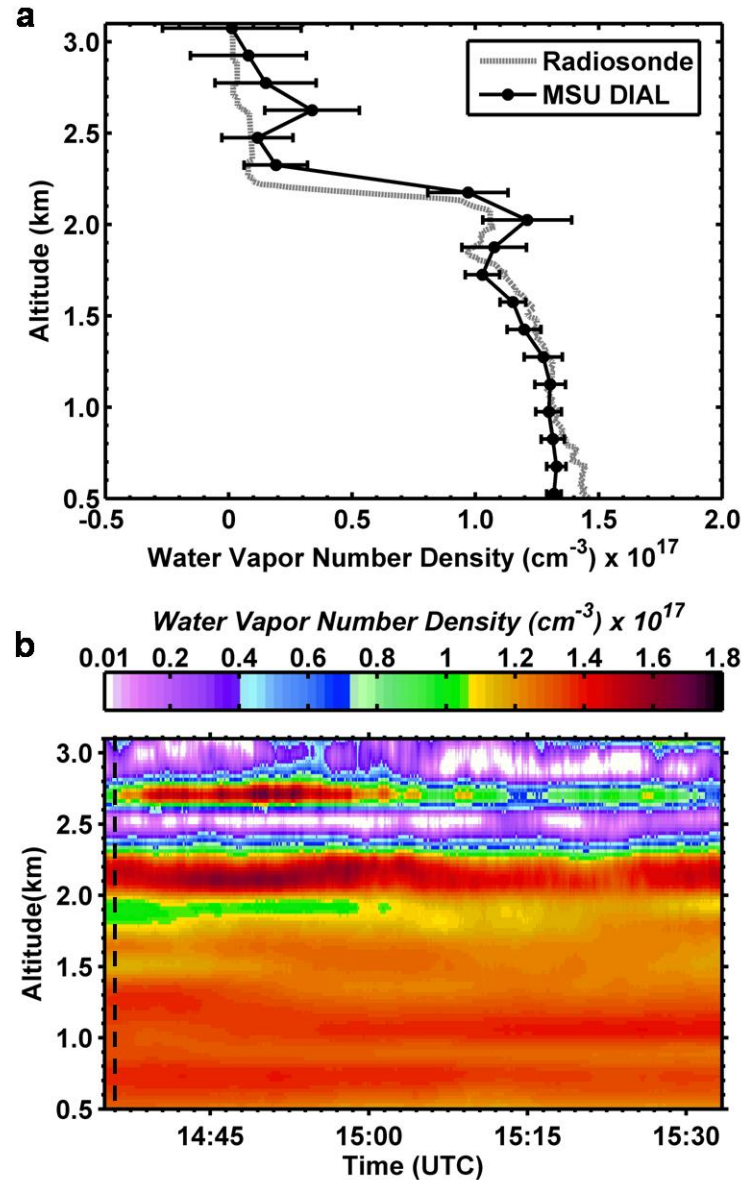


Figure 49 a) Vertical daytime water-vapor number-density profile recorded starting at 14:20 UTC (08:20 MDT) on 11 September 2009 using the atmospheric returns obtained from Figure 48. A 30 minute total integration period and 150 m vertical range resolution are displayed. Good agreement between the DIAL measurements and the co-located in situ measurements can be seen from near the surface up to the top of the boundary layer. b) Vertical time series of daytime water-vapor number densities measured during the morning of 11 September 2009 showing the evolution of a daytime shearing layer at the top of the planetary boundary layer. A 25 m vertical range resolution and 3.33-minute temporal resolution are displayed. The radiosonde measurement shown in part a of this figure is indicated by the black dashed line at 14:35 UTC in part b.

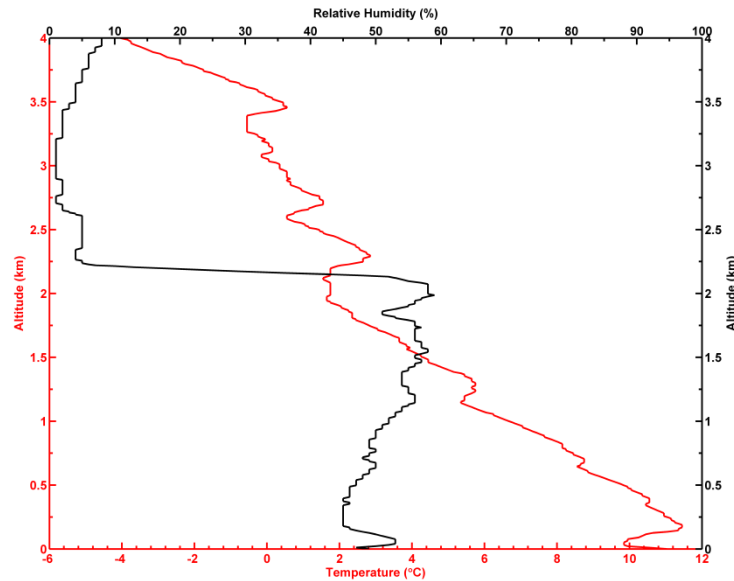


Figure 50 Radiosonde derived temperature (red) and relative humidity (black) profiles over Bozeman, Montana recorded at 12:35 UTC (08:35 MDT) on 11 September 2009.

heating of the surface begins to cause atmospheric turbulence. The shearing layer resulting from the strong westerly front, evident by the negative water-vapor gradient at approximately 2.25 km continues throughout the duration of the measurement.

Long-Duration Boundary Layer Measurements

Given the good daytime and nighttime performances of the second generation DIAL instrument, long duration data sets were thought to be achievable with integration periods and spatial resolutions fine enough to reveal typical tropospheric mesoscale features. In order to this, extended periods of clear skies were required such that online and offline signals could be recorded up through the planetary boundary layer. The second generation DIAL instrument was autonomously operated over a 60 hour period during which continuous profiles were recorded. Cross-sections of the atmospheric

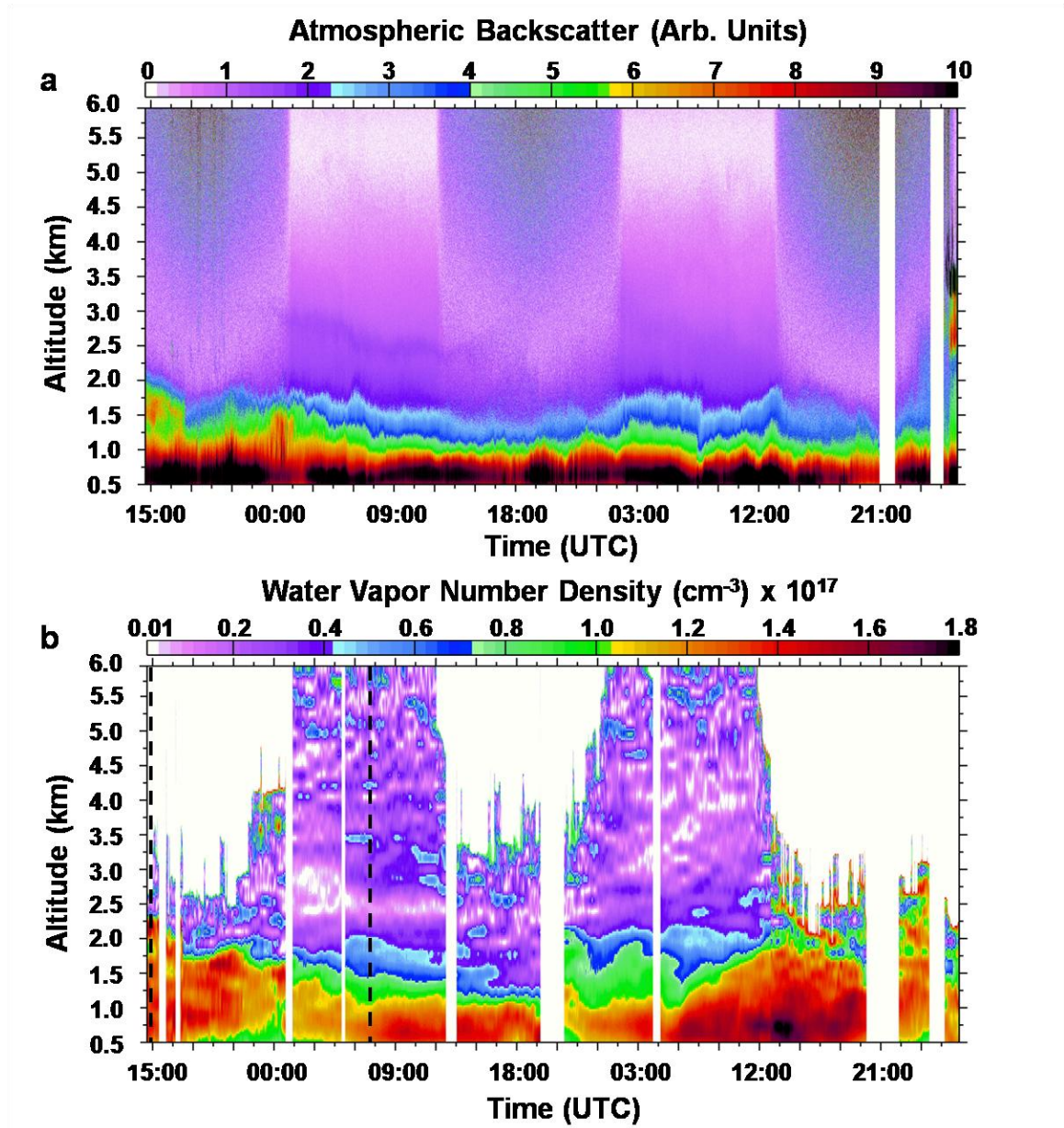


Figure 51 a) Vertical time series of the off-line range corrected backscattered returns for September 11-13 2009. A 7.5 m vertical range resolution and 1 s temporal resolution are displayed. b) Vertical time series of nighttime water-vapor number densities measured during 11-13 September 2009. A 25 m vertical range resolution and 3.33-minute temporal resolution are displayed. Two co-located radiosonde measurements indicated by the black dotted lines at 14:35 UTC on 11 September 2009 and 07:00 UTC on 12 September 2009 are shown in Figure 49 and Figure 53, respectively, demonstrating the daytime and nighttime capabilities of the second generation DIAL instrument.

backscatter and the associated water-vapor number-density cross sections over the 60 hour extended period starting from 14:20 UTC on 11 September 2009 are shown in Figure 51-a and Figure 51-b, respectively.

A one second integration period and 7.5-m vertical resolution was used for the online and offline atmospheric backscatter. Profile interpolation of a sliding 30 minute (15-minutes side-line, 15 minutes off-line) integration period used to calculate the tropospheric water-vapor content yields 3.33-minute temporal resolution and 25-m vertical resolution for the water-vapor cross-sections. White omitted areas in Figure 51-a and Figure 51-b are attributed to power outages and low spectral purities caused by mode hops in the master oscillator for the atmospheric backscatter and water-vapor cross-sections, respectively. Wide spatial and temporal variability in both the atmospheric backscatter and the water-vapor number-density cross-sections can be seen over the 60 hour period. The background solar radiation limits the maximum resolvable daytime water-vapor number-density measurement to between 2.0 and ~3-km depending on the atmospheric conditions.

Two co-located radiosonde measurements indicated by the black dotted lines in Figure 51-b were made to assess the daytime and nighttime performance of the DIAL instrument relative to an in situ measurement given a relatively clean atmosphere. The first radiosonde measurement launched at 14:35 UTC (08:35 MDT) is presented in Figure 49-a. As previously discussed, relatively good agreement between the two daytime measurements can be seen from 0.5 km up to the top of the boundary layer. The strong shearing layer caused by the westerly winds diminishes at approximately 17:00 UTC

(11:00 MDT) as the wind direction measured by a co-located weather station suddenly changed from SE to N, causing the boundary layer and the associated aerosol backscatter and water-vapor content to drop to approximately 1.75-km. Another shift in the wind direction from N to E occurred at approximately 21:00 UTC (15:00 MDT) on the 12 September causing noticeable convective turbulence in both the atmospheric backscatter and water-vapor number-density cross-sections. The strong westerly winds continued until 19:00 UTC (13:00 MDT) on 13 September 2009 when a low pressure system reached the valley.

Due to the presence of strong northwesterly winds, the valley surrounding the local area experienced minimal aerosol loading which resulted in an average AOD of 0.036 and 0.024 at 870 nm as measured by the CIMEL 318 solar radiometer for 11 September 2009 and 12 September 2009, respectively. As a result of the low optical thicknesses measured throughout the dataset, longer integration periods were required to achieve minimal SNR's ~ 3 -8 in the free troposphere just passed the PBL. Consequently, as a result of less scattering in the boundary layer, the beam transmission increased through the atmosphere and the backscatter and water-vapor number-density cross-sections could be obtained up to higher altitudes reaching well into the free troposphere at the cost of longer integration periods.

A plot of the background subtracted counts as of function of altitude for a 30 minute total integration period (15-minute side-line, 15-min off-line) centered around 07:00 UTC (01:00 MDT) on 12 September 2009 is shown in Figure 52. Once again, a large dynamic range of $\sim 10^4$ from initial overlap at 0.3-0.5 km up to 6.0 km can be seen

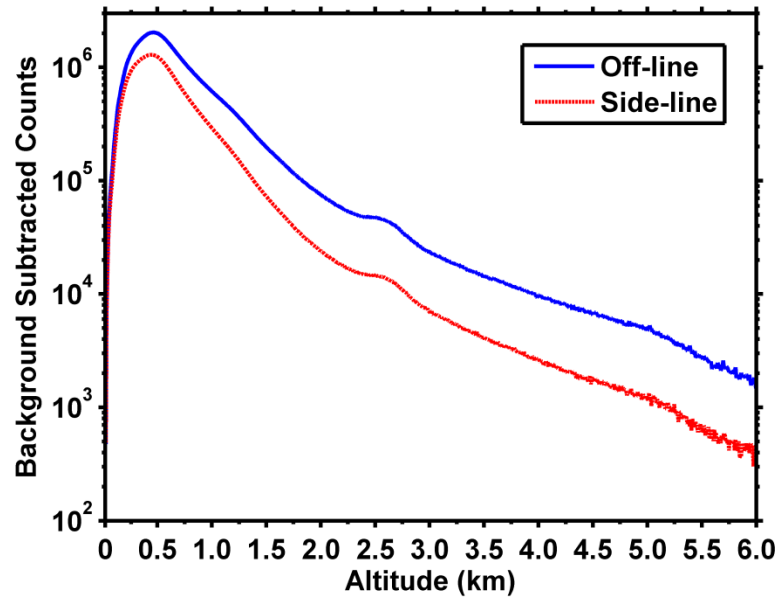


Figure 52 Log-Linear plot of nighttime background subtracted side-line and off-line atmospheric backscattered returns for a 30 minute (15 minutes side-line and 15 minutes off-line) total integration period centered around 07:00 UTC (01:00 MDT) on 12 September 2009. A 7.5 m range resolution and a 30 minute total integration period yields a high SNR of the backscattered returns beyond the boundary layer well into the free troposphere. An optically thin aerosol layer can be seen at approximately 2.5 km.

in the backscattered returns for the side-line wavelength. A thin aerosol layer at 2.5 km, corresponding to the approximate altitude of the top of the shearing layer from the previous day is visible in both the side-line and off-line returns. A water-vapor profile calculated using the backscattered returns shown in Figure 52 is compared to radiosonde measurement (indicated by the black dashed line in Figure 51-b at 07:00 UTC) shown in Figure 53. Good agreement between the two measurements from 0.5-km up to 4.5-km can be seen using 150-m averaged range bins and a 30-minute total integration period. As shown in Figure 54, a temperature inversion at the 2.5-km shearing layer measured by the radiosonde can be seen where the thin layer of aerosols was present. The warm lofted layer caused a strong capping inversion where a very low RH of 2.6% (note that the

radiosonde RH measurement is not very sensitive at RH content $< 85\%$) was measured. Below the inversion layer, a stable nocturnal boundary layer can be seen throughout the evening in Figure 51 where very little mixing of the boundary occurs the following day. Preceding a low pressure front, convective mixing of boundary layer aerosols and water-vapor is evident starting at approximately 20:00 UTC (14:00 MDT) on 12 September 2009. The boundary layer water-vapor content then begins to further increase rapidly as the front fully moves into the valley at approximately 06:00 UTC (00:00 MDT) on 13 September 2009. Appreciable cloud cover starting at approximately 20:00 UTC (14:00 MDT) on 13 September 2009 limited the maximum resolvable altitude for water-vapor measurements to between 2.0-km and 2.5-km due to the increase in brightness of the background (and resulting increase in photon shot noise) induced by the non-selective scattering of the cumulus clouds.

Daytime and nighttime water-vapor number-density profiles have been recorded using relatively short integration periods with minimal operator interaction. The goal of the low power DIAL instrument's development is to autonomously collect nighttime and daytime water-vapor and calibrated atmospheric backscatter cross-sections to begin studying the microphysical properties of clouds as well cloud formation. For the second generation DIAL instrument, its largest drawback for long term boundary layer water-vapor monitoring was the limited daytime maximum resolvable altitude for water-vapor retrievals. Despite having a sufficiently narrow FOV for the DIAL receiver and averaging over space and time to increase the SNR of the return signal, scattering from the low 1-2 μJ pulse energies are not discernable from the background solar radiation at

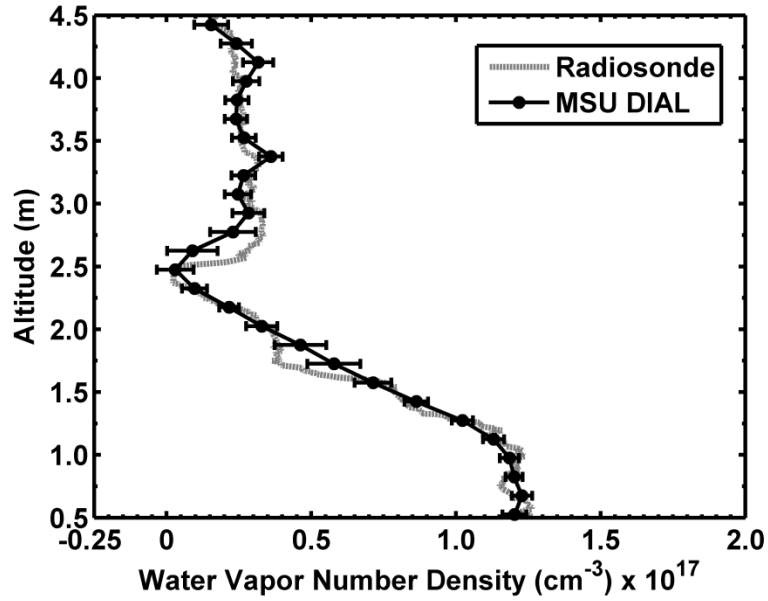


Figure 53 Vertical water-vapor number-density profile recorded starting at 06:45 UTC (00:45 MDT) on 12 September 2009 using the atmospheric returns shown in Figure 52. A 30 minute total integration period and 150 m down sampled vertical range resolution are displayed, yielding good agreement between the water-vapor DIAL measurements and the co-located in situ measurements from 0.5 km up to 4.5 km.

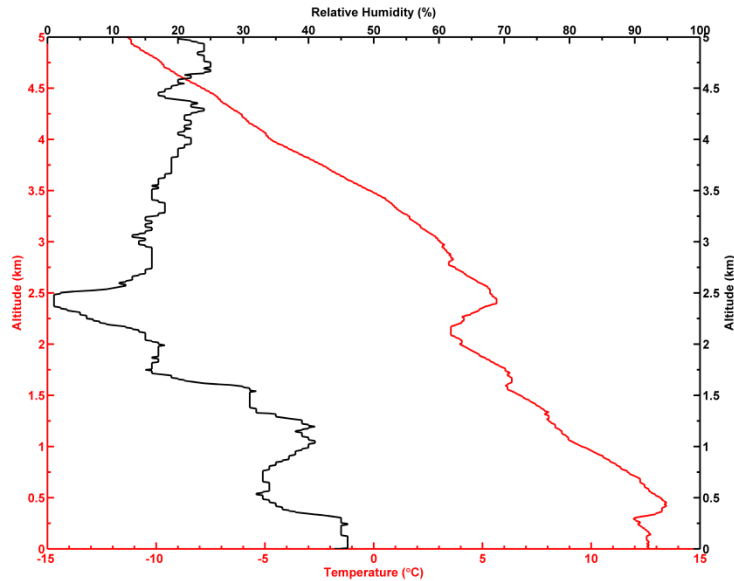


Figure 54 Radiosonde derived temperature (red) and relative humidity (black) profiles over Bozeman, Montana recorded at 07:00 UTC (01:00 MDT) on 13 September 2009.

higher altitudes for a given atmospheric composition. Errors in the daytime measurement arise from both random and systematic sources. Systematic errors such as the laser linewidth, spectral purity, and water-vapor line selection criteria have been discussed in detail in chapter 2. The major sources of error in the DIAL measurement are induced by random errors and are the most difficult to quantify. Inherent dark noise induced by the DIAL receiver's detector (which is negligible for our APD) and noise in the background signal are the two main sources of random error.

Using the Modtran database, the daylight background radiation level at a sun zenith angle of 35 degrees was simulated to better understand the daylight background signal level its effect on the APD detector. For a summer atmospheric model for a mid-latitude region, an average atmospheric background spectral radiance of $0.0058 \text{ Wcm}^{-2}\text{sr}^{-1}\mu\text{m}^{-1}$ was calculated, corresponding to $\sim 3 \text{ P}_e/\mu\text{s}$ (photoelectrons/microsecond) for the receiver specifications stated earlier. A background photon count measurement using the DIAL receiver for a sun zenith angle similar to that of the simulation resulted in an average of 1400 background counts per 20,000 laser shots, yielding $1.4 \text{ P}_e/\mu\text{s}$. This is well below the saturation point of the detector but is at the upper bound of the linear operating region of the APD and requires a linearity correction factor of approximately 1.1 during post processing. The manufacturer provided correction factor to the backscattered returns used for the water-vapor and aerosol retrievals is given by

$$CorrectionFactor = \frac{1}{1 - (t_d \cdot C_R)}, \quad (3.6)$$

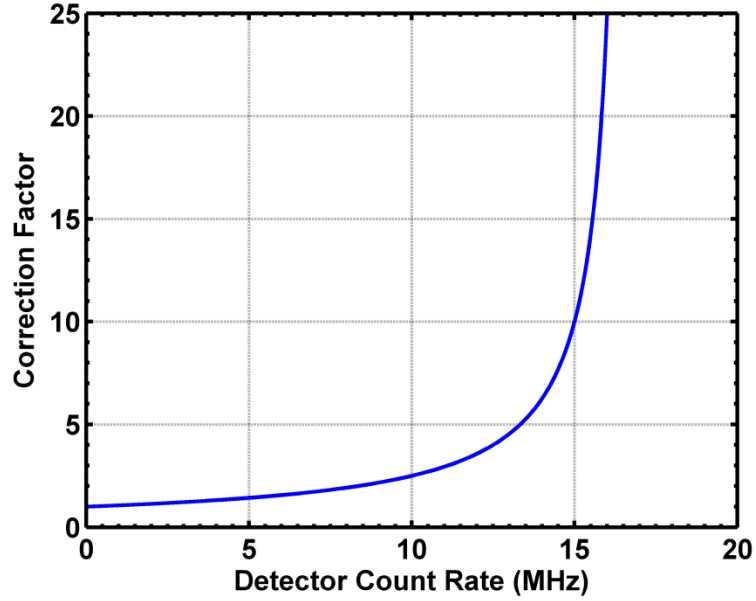


Figure 55 Perkin Elmer APD correction factor as a function of the detector output count rate. A 60 ns detector dead time was used for the simulation.

where t_d and C_R are the detector dead time and output photoelectron count rate, respectively. For a typical detector dead time of 60 ns, the APD correction factor is shown in Figure 55.

Although the APD performance is not directly affected by the solar background noise, the shot noise on the background radiation has a large effect on the DIAL calculation, especially for low pulse energy DIAL instruments. To account for the shot to shot variability in the background noise, two approaches can be used. First, a longer dead-time integration period can be used either before or after the laser pulse acquisition to more accurately sample the background noise. This technique would require a slight decrease in the PRF of the DIAL transmitter to accommodate the dead-time measurement. Second, given that the APD has a large operating bandwidth from 400

nm-1100 nm, a second narrowband optical filter can be placed in the DIAL receiver to further attenuate the background noise across the APD's full operating spectrum. At the cost of slightly decreasing the overall efficiency of the receiver, adding a second narrowband optical filter would decrease the background noise by another factor of $\sim 10^4$ (typical rejection ratio of BARR filter), allowing for routine daytime measurements up to the free troposphere.

The performance of the DIAL instrument is also highly dependent on the composition of the planetary boundary layer. Given a clear atmosphere with low AOD's, the background noise can significantly decrease due to the lack of multiple forward scattering from the sun, but will also require the need for longer integration periods due to the lack of Mie scattering in the atmosphere. Conversely, atmospheres dominated by high AOD's require less integration time to achieve the same SNR. Examples of DIAL backscattered returns for relatively high (0.071) and low (0.024) AOD's measured by the CIMEL 318 can be seen in Figure 44 and Figure 52, respectively. A decrease in the AOD by a factor of ~ 3 from 0.071 to 0.024 increased the maximum detectable altitude for water-vapor number-density measurements from 3.8-km to 4.5-km while increasing the required total integration periods to achieve acceptable SNR's from 20-minutes to 30-minutes. Thus, there is an inverse relationship between both the AOD of the atmosphere and the total integration period required for the DIAL measurement as well as between the AOD and the maximum detectable altitude for water-vapor measurements. Hence, for a given atmospheric condition, a trade-off between the maximum altitude, the spatial

resolution, as well as the temporal resolution of the DIAL measurement is necessary such that an optimal SNR can be achieved.

The second generation diode-based DIAL instrument has proven to be a viable technology for long term measurements of lower tropospheric water-vapor for weather forecasting and climate monitoring applications. To understand the coupled roles of water-vapor and aerosols in the lower troposphere and the effects they have on the microphysical properties of clouds, quantitative measurements of atmospheric aerosol optical properties in addition to water-vapor distributions are necessary. In a step towards measuring the aerosol indirect effect, wherein water-vapor and aerosols act together to alter the microphysical properties of clouds, the offline channel of the DIAL transmitter was calibrated and aerosol optical properties were retrieved and used to estimate the net cooling/heating effects of the aerosols on the Earth's surface through scattering and/or absorption of incoming solar radiation, which is referred to as the "aerosol direct effect".

AEROSOL RETRIEVALS

Qualitative Measurements

Coordinated observational data of atmospheric aerosols were collected over a twenty four hour period starting at 23:00 MDT on 27 August 2009 at Bozeman, Montana using the second generation water vapor DIAL, a co-located two color lidar, a solar radiometer, and a ground based nephelometer. The optical properties and spatial distribution of the atmospheric aerosols were inferred from the observational data collected using the co-located instruments as part of a closure experiment. In this section, attention will be drawn towards the need for calibration of the offline DIAL returns as the bulk of the closure study was based on aerosol modeling and is beyond the scope of this dissertation. A detailed description of the case study is presented in (Repasky et al. 2011).

The second generation DIAL instrument was used during this case study to monitor the spatial and temporal evolution of the stratified biomass burning aerosol layer as well as to provide insight into the moisture content of the lower atmosphere such that conclusions about the hydration of aerosols could be deduced. A time-height false color plot of the range corrected returns using the off-line data at 828.287 nm collected with the water-vapor DIAL during the 24 hour period is shown in Figure 56. The aerosol layer under investigation can be seen beginning to intrude into the PBL around 09:00 MDT. Background noise due to increased solar radiation is visible during the day at higher altitudes, limiting the maximum detectable range for the water-vapor measurements to ~

2-2.5 km. The corresponding water-vapor number-density and RH profiles obtained over the 24 hour period are shown in Figure 57. Temperature profiles were estimated using the surface temperature and a lapse rate of -5 C/km - 10 C/km depending on the atmospheric state, while pressure profiles were estimated using the surface pressure along with a modeled pressure profile (Machol et al. 2004), allowing the relative humidity to be calculated from the water-vapor number-density data.

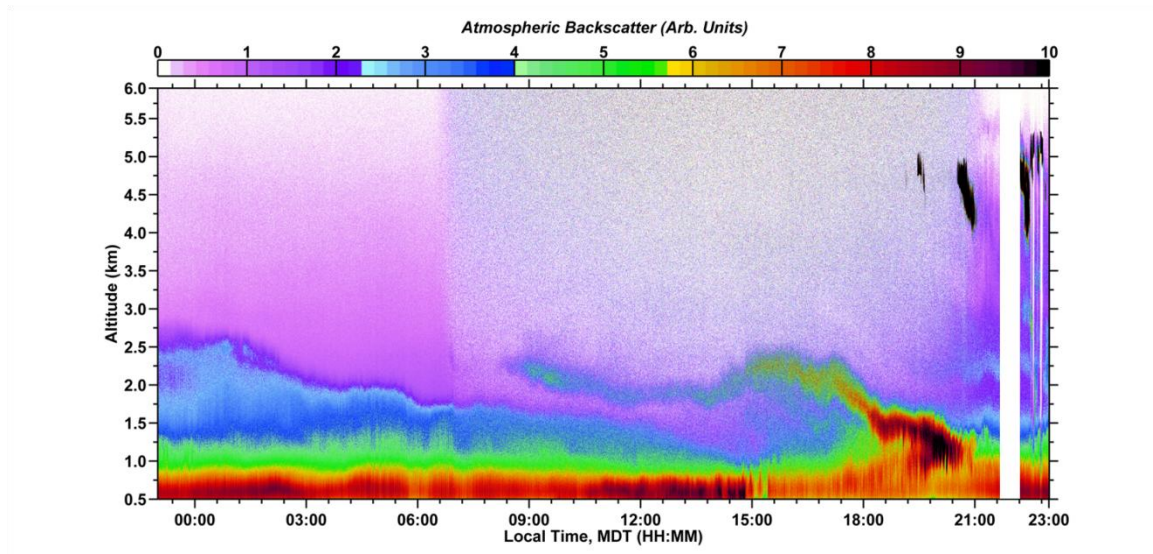


Figure 56 False color plot of the range corrected returns using the offline wavelength (828.287 nm) of the water-vapor DIAL as a function of range and time measured starting on 23:00 MDT on 27 August 2009.

The goal of this case study was to quantify the manner as well as the extent in which aerosols affect the shortwave incoming solar radiation on the Earth's surface. Particularly, the aerosol optical properties were sought after such that a correlation between the moisture content within an aerosol plume and the aerosol backscatter could

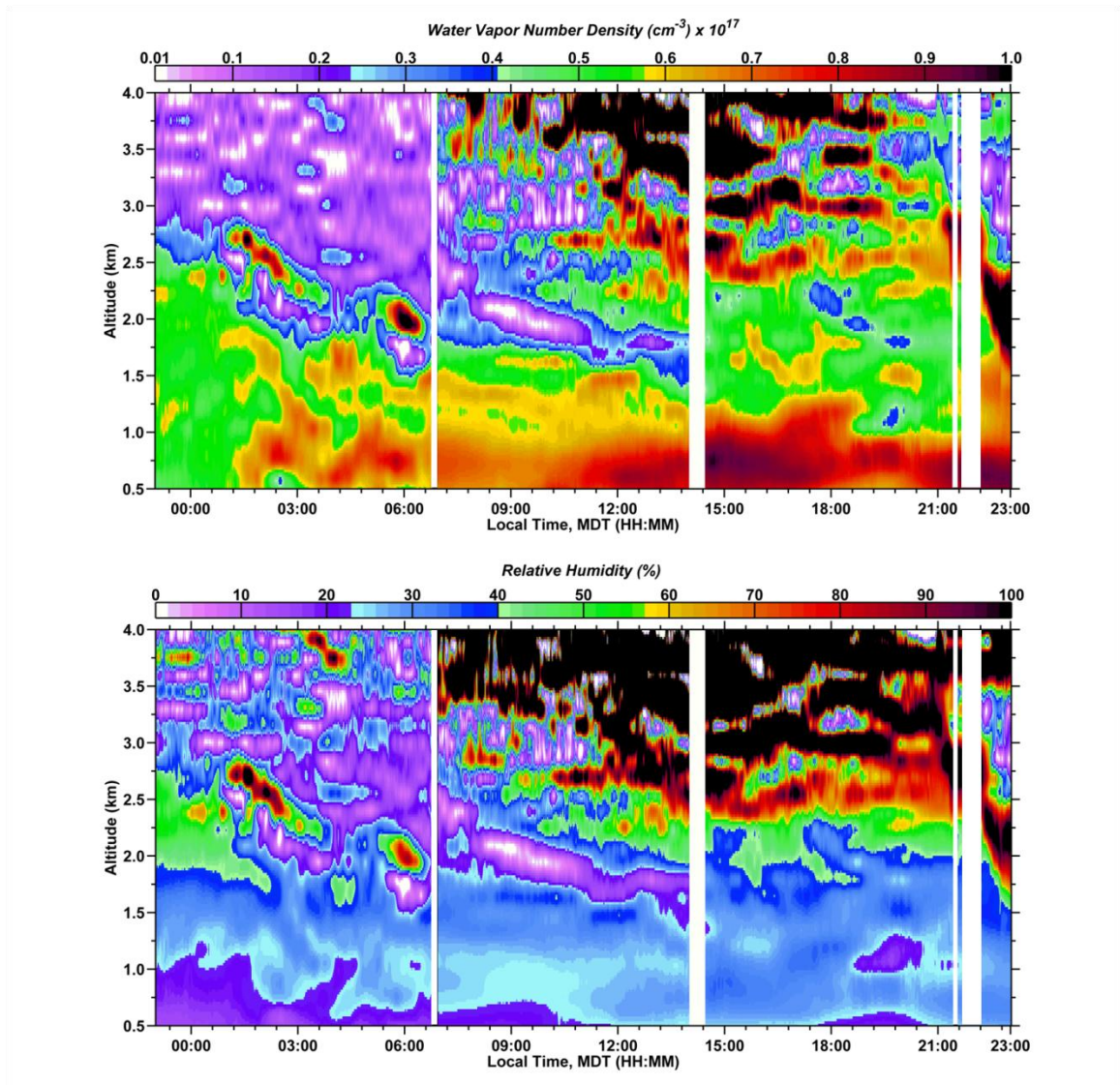


Figure 57 Top) Water-vapor number-density as a function of altitude and time beginning at 2300 MDT on 27 Aug 2009 and continuing through 2300 MDT on 28 Aug 2009. A 12 minute total integration period was used for these measurements. Bottom) The relative humidity as a function of range and time estimated using the number-density profiles from above. The temperature and pressure profiles used for the RH calculations are estimated using the surface temperature and pressure and a model atmosphere described in the theory section.

be obtained to provide evidence for the hygroscopic growth of aerosols. Such hygroscopic growth of aerosols can have a significant impact on the aerosol particle size and strongly influences the radiative forcing resulting from the aerosol direct effect (Wulfmeyer & Feingold 2000; Kotchenruther, Hobbs & Hegg 1999). The hygroscopic growth of aerosols requires a high relative humidity, approximately 80%, or greater before the aerosol backscatter is appreciably affected (Wulfmeyer and Feingold 2000; Kotchenruther et al. 1999). As can be seen in Figure 56 and Figure 57, during this observation period, the relative humidity in the vicinity of the aerosol layer below approximately 2.5 km remains fairly low, below 60%, indicating that very little hygroscopic growth of the aerosol is taking place. Aerosol extensive properties such as the range resolved aerosol extinction and backscatter were needed in order to assess the absolute enhancement of the backscattered signal resulting from the hydration of aerosols as well as to quantify the presence of different aerosols within the PBL. Because the offline channel of the water-vapor DIAL was not yet calibrated during this case study, the calibrated backscattered returns from the 532 nm channel of a collocated two color elastic lidar were used. The aerosol inversion was carried out using an iterative Fernald technique (Fernald, Herman & Reagan 1972; Fernald 1984) which will be described in the next section.

Profiles of the aerosol extinction derived from the two color lidar and the relative humidity from the DIAL as the plume intrudes into the PBL at 1500 MDT, 1600 MDT, 1700 MDT, and 1800 MDT are shown in Figure 58. The aerosol extinction from 750 m to 5 km was retrieved using the two color lidar, while the aerosol extinction at the surface

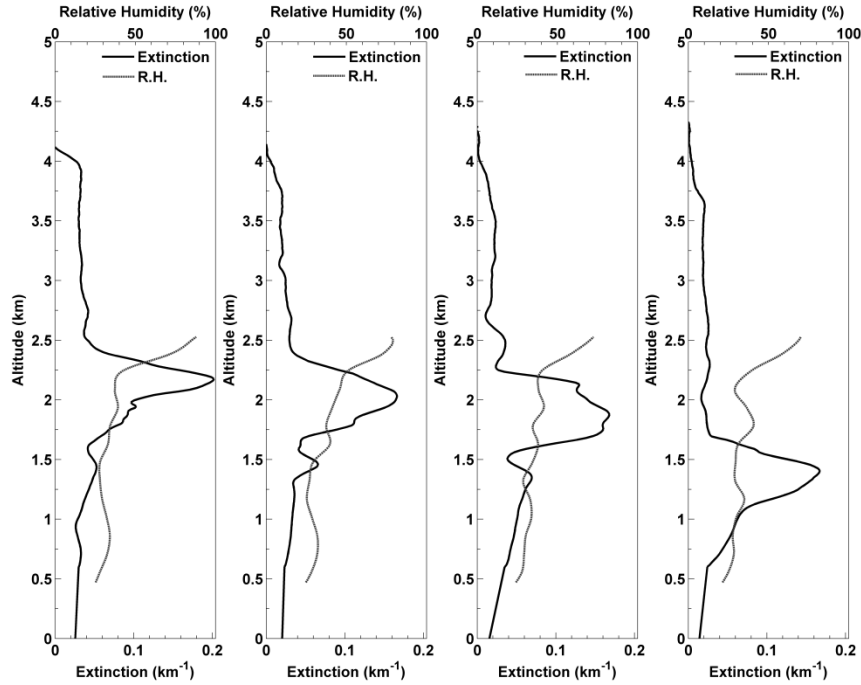


Figure 58 Plots of the aerosol extinction (532 nm) and relative humidity as a function of range at, 1500 MDT, 1600 MDT, 1700 MDT, and 1800 MDT from left to right. The aerosol extinction at the surface was measured using the scattering nephelometer. The two color lidar comes into overlap at 750 m and the change in aerosol extinction between the ground and 750 m was assumed to be linear.

was determined using the scattering nephelometer measurement and the single scatter albedo retrieved with the solar radiometer (Repasky et al. 2011; Nehrir et al. 2011). The change in aerosol extinction between the ground and 625 m was assumed to be linear. The increase in the RH profiles above 2.25 km is a result of noise in the return signal due to the increased solar background radiation. Due to the low RH, $< \sim 50\%$ in the aerosol loaded region of each panel in Figure 58, no enhancement of the backscattered signal was observed. Together, the two color lidar and the DIAL provide sufficient information about the state of the atmosphere and also provide insight towards optical and microphysical properties of aerosols and clouds. For operational simplicity as well as for

the added advantage of full time operation, the exclusive use of the eye-safe DIAL instrument for the retrievals of atmospheric water-vapor and aerosol optical properties is preferred.

Aerosol Inversion

Range resolved profiles of aerosol extinction and backscatter coefficients were retrieved using the offline channel of the second generation DIAL. An iterative solution to the Fernald lidar inversion (Fernald, Herman & Reagan 1972; Fernald 1984) technique was used for the retrievals of aerosol optical properties. The solution is derived by first considering the two component lidar equation as presented in equation (2.2). Combining all of the instrument specific parameters including the losses in the transmitting and receiving optics into a single calibration constant term C_λ , equation (2.2) can be written as

$$P(\lambda, r) = \frac{P_t(\lambda)C_\lambda}{r^2} [\beta_a(\lambda, r) + \beta_m(\lambda, r)] T_A^2(\lambda, r), \quad (4.1)$$

for altitudes above which the overlap function $O(r) = 1$, which is typically ~ 0.5 km for the second generation DIAL instrument. $T_A^2(\lambda, r)$ is the total atmospheric transmission resulting from absorption and scattering of light due to aerosols and molecules as well as molecular absorption. Assuming the offline channel wavelength is significantly far away from the center of the DIAL water-vapor absorption line, $T_A^2(\lambda, r)$ can be expressed as

$$T_A^2(\lambda, r) = T_a^2(\lambda, r) T_m^2(\lambda, r) = e^{-2 \int_0^r \sigma_a(\lambda, r') dr'} e^{-2 \int_0^r \sigma_m(\lambda, r') dr'}, \quad (4.2)$$

where $T_a^2(\lambda, r)$ and $T_m^2(\lambda, r)$ are the atmospheric transmission due scattering from aerosols and molecules, respectively. Because there are two unknowns in equation (4.1),

$\beta_a(\lambda, r)$ and $T_a^2(\lambda, r)$, the solution to the lidar equation for the aerosol backscatter coefficient following the technique presented by (Fernald, Herman & Reagan 1972) requires the assumption of a constant aerosol and molecular extinction to backscatter ratio (Lidar ratio), denoted as $S_a = \frac{\sigma_a(\lambda, r)}{\beta_a(\lambda, r)}$ and $S_m = \frac{\sigma_m(\lambda, r)}{\beta_m(\lambda, r)}$, respectively. From small particle scattering theory, $S_m \approx \frac{8\pi}{3}$ (Bohren & Huffman 1983; Measures 1984).

Using a modeled atmospheric temperature and pressure profile from equations (2.24) and (2.25), the atmospheric molecular backscatter coefficient in the backward direction can be computed to within a few percent using the following expression (Kovalev & Eichinger 2004)

$$\beta_m(r)(m^{-1}sr^{-1}) = 374280 \left[\frac{p(r)(kPa)}{T(r)(K)} \right] \left[\frac{1}{\lambda^4(nm)} \right]. \quad (4.3)$$

The atmospheric molecular extinction coefficient can then be found by $\sigma_m(r)(m^{-1}) = \beta_m(r) \cdot S_m$. A solution to equation (4.1) can be obtained if the unknown variables are expressed in terms of the aerosol round trip transmittance $T_a^2(\lambda, r)$ from (4.2). Using the transformation from extinction to backscatter using the assumption of a constant lidar ratio with height, differentiating $T_a^2(\lambda, r)$ with respect to altitude and solving for $\beta_a(\lambda, r)$ yields

$$\beta_a(\lambda, r) = \frac{-1}{2S_a(\lambda)T_a^2(\lambda, r)} \frac{dT_a^2(\lambda, r)}{dr}. \quad (4.4)$$

Substituting equation (4.4) in for the particulate scattering component in equation (4.1) and rearranging yields the first order differential equation

$$\frac{dT_a^2(\lambda, r)}{dr} - 2S_a(\lambda)\beta_m(\lambda, r)T_a^2(\lambda, r) = -\frac{2S_a(\lambda)r^2P(\lambda, r)}{P_t(\lambda)C_\lambda T_m^2(\lambda, r)}, \quad (4.5)$$

where $T_a^2(\lambda, r)$ takes the form

$$T_a^2(\lambda, r) = e^{2S_a(\lambda) \int_0^r \beta_m(\lambda, r') dr'} \left[1 - \frac{2S_a(\lambda)}{C_\lambda} \int_0^r \frac{r'^2 P(\lambda, r')}{P_t(\lambda) T_m^2(\lambda, r')} e^{2S_a(\lambda) \int_0^{r'} \beta_m(\lambda, r'') dr''} dr' \right]. \quad (4.6)$$

Rewriting the two component lidar equation (4.1) in terms of $T_a^2(\lambda, r)$ from equation (4.6) and solving for $\beta_a(\lambda, r)$ yields

$$\beta_a(\lambda, r) = \frac{L_\lambda(r) e^{-2(S_a(\lambda) - S_m(\lambda)) \int_0^r \beta_m(\lambda, r') dr'}}{C_\lambda P_t(\lambda) - 2S_a(\lambda) \int_0^r \frac{L_\lambda(r')}{T_m^2(\lambda, r')} e^{-2S_a(\lambda) \int_0^{r'} \beta_m(\lambda, r'') dr''} dr'} - \beta_m(\lambda, r), \quad (4.7)$$

where $L_\lambda(r) = P(\lambda, r) \cdot r^2$ is the range corrected returns accounting for the $\frac{1}{r^2}$ fall off of the returning laser energy with increasing distance from the transmitter. This retrieval technique assumes the complete overlap between the laser transmitter and receiver. To compensate for the incomplete overlap function for the second generation DIAL instrument between the surface and ~ 0.5 km, the transmission of the outgoing beam must be accounted for up to the initial overlap range by modifying equation (4.7) such that

$$\beta_a(\lambda, r) = \frac{L_\lambda(r) e^{-2(S_a(\lambda) - S_m(\lambda)) \int_{r_0}^r \beta_m(\lambda, r') dr'}}{C_\lambda P_t(\lambda) T^2(r_0) - 2S_a(\lambda) \int_{r_0}^r \frac{L_\lambda(r')}{T_m^2(\lambda, r')} e^{-2S_a(\lambda) \int_{r_0}^{r'} \beta_m(\lambda, r'') dr''} dr'} - \beta_m(\lambda, r), \quad (4.8)$$

where $T^2(r_0)$ is the total (molecular and aerosol) transmission of the laser beam from 0 to range r_0 and has been found to typically range between 0.97-0.99. As stated previously, this transmission term can be set to unity if the overlap function is directly

measured or if an aerosol scattering extinction measurement is made at the ground and that a linear interpolation is used to extend the lidar aerosol extinction and backscatter profiles to the surface.

The calibration constant for the aerosol retrieval is obtained via Rayleigh normalization at high altitudes where molecular scattering dominates the backscattered returns. At sufficiently high altitudes such that $\beta_a(\lambda, r) = 0$, typically 5-10 km given a clear sky, the lidar equation shown in (4.1) can be written as

$$L_\lambda(r) = P_t(\lambda) C_\lambda \beta_m(\lambda, r) e^{-2 \int_0^r \sigma_a(\lambda, r') dr'} e^{-2 \int_0^r \sigma_m(\lambda, r') dr'}. \quad (4.9)$$

The transmission of the laser energy through the aerosol loaded lower atmosphere is scaled via the aerosol optical depth $AOD = \int_0^r \sigma_a(\lambda, r') dr'$ which is a known quantity measured from an independent source. The AOD measurements as well as a plethora of other aerosol optical properties are retrieved from a collocated sun-sky scanning solar radiometer (CIMEL 318) as a part of the NASA AErosol RObotic NETwork (AERONET). Using modeled molecular backscatter and extinction profiles at 828 nm derived using equation (4.3) and also accounting for the transmission loss of the laser energy up to an aerosol free atmosphere, the range resolved calibration $C_\lambda(r)$ can be retrieved as

$$C_\lambda(r) = \frac{L_\lambda(r)}{P_t(\lambda) \beta_m(\lambda, r) e^{-2 \cdot AOD} e^{-2 \int_0^r \sigma_m(\lambda, r') dr'}}. \quad (4.10)$$

The calibration constant used for the retrieval of the aerosol backscatter coefficient is

calculated in the free troposphere such that $\left. \frac{dC_\lambda(r)}{dr} \right|_{r=5km}^{r=6km} = 0$ and $C_\lambda = \text{constant}$. Within

this region, the measured signal is dominated by molecular returns and $L_\lambda(r)$ is proportional to $\beta_m(\lambda, r)$ and $T_m^2(\lambda, r)$.

The retrieval of the attenuated aerosol backscatter coefficient from equation (4.8) is completed by assuming an initial first guess for the lidar ratio $S_a(\lambda)$ and using the AOD measured from a solar radiometer as a constraint on the inversion. The flow diagram for the iterative aerosol inversion technique is schematically shown in Figure 59. The spatially and temporally averaged (typically 0.75 m, and 1-4 minutes, respectively) range corrected returns as well as the surface temperature, surface pressure, and AOD are provided as inputs to the inversion algorithm. A range resolved molecular profile is then modeled for each surface temperature and pressure measurement. The instrument calibration constant is then calculated in the free troposphere using equation (4.10) and the AOD as a beam transmission scaling factor.

With a prior knowledge of the typical range for $S_a(\lambda)$ (~ 20 -100 sr) of the major aerosol types representative of the Earth's atmosphere (Cattrall et al. 2005; Omar et al. 2005; Omar et al. 2009), an initial value of $S_a(828.2nm) = 45$ (sr) is chosen and the Fernald inversion is completed using equation (4.8). The lidar measured AOD is then calculated as $\tau_a = S_a \int_0^r \beta_a(\lambda, r') dr'$ and compared with the independent measurement of the AOD retrieved from the solar radiometer. Using a bisectional root finding method, a new S_a between 20-100 (sr) is chosen based on the sign of the relative error between the calculated and measured AOD. This process is repeated until the measured and calculated AOD's agree to within ± 0.5 %. The general basis for this technique is demonstrated in Figure 59 where the lidar AOD (blue dashed line) is calculated as a

function of $S_a(\lambda)$ from the retrieved $\beta_a(\lambda, r)$ using the solar radiometer derived AOD from the morning of 9-24-2009 as the constraint. A minimum in the AOD error can be seen at $S_a(\lambda) = 61.3(sr)$, corresponding to a lidar measured AOD of 0.0281. The low AOD is typical of the pristinely clear air in the Gallatin valley while the lidar ratio of ~ 60 indicates the weak presence of a mixture of polluted continental aerosols and biomass burning aerosols (Omar et al. 2005; Omar et al. 2009; Cattrall et al. 2005). An example of a retrieval of the total backscatter coefficient using the iterative Fernald solution from early morning on 24 September 2009 over Bozeman, Montana is presented in Figure 60. The total backscatter coefficient retrieved from the lidar approaches the modeled molecular profile at higher altitudes where Rayleigh scattering dominates the backscattered returns.

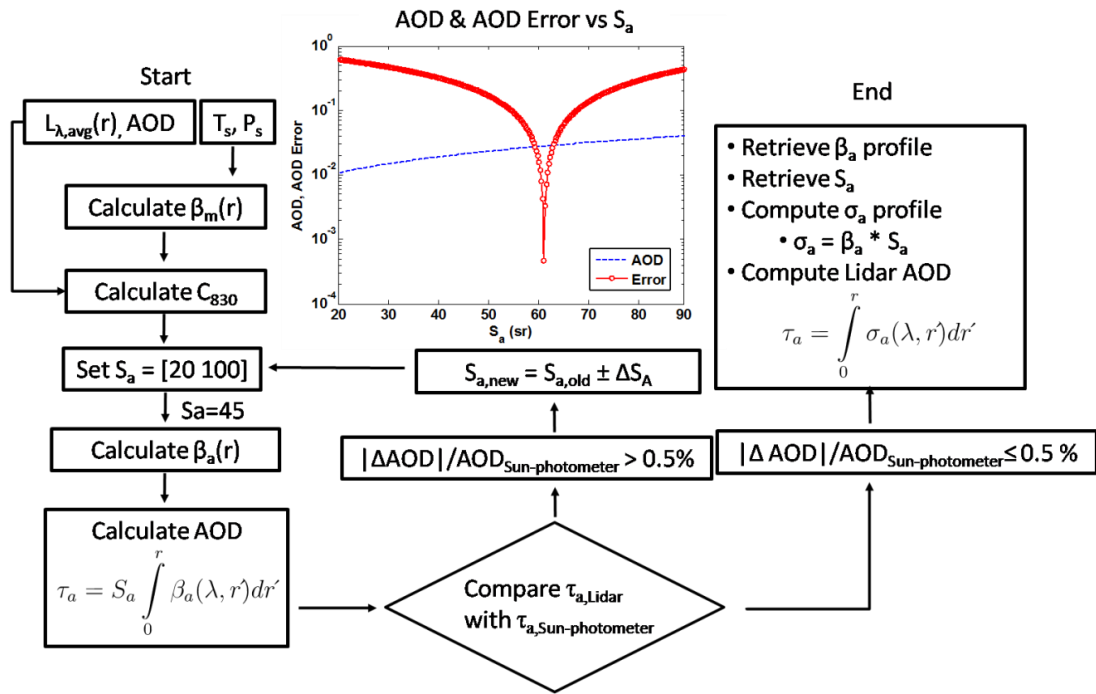


Figure 59 Simplified flow diagram showing basic principles used in the Fernald aerosol inversion.

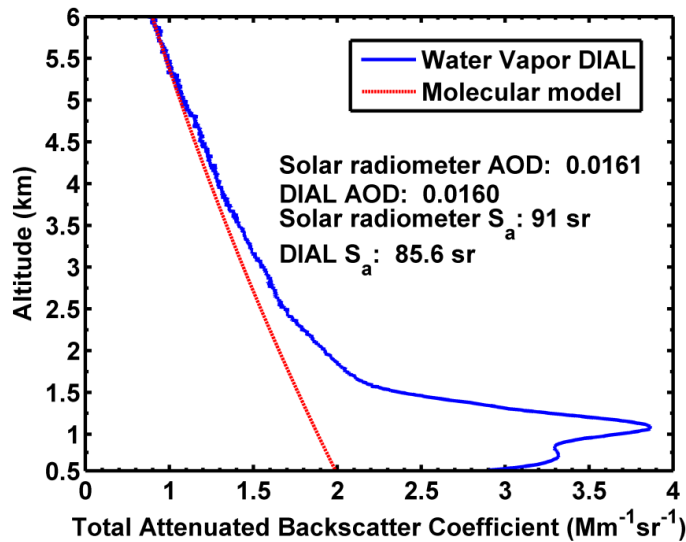


Figure 60 Retrieval of the total backscatter coefficient using the Fernald solution to the lidar equation with a 5 minute averaging time. Agreement between the retrieval and the molecular model at higher altitudes is observed where Rayleigh scattering dominates the returns.

Quantitative Measurements: Experimental Results

To test stability of the inversion technique over varying atmospheric conditions over an extended period, atmospheric aerosol optical properties and water-vapor profiles were observed from September 21-27, 2009 over Bozeman, Montana where the subsequent direct radiative forcing was calculated due to the aerosol direct effect. During this case study, a transition between an atmosphere consisting of a combination of polluted rural continental aerosols and well aged biomass burning aerosols to that of an atmosphere dominant by extremely fresh biomass burning aerosols resulting from forest fires burning in the northwestern United States and Canada was observed. Aerosol optical properties and water-vapor number-density profiles were retrieved using an eye-safe micro-pulse water-vapor DIAL (MP-DIAL), a single channel backscatter lidar, a CIMEL solar radiometer as part of AERONET, a ground based integrating scattering nephelometer (550nm), and aerosol data products from MODIS Terra and Aqua satellites. A detailed description of the case study is presented in (Nehrir et al. 2011).

Satellite Observations

The aerosol optical properties obtained from a combination of active and passive remote sensors from ground and satellite based platforms can be used to estimate the regional aerosol radiative forcing. To evaluate the spatial variability of the various types

of aerosols measured throughout this case study, aerosol data products were used from the MODerate resolution Imaging Spectrometer (MODIS) instrument on board the Terra and Aqua satellites. Figure 61 shows the MODIS-Aqua true color and hot spot fire activity in the near vicinity of Bozeman, MT, the AOD from MODIS-Terra, and the 5 day NOAA HYSPLIT back trajectory analysis in columns a, b, and c, respectively, for September 24, 25, 26, and 27. These four days correspond to periods of rapid transition from a relatively clean aerosol background level dominated by a combination of aged biomass burning aerosols and polluted continental aerosols to an atmosphere dominated by aged and relatively fresh biomass burning aerosols in succession.

The daily MODIS-Terra AOD (MOD04) at 550 nm and MODIS-Aqua visible hot spot images show the development and progression of biomass burning aerosols over the northwest region of the country. The true color/hot spot images show light fire activity in the northwestern region of Montana on September 24 as indicated by the red dots, but also shows little presence of biomass burning aerosols over Bozeman indicated by the blue target. MODIS-Terra measurements for the same day show seasonably low AOD's of less than 0.05 near Bozeman, but also show the presence of a large aerosol plume extending from northwestern California into northwestern Montana and Canada. The HYSPLIT back trajectory analysis and knowledge of fire activity in the northwest region between September 24 and 25 confirms the broad aerosol source to be biomass burning. On September 25, the aerosol plume was pushed down into central Montana, resulting in relatively high AOD's ranging between 0.1-0.35 dominated by 3-4 day aged biomass burning aerosols. The short-lived plume was then pushed out on the 26th with a north-

westerly front causing a brief void of an aerosol loaded atmosphere over Bozeman before a plume of fresh smoke resulting from advected biomass burning aerosols from forest fires in western Montana intruded directly over Bozeman. This event is clearly depicted from the MODIS-Terra AOD and MODIS-Aqua true color images from September 26. The temporal difference between the MODIS-Terra AOD measurements (18:20 UTC) and the MODIS-Aqua true color images (composite between 20:05, 20:10, and 21:45 UTC) shows the flushing out of the broad aged aerosol plume and the subsequent intrusion of the fresh smoke directly over Bozeman. The HYSPLIT back trajectory analysis between September 25, 26, and 27 also indicates the shift in the wind direction from northwest to west, advecting fresh biomass burning aerosols from western Montana directly over the observation site. MODIS-Aqua AOD measurements from September 27 indicate the presence of a highly directional aerosol plume from west central-Montana over Bozeman. MODIS rapid response hotspot imagery and the HYSPLIT back trajectory analysis indicate the source and origin of the relatively un-aged aerosols to be biomass burning resulting from forest fire smoke in the Bitterroot mountain range in west-central Montana.

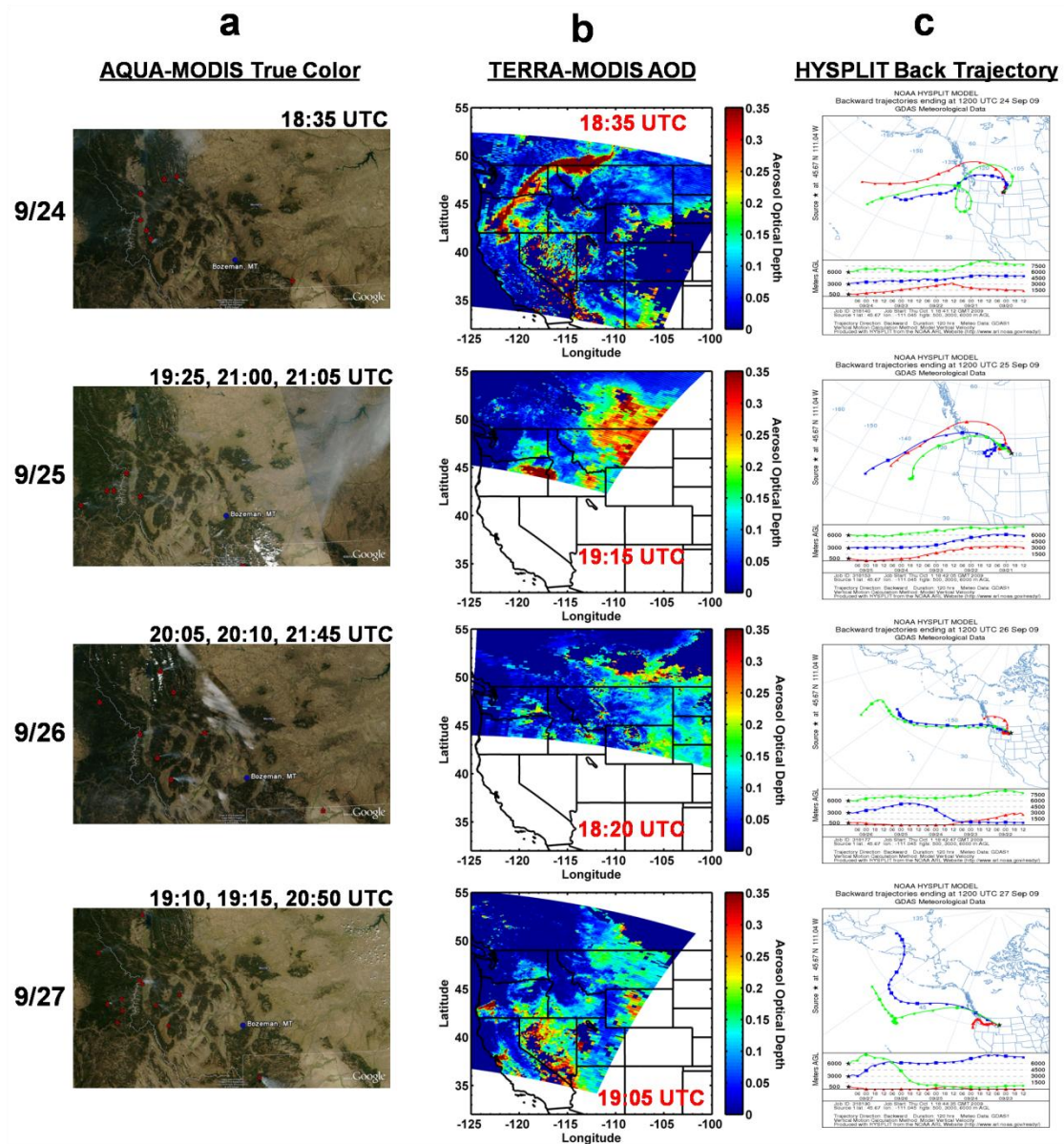


Figure 61 a) Aqua MOIDS rapid response fire counts surrounding Bozeman MT, from 9/24-9/27 2009. b) Terra MODIS MOD04 AOD over the northwestern United States and Canada during the same time period. c) NOAA HYSPLIT 5 day back trajectory analysis.

Ground-Based Observations of Aerosol Optical Properties

The eye-safe water-vapor MP-DIAL operating at 830 nm provided near full time data during the seven day study while the non eye-safe backscatter lidar operating at 532 nm only had Federal Aviation Administration (FAA) permissions to operate from 2:30 pm to 1:00 am local time (UTC-6). The AOD measurement from the CIMEL solar radiometer was used to provide a constraint on both of the lidar inversions to retrieve the aerosol extinction profiles as presented in the retrieval section above. The estimate of the aerosol extinction profile from the ground to initial overlap, as noted earlier was calculated using the integrating nephelometer surface measurement.

A plot of the comparison of the AOD measured by the solar radiometer and the two lidars as a function of time is shown in Figure 62. The solar radiometer AOD at 532 nm (830 nm) was calculated using the extinction Angstrom exponent which was calculated using the solar radiometer AOD measurements between the 500 nm and 675 nm (675 nm and 870 nm) channels of the CIMEL (Eck et al. 1999). The Angstrom exponent, α , represents the wavelength dependence of the aerosol extinction coefficients and is calculated using $\tau_{\lambda} = \tau_{\lambda_0} \left(\frac{\lambda}{\lambda_0} \right)^{-\alpha}$, where τ_{λ} is the AOD and λ is the wavelength. The Angstrom exponent retrieved from AERONET AOD measurements provides information regarding the column average size of the dominating aerosol type where larger values imply a relatively higher ratio of small particles and smaller values for higher ratios of larger particles.

The AOD constraint for nighttime inversion was achieved by assuming a linearly changing AOD between the last CIMEL AOD measurement made during the evening and

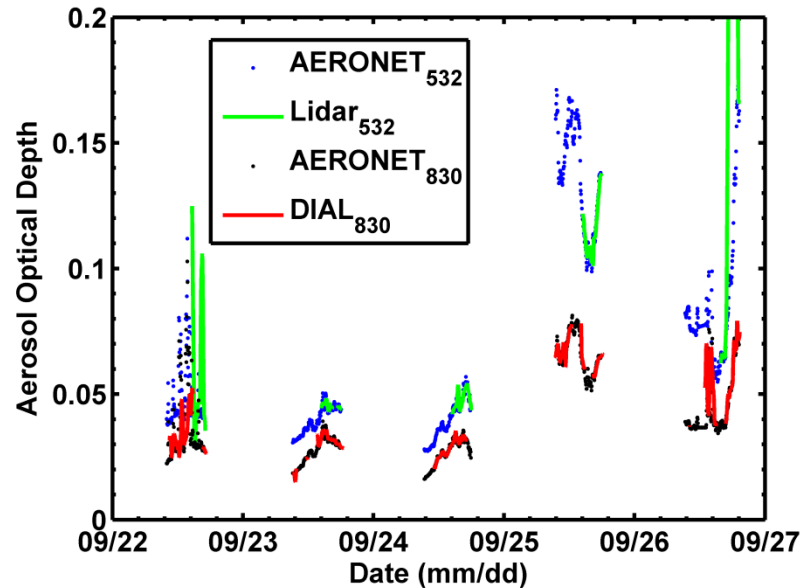


Figure 62 Aerosol optical depth observations from AERONET (532 nm (830 nm) AOD estimated from the 500 nm-675nm (675 nm-870 m) channels using the Angstrom exponent), single channel elastic lidar integrated extinction resulting from AEROENT AOD constrained Fernald inversion, and 830 nm DIAL integrated extinction also resulting from AERONET AOD constrained Fernald inversion.

the first AOD measurement made the following morning allowing for qualitative assessment of the changing aerosol extinction profiles during the nighttime. A clear transition can be seen from a clean atmosphere with average AOD's ranging from .02 to .05 at 830 nm and 532 nm, respectively, to higher AOD's approaching .15 at 532 nm as the biomass burning aerosols were transported into the Gallatin valley. Patchy cirrus cloud contamination of the lidar and solar radiometer AOD measurements is evident at the beginning and end of the case study and limited the accuracy of the aerosol optical properties at these times. The agreement otherwise between the AOD measured using the solar radiometer and the AOD resulting from the completed lidar inversions at the 532 nm and 830 nm wavelengths is expected since the AOD measured using the solar

radiometer is used to constrain the lidar inversions. However, as the lidar AOD determination includes the influences of the lidar equation retrieval assuming $S_a(\lambda)$ constant, an overlap correction, and system calibration via Rayleigh normalization at a high altitude, this AOD agreement provides some indication that these influences have not significantly biased the lidar AOD determination. The relatively good agreement achieved between the lidar $S_a(\lambda)$ retrievals and the CIMEL derived $S_a(\lambda)$, to be discussed next, provides stronger indication that these various influences have not significantly impacted the lidar retrievals.

The iterative lidar retrievals based on the Fernald inversion technique described in the previous section provide an average $S_a(\lambda)$ which can be used to classify different aerosol types based on clustering analysis (Cattrall et al. 2005; Omar et al. 2005). Figure 63 shows plots of the $S_a(\lambda)$ and the corresponding measurement standard deviations (in red) for the 532 nm (830 nm) wavelength over the seven day period retrieved from both the solar radiometer (green boxes) and lidar's (black solid line). The CIMEL derived $S_a(\lambda)$ were calculated using the level 1.5 AERONET phase function and single scatter albedo (SSA) products retrieved using the almucantar geometry scans. The standard deviation of the lidar retrievals of $S_a(\lambda)$ are shown as a result of the uncertainty in the AOD measurements from the solar radiometer, typically 0.005-0.01 for a well calibrated system. Reasonable agreement between the solar radiometer and the lidar's retrievals can be seen throughout the duration of the observation period. Diurnal variability in the $S_a(\lambda)$ at both wavelengths was clearly evident from both the lidar and solar radiometer

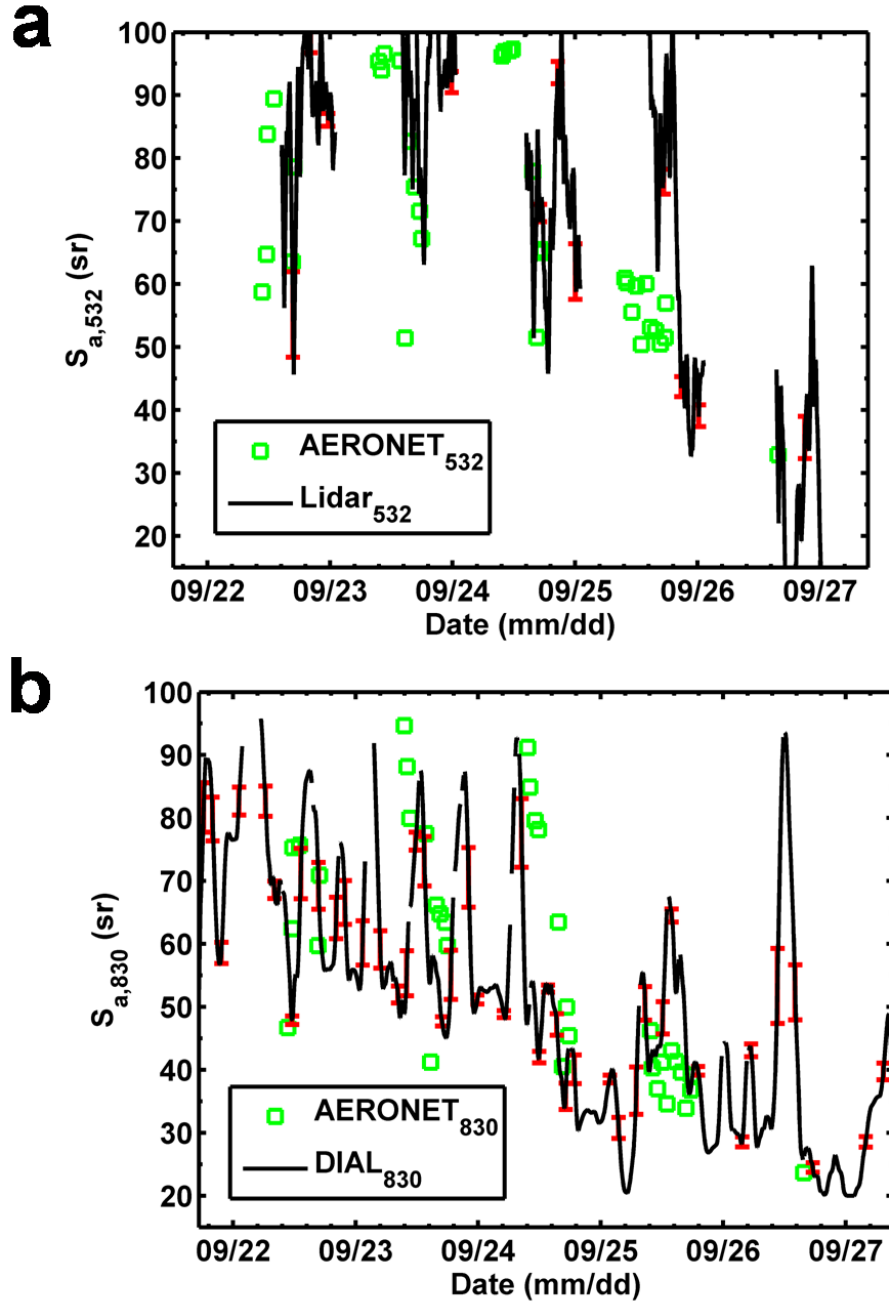


Figure 63 a) Summary of 532 nm S_a retrievals, from AERONET (estimated from the 500 nm channel) almucantar scan inversions, and elastic Lidar inversions resulting from the constrained iterative Fernald inversions. b) Summary of 830 nm S_a retrievals, from AERONET (estimated from the 870 nm channel), and DIAL retrievals resulting from the constrained iterative Fernald inversions.

measurements in the first three days of the study and was primarily attributed to the local mountain-plains wind systems (Banta & Cotton 1981).

The tracking of the diurnal trends of the $S_a(\lambda)$ given low background AOD's in both the CIMEL and lidar measurements suggests the validity of the lidar retrievals. Westerly upslope daytime winds at lower elevations blowing from the valley towards the mountains resulted in the transport of anthropogenic aerosols such as polluted continental aerosols from nearby urban areas; resulting in lower $S_a(\lambda)$'s ranging on average from 60-80 sr (50-70 sr) at 532 nm (830 nm) which are generally consistent with the AERONET clustering models (Catrall et al. 2005; Omar et al. 2005). Clear skies and a stable nocturnal boundary layer brought nighttime down slope winds blowing east from the mountains to the valley floor, transporting relatively clean background aerosols with a weak accumulation mode ($\sim 1 \mu\text{m}$ - $2 \mu\text{m}$ diameter) of which was observed to have significantly higher peak values of $S_a(\lambda)$ of approximately 55-95 sr (50-90 sr) at 532 nm (830 nm) by the morning.

During the second half of the case study, the average daily $S_a(\lambda)$ measured by both the lidar's as well as the solar radiometer were noticeably lower due to the influx of biomass burning aerosols over Bozeman, Montana. Average $S_a(\lambda)$'s ranged between 35-60 sr (20-45 sr) at 532nm (830nm) which show moderate agreement with the $S_a(\lambda)$'s derived from AERONET cluster analysis for biomass burning aerosols. Overall, agreement between both the diurnal and episodic trends in the $S_a(\lambda)$'s measured using the active and passive sensors resulting from the AOD constrained lidar retrieval and the lidar ratio retrieved from the solar radiometer lends credence to the accuracy of the

daytime lidar retrievals during this case study and is also a good indication that the overlap correction, the Rayleigh calibration method, and the variability in $S_a(\lambda)$ do not significantly impact the lidar retrievals. These active/passive derived aerosol inversions have also been successfully demonstrated in a previous case study (Repasky et al. 2011) where lidar and AERONET sunphotometer measurements of $S_a(\lambda)$ showed good agreement during a biomass burning aerosol intrusion event over Bozeman, Montana.

Aerosol extensive properties were also measured using the two lidar's to monitor the temporal-spatial distributions of aerosols over Bozeman, Montana. Time-height cross-sections of the aerosol extinction at 532 nm and 830 nm using the iterative Fernald lidar inversion technique are shown in Figure 64. A relatively clean (i.e., low AOD) atmosphere was present in the first half of the case study as indicated by the low aerosol extinctions in the boundary layer as well as from the low AOD's shown in Figure 62. Average boundary layer extinction coefficients between the 21st and 24th of September were approximately 18 Mm⁻¹ and 12 Mm⁻¹ at 532nm and 830 nm, respectively, with an average boundary layer height of approximately 1.5 km. High altitude cirrus clouds early in the case study contaminated the return signals from the high pulse repetition rate MP-DIAL, but allowed for continuous qualitative measurements of the aerosol extinction profiles.

The biomass burning aerosols can be seen pushing into the Gallatin valley starting late on September 24. Flushing out of the aged smoke transported from the northwest

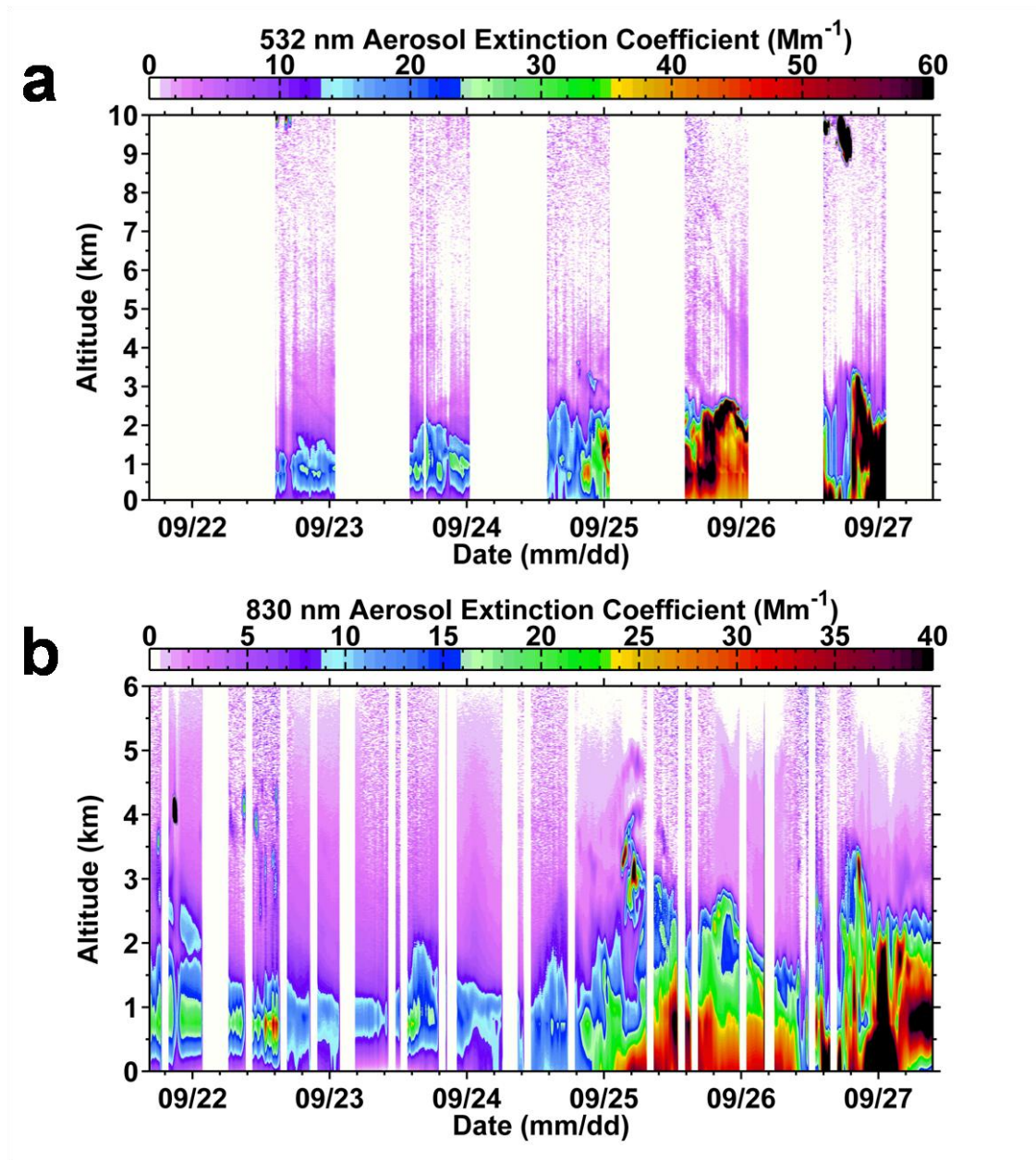


Figure 64 a) Lidar measured 532 nm aerosol extinction coefficient from 9/21-9/27 2009, over Bozeman, MT with 2 minute and 15 m temporal and spatial resolution, respectively. b) Water-vapor DIAL measured 830 nm aerosol extinction coefficient from 9/21-9/27 2009, over Bozeman, MT with 4 minute and 7.5 m temporal and spatial resolution, respectively.

region of the country from the 25th-26th as shown in Figure 61 can be seen on the evening of the September 26. Fresh smoke transported from nearby fires in western Montana shown in Figure 61 is indicated by high aerosol extinction coefficients during September 26-27. The average boundary layer aerosol extinction coefficients between the 24th and 27th of September were approximately 50 Mm^{-1} and 35 Mm^{-1} at 532nm and 830 nm, respectively, with an average boundary layer height of approximately 2.5 km, a noticeable increase over the background levels.

The retrievals of the aerosol extinction and backscatter profiles from the offline channel of the DIAL as well as from the two color lidar allowed for quantitative assessment of the influence different types of aerosols have on the Earth's surface albedo, which is otherwise referred to as the aerosol direct effect (Nehrir et al. 2011). Although aerosol optical properties were retrieved with the offline channel of the DIAL, water-vapor profiles were not measured throughout the entire duration of the 7 day case study. A time series of the water-vapor profiles corresponding to the same timeline shown in Figure 64 is presented in Figure 65. Water-vapor profiles in the lower troposphere were obtained over a large percentage of the case study where the aerosol distributions were nominally homogeneous. Due to the long 60 second dwell time at each wavelength required for the DIAL technique, large random errors due to air mass miss sampling are introduced into the DIAL retrievals. Given a heterogeneous aerosol layer, such as the fresh smoke plume that entered over Bozeman 26 September 2009 (or cloudy conditions), accurate water-vapor profiles were not attainable, hence no water-vapor data was acquired during the last part of the case study. This major drawback which

significantly limited the operating conditions of the second generation DIAL instrument led to the design and development of a more powerful, faster spectrally switching third generation DIAL transmitter.

The second generation water-vapor DIAL instrument demonstrated the potential of diode laser based DIAL instruments for long term water-vapor and aerosol profiling in the lower troposphere. However, the second generation DIAL instrument can be greatly improved by addressing three major topics including increasing the laser transmitter pulse energy, decreasing the switching time between the on-line, side-line, and off-line wavelengths, and packaging (mechanical vibration and temperature compensation) the DIAL instrument for long term operation and potential field deployment. A third generation water-vapor DIAL instrument was developed to address all three of these major limiting factors.

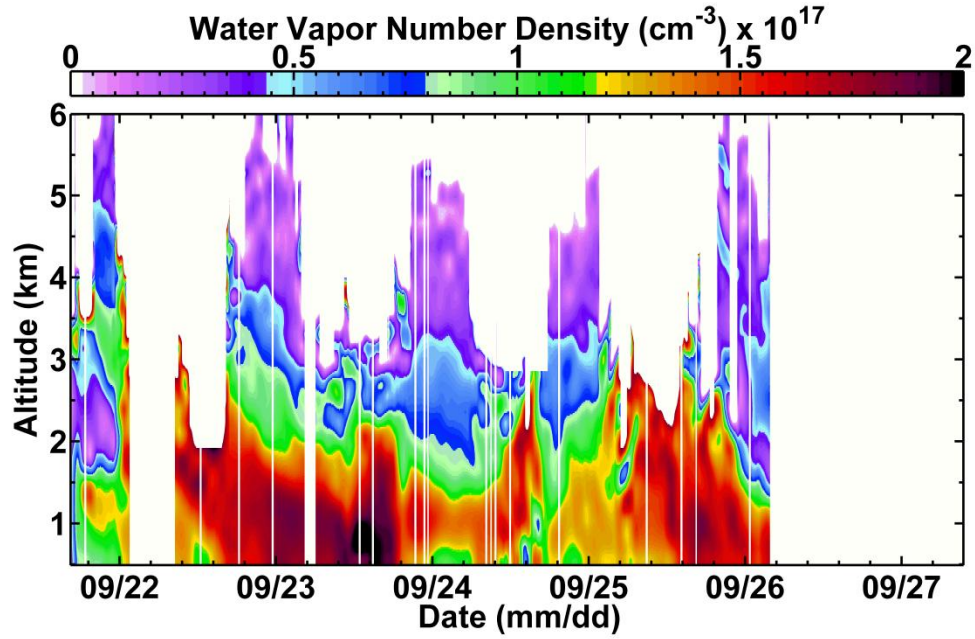


Figure 65 Water-vapor number-density time series from 9/21-9/27 2009, over Bozeman, MT with 30 minute (total) and 150 m temporal and spatial resolution, respectively. An up sampled profile interpolation of 25 m spatial and 3.33 minutes was used to enhance the viewing resolution.

THIRD GENERATION DIAL

A third generation DIAL transmitter has been built to overcome the major limitations of the prior two instruments. A schematic showing the major components of the third generation DIAL transmitter is shown in Figure 66. Pictures of the built transmitter as well as the major components are also shown in Figure 67. Two compact high power Littrow configured ECDL's were designed and built to alleviate the need for a transmitter pre-amplification stage, hence significantly reducing the transmitter footprint. The two ECDL's are operated continuously at the online (or sideline) and offline wavelengths, significantly increasing the frequency stability over the use of a single tunable seed source. The two ECDL's are fiber coupled into a 2x1 fiber optic electromechanical switch to sequentially seed a single pulsed TSOA at the online and offline wavelengths with short switching times ~ 1 -6 seconds. The decrease in the atmospheric sampling time between λ_{on} and λ_{off} significantly decreased the error introduced in the DIAL retrievals due to air mass miss-sampling resulting from the slow spectral switching times. This was especially evident in the presence of optically thin clouds and heterogeneous aerosol layers. Furthermore, the commercial availability of new 4.0 mm length TSOA's has allowed for significantly higher pulse energies to be extracted from the third generation DIAL transmitter, allowing for water-vapor and aerosol profiling up to 6 km and 15 km, respectively. The inclusion of the new transmitter components has given way to a compact DIAL transmitter/receiver design which has the potential for making 3-D full-sky scanning measurements of water-vapor and aerosols using a commercial telescope scanning tripod mount.

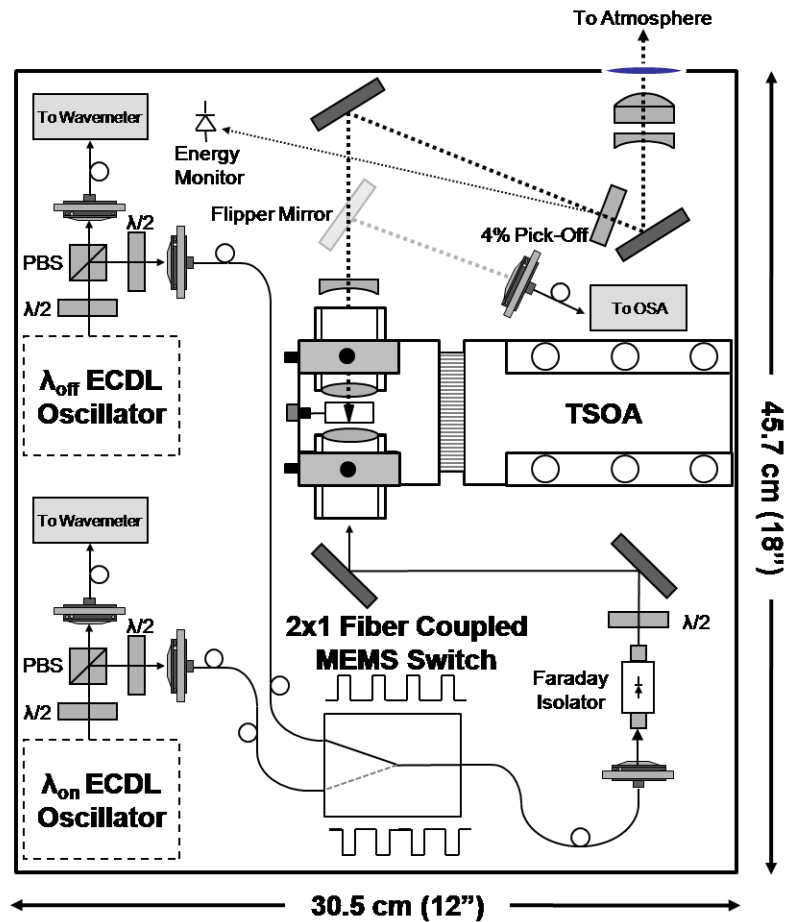


Figure 66 Schematic of the third generation DIAL transmitter. The transmitter is housed in a 45.7 cm x 30.5 cm Poloxymethylene (Acetal resin or Delrin) enclosure that is mounted directly on the back of the DIAL receiver. The entire third generation DIAL instrument is mounted on a motorized Celestron telescope full-sky scanning tripod.

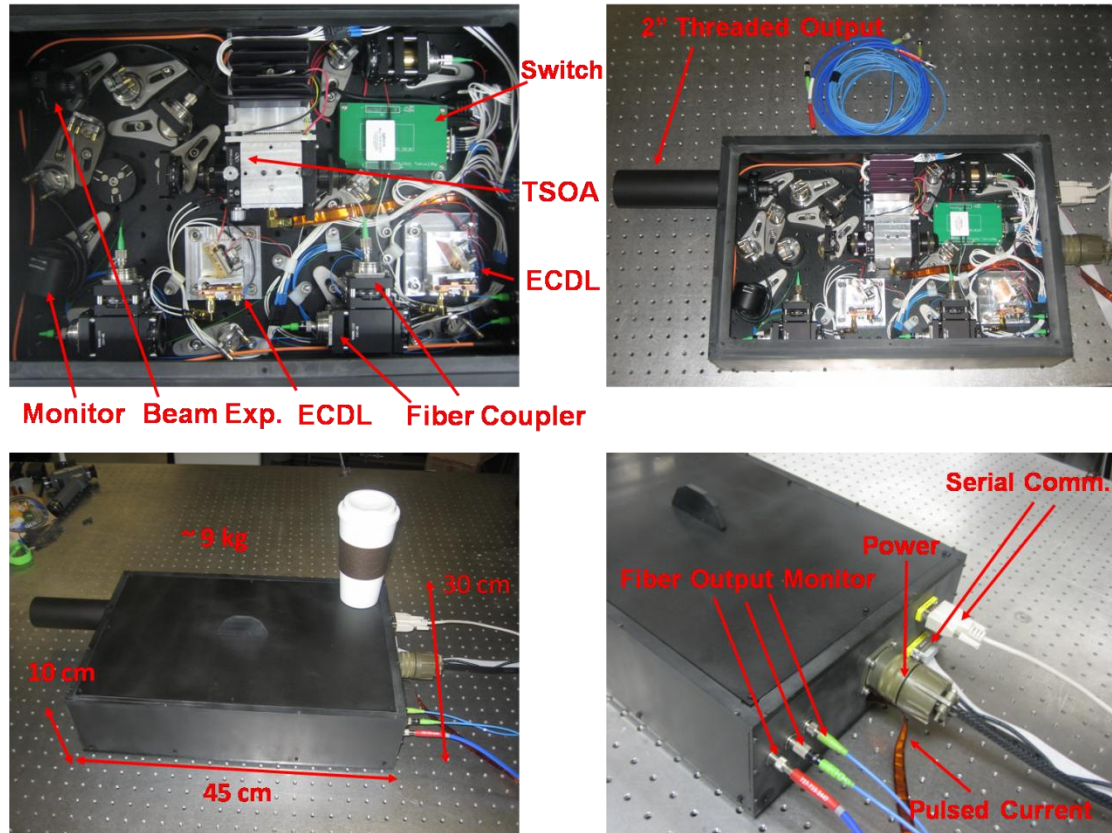


Figure 67 Pictures of the DIAL transmitter. The major components are denoted and captioned in red.

High Power Littrow ECDL's

Two identical high powered ECDL's were designed and built as the seed sources for the DIAL measurements. A schematic showing the major components of the Littrow configured ECDL is shown in Figure 68. The highly divergent output from a C-mounted laser diode is collimated using two AR coated aspheric lenses. The spectrally broad output from the AR coated front facet of the laser diode is incident on a 2100 lines/mm holographic diffraction grating which spatially separates the different spectral

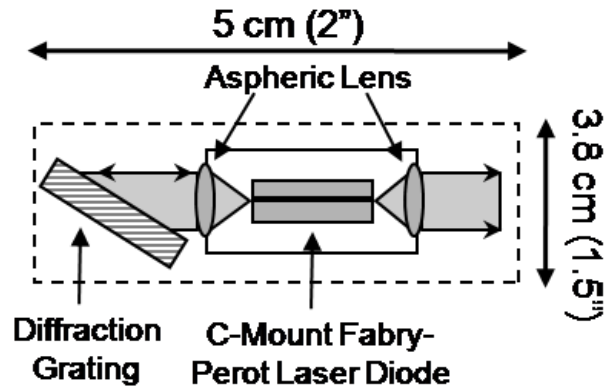


Figure 68 Optical schematic of the Littrow configured ECDL using a C-mount Fabry-Perot laser diode.

components. The 1st order spectral component is fed directly back into the laser diode via the aspheric collimation lens causing the laser to operate with the single longitudinal mode that was fed back. The laser cavity is formed between the diffraction grating and the uncoated back facet of the laser diode chip. Tuning of the ECDL wavelength is achieved by rotating the diffraction grating around a pivot point which provides feedback to the laser at a different wavelength from the grating. Typically, Littrow configured ECDL's use the 1st diffraction a grating to provide feedback to the laser where the specular 0th order reflection is used as the laser output. These types of ECDL's typically exhibit 5-15 mW of cw output power. A C-mount diode laser was used in this Littrow configured ECDL's in order to reduces the 1st order loss beam that typically circulates within the classical Littrow configured ECDL's. By utilizing a diffraction grating that is highly efficient in the 1st order diffraction (> 90 %), the output power of the ECDL is significantly increased to ~35-50 mw.

Laser Diode Facet Reflectivity

A 100 mW C-mount AR coated Fabry-Perot single mode laser diode (Sacher Lasertechnik SAL-830-100) was chosen as the lasing medium in the Littrow configured ECDL. The power vs current (PI) curve for the two diodes used in the ECDL's is shown in Figure 69. The cleaved facets on the front and back of the laser diode chip inherently act as reflectors due to the large step index between the Gallium Arsenide (GaAs) gain medium ($n \sim 3.2$) and the air ($n=1$). The reflectivity of the diode facets resulting from the step index is given by

$$R = \left(\frac{n_{laser} - n_{air}}{n_{laser} + n_{air}} \right)^2, \quad (5.1)$$

yielding a net reflectivity of 27.4 %. The reflective surface formed at the two facets of the laser diode act to form a small Fabry-Perot cavity, causing longitudinal modes to form with mode spacing's given by

$$\Delta\nu = \frac{c}{2n_{laser}L_{laser}}, \quad (5.2)$$

where L_{laser} is the chip length. For $n_{laser} = 3.2$ and $L_{laser} = 1000\mu m$ (from manufacturer), a cavity mode spacing of 46.9 GHz is calculated.

The facet longitudinal modes within an ECDL (Littman-Metcalf or Littrow configured) are not desired due to the mismatch between the external cavity modes (typically .1-5 GHz) and the facet modes, causing mode pulling in the overall extended cavity. Mode competition between the external cavity and the diode cavity can be minimized by depositing an AR coating on one facet of the diode chip. Typically, ECDL's utilize ridge waveguide Fabry-Perot laser diodes in a TO 5.6 or TO 9 mm can

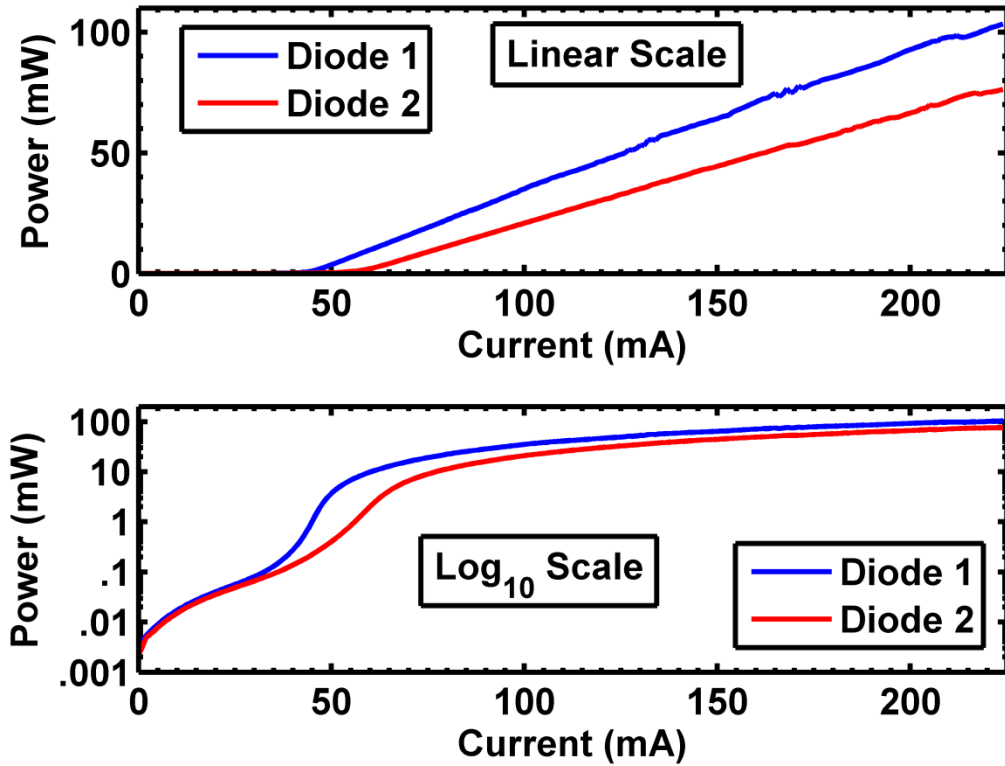


Figure 69 Linear (top) and $\log_{10}$ (bottom) PI curves for the AR coated laser diodes. Lower output power is observed for Diode 2 potentially resulting from a poor AR coating or a bad semiconductor batch. A lasing threshold of 45 mA and 60 mA was observed for diode 1 and diode 2, respectively.

configuration where one facet is AR coated and the other has a high reflectivity (HR), forming the second reflector in the ECDL cavity. The designed used for the third generation DIAL seed laser(s) utilized a C-mount laser diode where the front facet was AR coated and the back facet was uncoated. The manufacturer specified AR coatings on the front facet of the laser diodes used for the online and offline ECDLS were 6.625×10^{-6} and 1.187×10^{-6} at 828 nm, essentially reducing the reflectivity to zero. The reflectivity of the back facet of the laser diodes were not provided by the manufacturer but are thought to be uncoated and are calculated using equation (5.1) to be $\sim 27\%$. The absolute facet

reflectivity's can be measured using external feedback to the laser diode using methods presented by (Repasky et al. 2000).

External Cavity Longitudinal Modes

The Littrow configured ECDL's were designed to operate on a single longitudinal mode, allowing for precision spectroscopy of water-vapor absorption lines both at the ground as well as the Doppler broadened case at higher altitudes. Assuming that the AR coated reflectivity of the front facet of the diode is negligible, the longitudinal modes arise from the external cavity formed between the diffraction grating and the uncoated back facet of the laser diode as shown in Figure 68. The optical path length of the resonator formed between the diffraction grating and the back facet of the laser diode is given by

$$L_{ECDL} = n_{laser}L_{laser} + L_1 + n_{lens}L_{lens} + L_2, \quad (5.3)$$

where L_1 and L_2 is the distance between the front facet of the diode and the front side of the collimation lens, and the distance between the back side of the collimation lens and the diffraction grating, respectively. Table 6 lists the index of refraction, as well as the physical and optical path lengths for the different segments of the external cavity built for the third generation DIAL seed lasers. The free spectral range (FSR) or spacing between

Table 6 Physical and optical path lengths for each element within the Littrow external cavity for feedback from a 2100 lines/mm diffraction grating at 828 nm.

Actual Length (mm)	n ($\lambda=828$ nm)	Optical Path Length (mm)	Description
$L_{laser} = 1.0$	3.2	3.2	Length of laser diode
$L_1 = 5.92$	1	5.92	Laser diode to lens
$L_{lens} = 3.69$	1.517	5.6	Lens thickness
$L_2 = 13.64$	1	13.64	Lens to diffraction grating

longitudinal modes created by a cavity of optical length L_{cavity} is described by

$$FSR = \frac{c}{2L_{cavity}}, \quad (5.4)$$

where c is the speed of light within the medium. For a total optical path length of 28.36 mm from Table 6, a longitudinal mode spacing of 5.29 GHz is calculated, almost a factor of 10 less than the 46.9 GHz mode spacing resulting from the cavity formed from the laser diode facets alone.

The shape and depth of the longitudinal modes formed by the external cavity greatly depends on the reflectivity of the cavity mirrors. For this design, the diffraction grating and the uncoated back facet of the laser diode act as the two cavity mirrors. A 2100 line/mm holographic grating from Spectragon (PC 2100 30x30x6 NIR) was used as the dispersive element in the external cavity. A grating diffraction efficiency into the 1st order of ~94 % was measured for a 60 degree incidence angle. A grating with a high diffraction efficiency for TM (parallel to the grooves) polarized light was chosen such that the TE polarized light (perpendicular to junction plane) from the diode laser would have good diffraction efficiency into the first order without the need for a half wave plate in the cavity. The linewidth of the external cavity longitudinal modes is directly proportional to the dispersion in the cavity, which depends on the total number of lines N illuminated by the incident beam. The 2100 lines/mm grating was chosen to provide a relatively steep incidence angle such that the 1st order diffracted light is fed back into the laser diode, hence maximizing the number of dispersive elements (grating grooves) illuminated by the beam. At the cost of potentially vignetting part of the beam, an 8.0 mm focal length 0.5 NA aspheric lens (Thorlabs C240TME-B) was used to collimate the

front side output beam to a relatively large diameter to further maximize the number of grooves illuminated by the front facet beam, a factor of 2 greater than the 4.0 mm 0.5 NA lens typically used in other ECDL's .

For an incidence angle β , the first order diffracted beam off of a diffraction grating with line spacing d is sent back to the laser diode at an angle α which is described by (Saleh & Teich 1991)

$$\lambda = d (\sin\alpha + \sin\beta). \quad (5.5)$$

For the Littrow configuration used here, $\alpha = \beta$ and $d = 1 \text{ mm}/2100 \text{ lines}$ (0.476 $\mu\text{m}/\text{line}$). For the specified DIAL operating wavelength in the vicinity of $\lambda \approx 828 \text{ nm}$, $\alpha = 60.43^\circ$. The shape of the longitudinal modes of a Fabry-Perot resonator are proportional to the overall cavity transmission, or reflectivity. The cavity finesse, which is defined as the ratio of the FWHM of the cavity mode linewidth to the FSR is highly dependent on the cavity reflectivity and is given by

$$F = \frac{\pi\sqrt{R}}{1 - R}, \quad (5.6)$$

where R is the effective reflectivity of the two cavity mirrors. For a cavity who's two mirrors (in this case an efficient diffraction grating and the back facet of the diode) have different reflectivity's of R_1 and R_2 , the cavity will have the same spectral behavior if it were to have identical mirrors with a reflectivity of $R = \sqrt{R_1 R_2}$. As described above, the back facet of the diode laser has a calculated reflectivity of $R_1 \approx 27 \%$. Assuming that the AR coating of the diode front facet is sufficiently high, the reflectivity at this surface is set to zero. The reflectivity of the second mirror in the resonator is then the

product of all of the intracavity losses excluding the loss due to the diode absorption and is expressed as

$$R_2 = R_{lens}^2 R_{grating} R_{coupling}, \quad (5.7)$$

where $R_{coupling}$ is the coupling efficiency of the 1st order diffracted beam back into the laser diode. The R_{lens}^2 term is introduced due to the double passing of the lens when coupling the light back into the laser diode. Using the parallel between the size of a single mode fiber and typical fiber coupling efficiencies, and the emitting area of typical single mode laser diodes, a coupling efficiency of 50 % back into the laser diode front facet is assumed. For a grating efficiency of 94 % and an assumed lens transmission of 95 %, $R_2 = 42.4$ %, yielding a net cavity reflectivity of $R = 33.8$ % and a relatively low

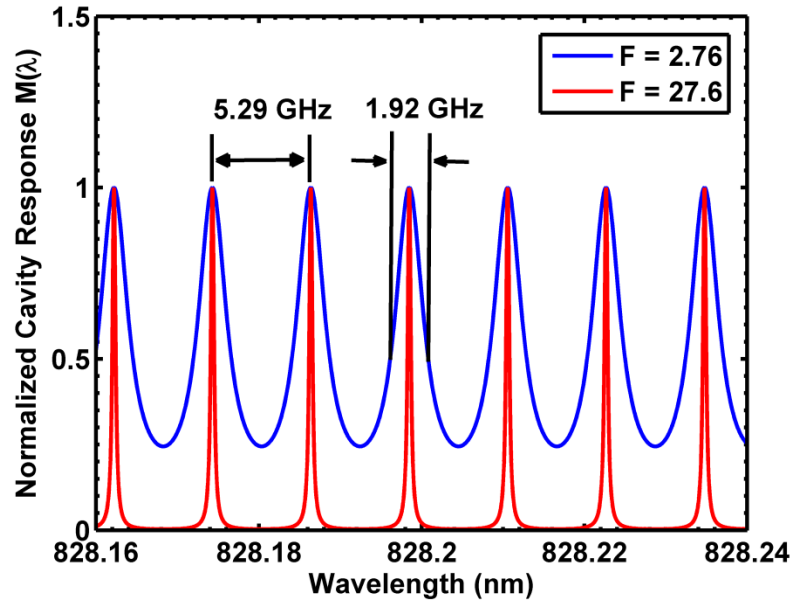


Figure 70 Calculated longitudinal modes of the third generation DIAL ECDL. The cavity response for a calculated finesse of 2.76 and cavity length of 28.36 mm is shown in blue. The response for a decrease in the cavity loss corresponding to an increase in the finesse by a factor of 10 to $F=27.6$ is also shown for reference in red. finesse of 2.76.

For a calculated net cavity reflectance R and effective optical path length L_{cavity} , the normalized spectral response can be written in terms of the wavelength as (Saleh & Teich 1991)

$$M(\lambda) = \frac{1}{\left[1 + \left(\frac{2F}{\pi}\right)^2 \sin^2\left(\frac{2\pi L}{\lambda}\right)\right]}. \quad (5.8)$$

The normalized spectral response for the Littrow configured for the ECDL designed as the third generation DIAL transmitter seed source is shown in Figure 70.

Single mode operation of an ECDL can be achieved when the mode spacing of the external cavity is approximately equal to or less than the FWHM linewidth of the grating dispersion curve. The normalized spectral intensity response of a diffraction grating is given as (Switzer 1998)

$$G(\lambda) = \left[\frac{\sin\left(\frac{N\pi d}{\lambda}(\sin\alpha + \sin\beta)\right)}{N \sin\left(\frac{\pi d}{\lambda}(\sin\alpha + \sin\beta)\right)} \right]^2. \quad (5.9)$$

As stated previously, $\alpha = \beta$ within a Littrow cavity and $d = \frac{1 \text{ mm}}{2100 \text{ lines}}$ is the line spacing between the grating lines. N is the number of lines illuminated by a beam with a given beam diameter 2ω . The number of lines illuminated by a beam projected onto a grating at an incidence angle α is given as

$$N = \frac{1}{d} \left[\frac{2\omega}{\cos(\alpha)} \right]. \quad (5.10)$$

The beam exiting the front facet of the laser diode is collimated to ~ 6.5 mm in diameter, illuminating 27,660 grating lines for an incidence angle of $\alpha = 60.43^\circ$ such that the first order diffracted beam is directed back to the laser diode. The normalized grating

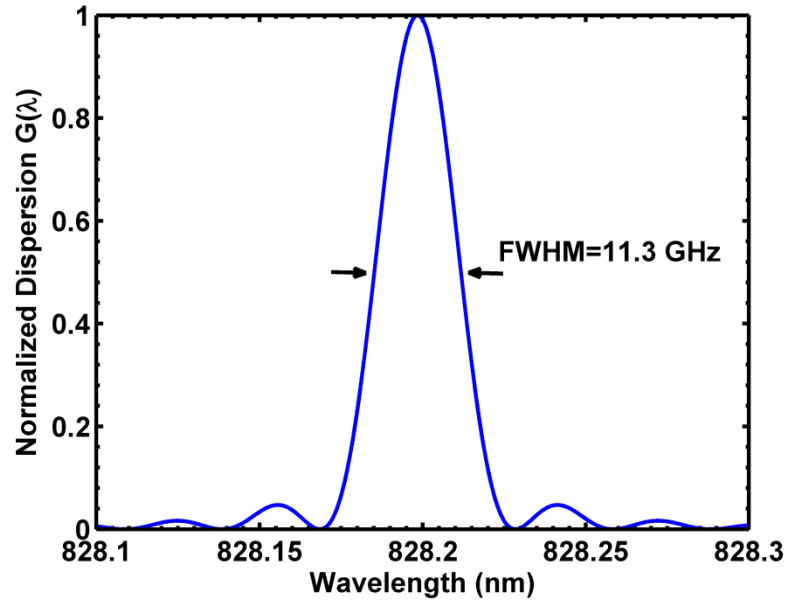


Figure 71 Dispersion curve for the 2100 lines/mm diffraction grating used in the ECDL's where $\sim 27,000$ lines are illuminated.

intensity response for $\alpha = 60.43^\circ$, $N = 27,660$ lines, and $d = .476\mu m$ is shown in Figure 71.

Single mode operation of an ECDL is best achieved when a single external cavity longitudinal mode overlaps with the grating dispersion curve. For the calculated external cavity parameters presented above for the Littrow configured ECDL, the overlap between the cavity longitudinal modes from Figure 70 and the grating dispersion curve from Figure 71 is shown in Figure 72. For a calculated external cavity optical path length of 28.36 mm, overlap between the grating dispersion profile and several external cavity longitudinal modes is observed, allowing for multimode operation of the ECDL output. To achieve single mode operation which is required for the DIAL technique, the external cavity length was decreased in order to increase the FSR and to ensure overlap of a single external cavity longitudinal mode with the grating dispersion profile. Because of the

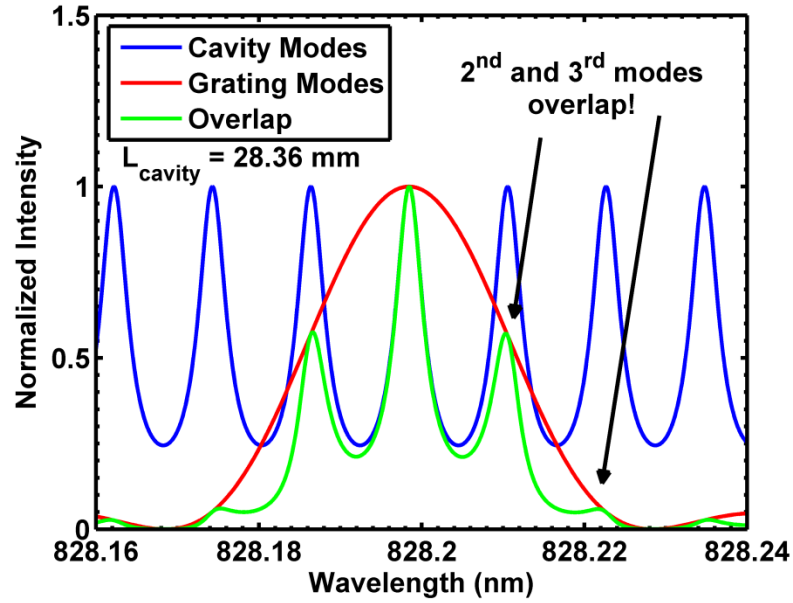


Figure 72 Spectral overlap between the external cavity longitudinal modes and the grating dispersion curve. Overlap between the grating dispersion profile and several external cavity modes supports multimode operation in the external cavity which is not acceptable for high resolution spectroscopy.

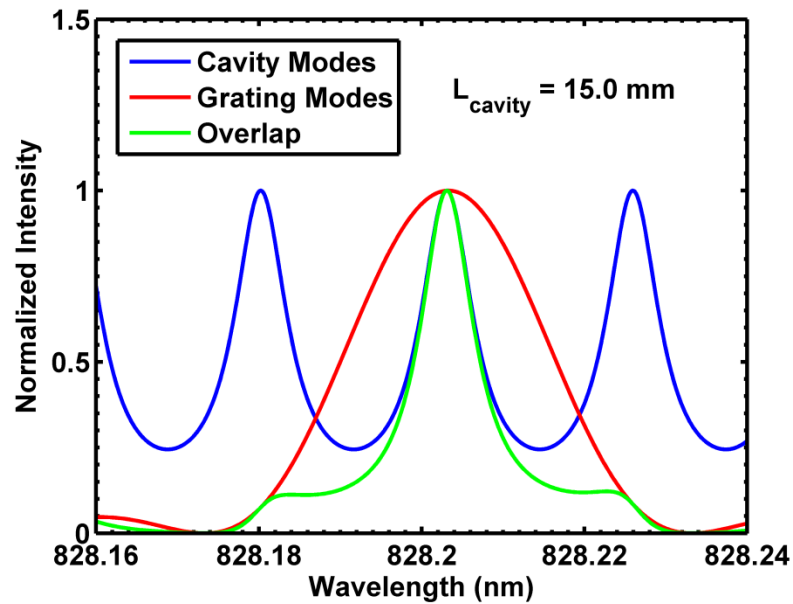


Figure 73 Same as Figure 72 except with $L_{\text{cavity}}=15.0 \text{ mm}$.

design limitations, a mechanically limited minimum cavity length of 15.0 mm is allowed before the grating makes contact with the front facet collimation optic housing.

The overlap between external cavity modes and the grating modes for the extended cavity length is shown in Figure 73.

The increase in the FSR provides better overlap between a single cavity longitudinal mode and the grating mode, hence decreasing the gain contributions within the external cavity from other cavity longitudinal modes. Ideally, a single longitudinal mode is desired under the grating dispersion curve where the grating profile nulls would be placed at the spectral position of the outlier cavity modes. Although not optimal, the enhanced "single mode" external cavity profile for the shortened cavity length shown in Figure 73 was thought to be sufficient considering the improved seeding efficiency resulting from the increased feedback provided by the design of the modified Littrow cavity using a C-mount diode. Lastly, it should be noted that the exact pivot point of the diffraction is not important for this application as the ECDL's were not designed to be widely tunable, hence maintaining the cavity resonance conditions for vary wavelengths was not necessary. For a given cavity length described above, temperature and current tuning can be employed to precisely overlap the cavity and diffracting grating modes at the online and offline wavelengths.

Final Littrow ECDL Design

The final design for the two modified Littrow configured ECDL's utilize a 17 mm external cavity length due to unforeseen sizing limitations imposed by the diffraction

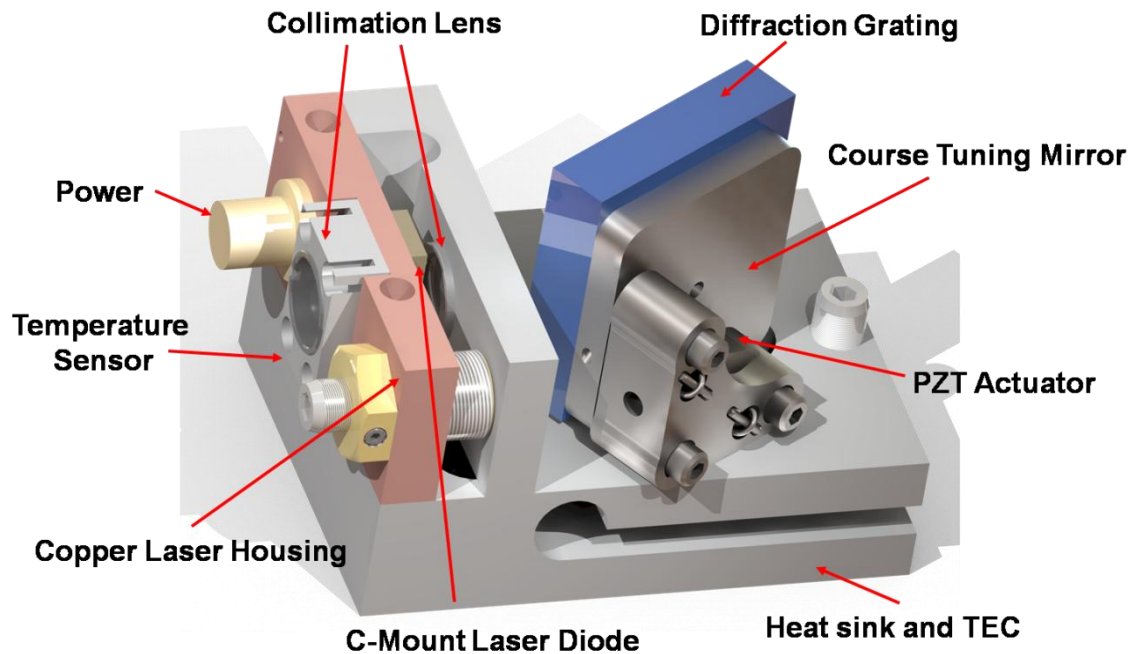


Figure 74 SolidWorks drawing of the modified Littrow configured ECDL. The ECDL was designed to be compact with a footprint of 2"x1.5".

grating. The two identical ECDL's were designed using SolidWorks and machined in the ECE machine shop. A rendered image of the SolidWorks model and the major components of the ECDL is shown in Figure 74. The 100 mW C-mount laser diode is mounted upside on a copper housing that is connected to a 2"x1.5" aluminum base plate. The diode is mounted upside down to prevent dust from settling on the ridge waveguide or the facets which could potentially damage the laser chip. An aluminum L bracket hinged to the center copper piece houses an 8 mm 0.5 NA aspheric lens. The output from the front facet is collimated by moving the lens using a 3/16"-100 ultra-fine hex adjusted screw where the bushing and the nut are tapped directly into the laser diode copper housing. A 30x30x6 mm diffraction grating used to provide feedback to the laser is fastened to a miniature 3 axis mirror mount (NewFocus 9873-K) using UV cured epoxy.

The mirror mount is fastened to the aluminum base plate using a 2-56 (M2) screw. Feedback to the laser diode is optimized by making small adjustments to the three 6-80 adjustment screws on the mirror mount. Course adjustment to the ECDL output wavelength is achieved by changing the angle of the grating/mirror mount relative to the laser diode using the outer most bottom screw adjustment (towards the back). Fine or continuous frequency tuning of the ECDL wavelength over the FSR of the cavity is achieved by applying a voltage to the PZT placed between the back of the mirror housing and the same hex head ball driven screw.

The ECDL output is taken from the back facet of the uncoated C-mount laser diode. An aluminum housing for the output collimation optic is screwed directly into the laser diode copper housing. A 6.24 mm focal length 0.4 NA asphere (Thorlabs C110TME-B) was used to collimate the ECDL output to a nominal beam waist diameter of 2.5 mm measured ~ 5 m behind the laser. The aspect ratio of the output beam from the two ECDL's is 3:1 due to the asymmetric geometry of the diode chip. Typically, the perpendicular axis of a ridge waveguide is smaller to ensure single mode operation. The higher confinement of the field in the vertical direction yields a higher beam divergence, hence collimation of the fast vertical axis yields a slowly changing beam waist in the less divergent horizontal axis. Hence, using a single aspheric lens to collimate the output of a laser diode yields an astigmatic beam with the aspect ratio proportional to the waveguide dimensions.

The forward current to the laser diode cathode is provided via a detachable SMA connector. The body of the laser diode (cathode) which acts as a heat spreader is

connected to ground, making the entire ECDL body also at ground potential relative to the cathode. A 10 k Ω thermistor placed directly in the copper housing under the laser diode is used with thermal grease to provide temperature feedback to the laser diode to within 0.1 C using a current/temperature controller (ILX Lightwave LDD3722). The laser diode is temperature stabilized using a 4 A TEC that is placed under the aluminum block that houses the ECDL. A base plate used as a heat sink for the TEC is thermally isolated from the ECDL using ceramic screws. The base plate is connected to the DIAL transmitter optical breadboard which also acts as a heat sink for the base plate. Pictures from the front and back of one of the Littrow configured ECDL used in the DIAL transmitter is shown in Figure 75. The second ECDL built for the offline wavelength is identical to the one described here.

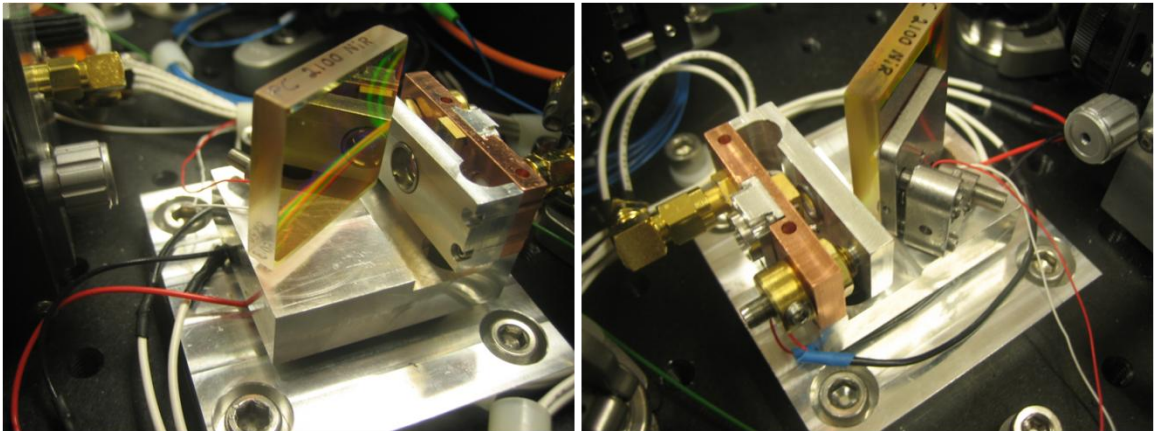


Figure 75 Pictures of the modified Littrow ECDL used in the third generation DIAL transmitter.

ECDL Characterization

The efficient seeding of an ECDL is important for high resolution spectroscopy. A properly seeded ECDL will sufficiently narrow the laser linewidth compared to the broad ASE spectrum of the laser diode. The wavelength spectra for the online and offline ECDL's built captured using a 26 GHz resolution optical spectrum analyzer (OSA) (Agilent 86142B) is shown in Figure 76. In both cases, the narrowing of the laser linewidth is observed for the seeded ECDL (blue spectra) over the broad ASE spectrum of the diode laser (red spectra). An excellent ASE side mode suppression ratio (SMSR) exceeding 45 dBm is observed for both ECDL's, allowing for high accuracy spectral probing of the water-vapor absorption line. Excellent SMSR's were also observed as shown in Figure 76 (right spectra) for grating selected ECDL operating wavelengths outside of the gain- or ASE bandwidth of the laser diode. The suppression of the ASE

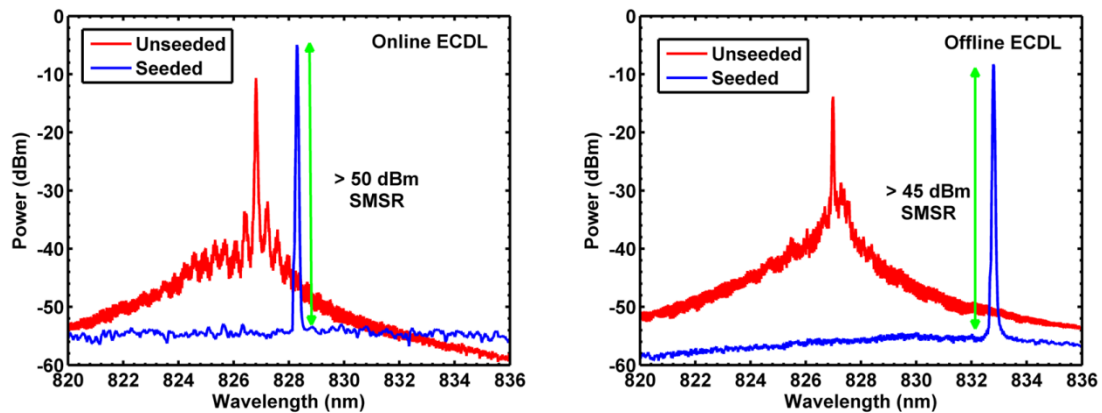


Figure 76 Wavelength spectra of the seeded and unseeded online(left) and offline (right) ECDL's. Narrowing of the laser linewidth is observed when the ECDL has sufficient feedback from a diffraction grating. The ASE in both ECDL's is suppressed to greater than 45 dBm below the peak of the seeded linewidth.

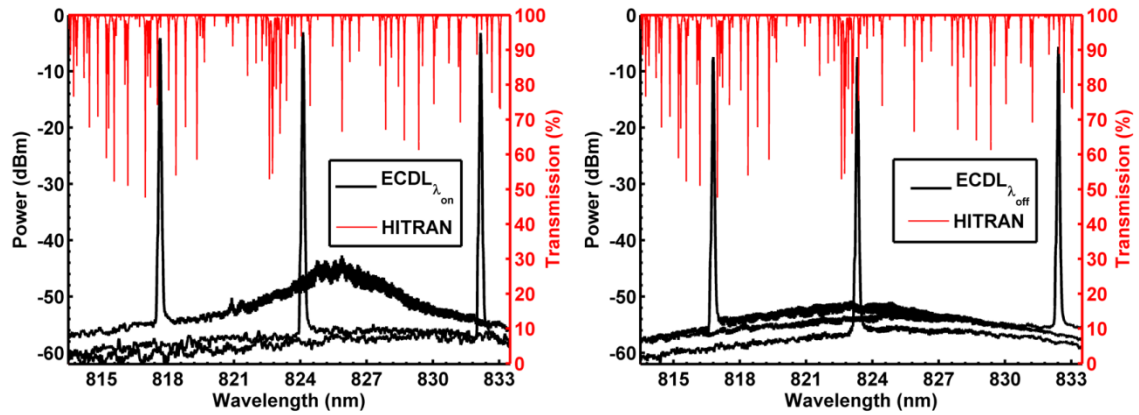


Figure 77 Wavelength tuning spectrum for the online and offline ECDL's. Water-vapor absorption lines accessible by coarse tuning of the online and offline ECDL's is also plotted on the right vertical axis using a HITRAN simulation over a 1 km path length.

spectrum away from the center of the laser diode gain profile provides evidence of sufficient small signal gain resulting from the modified Littrow configured cavity as well as good seeding from the diffraction grating back to the laser diode. It should also be noted that the AR coating on the laser diodes were not as good as they were initially specified. This was observed by the weak preferential lasing modes of the free running diode shown in Figure 76. A good AR coating on a laser diode will decrease the finesse of the cavity formed between the two facets and provide a smooth ASE spectrum over the diode gain bandwidth.

A major benefit of using an ECDL as the seed source in a DIAL transmitter is the widely tunable wavelength range that is accessible while maintaining good laser spectral properties such as frequency stability and a narrow laser linewidth. The broad tunability of the custom built ECDL's gives access to numerous variable strength water-vapor absorption lines in the 830 nm spectral region, allowing for operation in varying atmospheric conditions as well as geographic locations. The coarse tuning range for the

online and offline ECDL's are shown in Figure 77. A broad coarse tuning range exceeding 15-20 nm can be seen for both lasers where good spectral properties are maintained over the full ECDL tuning range. For reference, the accessible water-vapor lines within the broad tuning spectrum are also shown in red and were simulated using the HITRAN database for a 1 km horizontal path length.

The motivation towards building a modified Littrow ECDL using C-mount laser diodes was to achieve higher output powers while still maintaining good laser spectral properties. Typical ECDL's have an intracavity loss beam from the 1st order diffraction off of the grating, hence limiting the output power available via the specular 0th order reflection to 5-15 mW. The modified Littrow ECDL's have no loss beam where the 1st order diffracted light is sent directly back into the laser diode, giving way to output powers at the back facet of the laser diode ranging between 35-50 mW. Figure 78 shows the PI curves for the two ECDL's where the operating wavelength is also presented as the color at each data point. A lasing threshold of 56 mA and 38 mA can be seen for the online and offline ECDL's, respectively. A maximum output power of ~ 35 mW was achieved for a fixed grating position. It was experimentally verified that much higher output powers could be achieved by slightly misaligning the cavity at the cost of increasing the output ECDL laser linewidth, which for the DIAL application is unacceptable. The sensitivity of the external cavity to very small changes in the optical path length is also evident from Figure 78. Tuning of the ECDL's wavelength can be seen as the forward current to the laser diode is changed where mode hopping inevitably limits the maximum continuous tuning range of the extended cavity. The wavelength

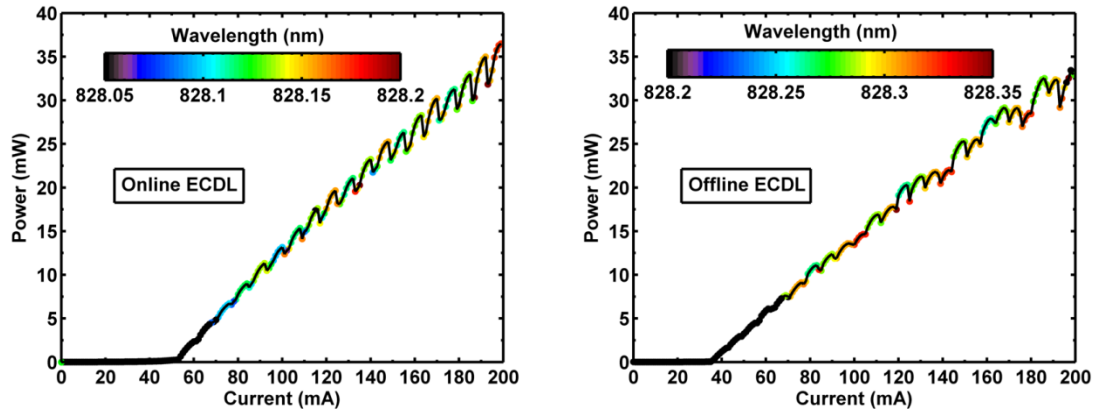


Figure 78 PI curves for the online and offline ECDL's. The output wavelength is plotted in color and shows the wavelength tuning and mode hopping as the forward current is increased.

tuning as the forward current is increased results from the increase in the laser diode charge carrier density within the gain medium which effectively increases the index of refraction. The increase in the index increases the optical path length, hence changing the resonant wavelength condition within the cavity. The tuning continues with increasing current until a mode hop occurs.

Fine tuning of the ECDL wavelength is achieved by making small adjustments to the angle of the diffraction grating relative to the laser diode by applying a voltage to the PZT. A typical frequency tuning curve relative to the online wavelength (frequency) for the ECDL's built is shown in Figure 79. Continuous tuning of the ECDL as a function of the applied voltage to the PZT is seen over the FSR of the external cavity, ~ 6.45 GHz. The measured FSR corresponds to a 23.3 mm cavity length, slightly shorter than that calculated during the design process. The discrepancy is most likely due to the lack of knowledge of the absolute index of the laser diode gain medium but does not seem to be a big problem as two widely tunable narrow linewidth lasers have been successfully

demonstrated. Although having good spectral properties, because the two ECDL's were designed to operate at a single wavelength (online and offline) and therefore care was not taken to choose an appropriate grating pivot point, mode hopping can be seen resulting from a mismatch between the external cavity length and the wavelength of light fed back to the laser diode from the grating. From Figure 79, continuous tuning of the ECDL is achieved over ~ 6.5 GHz with a slope efficiency of 0.511 GHz/V. With a manufacturer specified maximum voltage of 120 V to the PZT, continuous tuning of the ECDL over the ~ 3 GHz FWHM pressure broadened water-vapor absorption line can be achieved, allowing for sideline tuning in order to decrease the water-vapor OD.

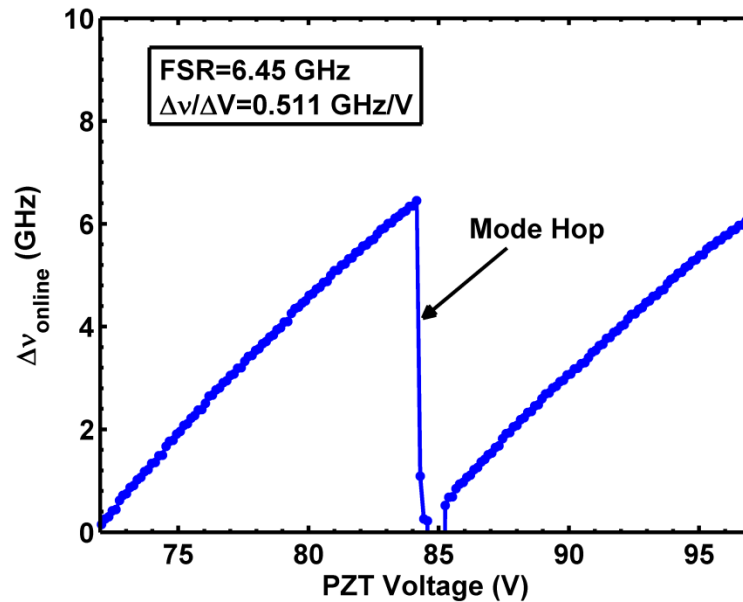


Figure 79 Typical fine tuning response of the Littrow configured ECDL's using the PZT actuator on the back of the diffraction grating to change the wavelength of the spectral component feedback to the laser diode. A FSR of 6.45 GHz was measured, corresponding to a 23.0 mm external cavity length. A mode hop is seen around 84 V where a mismatch between the cavity length and the wavelength of light fed back to the laser diode occurred.

Frequency Stability and Laser Linewidth

Similar to the method described for the second generation transmitter, the online ECDL is locked to any spectral position along the water-vapor absorption line using a Burleigh WA-1500 wavemeter to provide feedback the diffraction grating PZT. The PZT voltage corresponding to the offline wavelength is predetermined and is allowed to drift in the valley minimum between two water-vapor absorption lines. The wavelength/frequency of the ECDL can be polled from the wavemeter at maximum of 2 Hz. It was experimentally found that a frequency polling rate of $\sim 1/6$ Hz yields the same ECDL output frequency stability, and significantly decreases the amount of data acquired by the system. Figure 80 shows the frequency locking of the online ECDL to the center of a water-vapor absorption line using the wavemeter to provide feedback to the grating PZT over a 120 minute period where the locking was engaged 60 minutes after the start of the measurement.

Prior to the locking, the ECDL was allowed to drift to demonstrate the sensitivity of the laser cavity to changes in temperature and pressure. A heat gun was placed near the ECDL 50 minutes after the start of the measurement to assess the resilience of the cavity to anomalous fluctuations in the temperature. A large swing in the external cavity frequency shift can be seen where after several minutes, the cavity recovered from the large frequency jump where then the locking was engaged. Stable operation of the locked ECDL can be seen for the subsequent 120 minutes after the locking was engaged. Continuous locking of the online ECDL has been observed for over a 24 hour period where a large temperature gradient between outside air and the roof port in the early

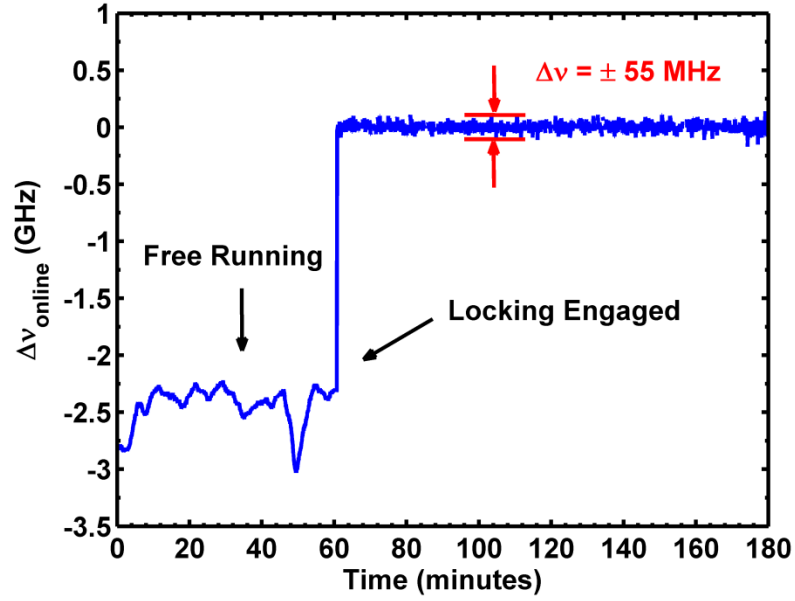


Figure 80 Frequency locking of the online ECDL to the center of the 828.187 nm water-vapor absorption line. The locking using a Burleigh wavemeter was engaged at 60 minutes after start of the measurement set.

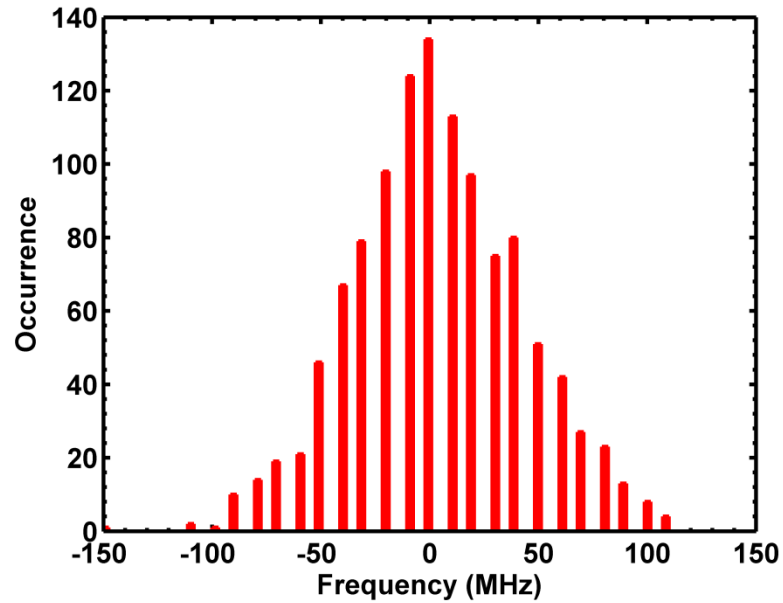


Figure 81 Histogram showing the measured spread in frequency of the online ECDL locked signal from Figure 80. The ± 55 MHz frequency resolution of the wavemeter is clearly seen.

morning cause a mode hop in the ECDL. A newer Burleigh WA 1500 wavemeter is used for the wavelength monitoring of the third generation transmitter which has an increased frequency resolution of ± 55 MHz. A histogram of the spread in the measured frequency relative to the center of the spectral position of the water-vapor line for the locked ECDL signal shown in Figure 80 is presented in Figure 81. For a 1/6 Hz acquisition rate, the ± 55 MHz spread in the frequency resolution of the wavemeter is clearly seen.

Accurate measurements of atmospheric water-vapor using the DIAL technique require good laser spectral properties (Bosenberg 1998). The laser linewidth of the two ECDL's used as the seed sources for the third generation DIAL were measured using a heterodyne technique. The experimental setup used to measure the laser linewidths is shown in Figure 82. The output from the two ECDL's were sent through 30 dB isolators

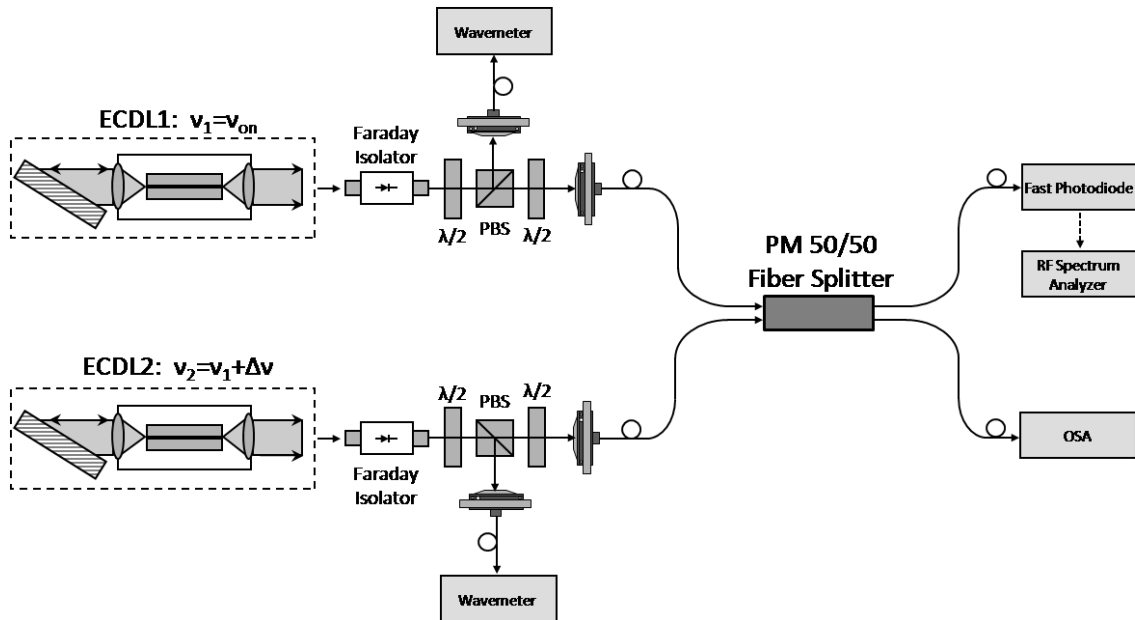


Figure 82 Experimental setup used to measure the linewidth of the two ECDL's. PM; polarization maintaining.

to prevent unwanted feedback to the laser diodes although similar results were also obtained without the use of isolators. A small fraction of the light from each laser was picked off using a half wave plate and a PBS and fiber coupled for wavelength monitoring using a wavemeter. The remainder of the light from each ECDL was fiber coupled into a 2x2 polarization maintaining 50/50 fiber beam splitter. ECDL1 was locked to the center of the 828.187 nm absorption line while ECDL2 was locked to a spectral position ~ 250 MHz away from the line center. The use of a polarization maintaining (PM) fiber splitter allows for a relatively long interaction length between the two beams while ensuring the polarization of the two fields are aligned to one another (using either fast or slow axis of the panda fiber in this case), giving way to interference at the detector. The photocurrent i_{pd} measured at the detector in terms of the two optical electric field strengths E_1 and E_2 from the PM fiber is expressed as

$$i_{pd} = k [E_1 \cos(\omega_1 t) + E_2 \cos(\omega_2 t)]^2, \quad (5.11)$$

where ω_1 and ω_2 are the radian frequencies and are separated by ~ 250 MHz and k is a proportionality constant. Expanding equation (5.11) yields

$$i_{pd} = k [E_1^2 \cos^2(\omega_1 t) + E_2^2 \cos^2(\omega_2 t) + E_1 E_2 \cos((\omega_1 - \omega_2)t)], \quad (5.12)$$

where the first two terms are the time varying intensities of each oscillating electric field and the last term is the heterodyne term which oscillates at the difference frequency between the two lasers, ~ 250 MHz. Using a 12 GHz bandwidth photo-receiver (NEWPORT 1554-B), the first two terms in equation (5.12) are measured as the time average intensity of the electric fields and the cross term between the two fields yields a measurable beat note at the detector.

The width of the heterodyne beat note is proportional to the spectral width of each ECDL and was measured using a 21 GHz RF spectrum analyzer. The measured heterodyne spectra from the two ECDL's described above is shown in Figure 83. With a 100 kHz resolution bandwidth and a ~ 1 ms sweep time set on the RF spectrum analyzer, an 852 kHz 3dB bandwidth around the central peak of the beat note signal was measured. Assuming the spectral properties of the two lasers are similar, the linewidth of the each ECDL is then estimated to contribute to half of the FWHM width of the measured heterodyne signal, yielding a 426 kHz FWHM linewidth for each laser. The measured laser linewidths are well below the 390 MHz linewidth required for accurate measurements of water-vapor as presented in Table 3. This allows for high spectral resolution tuning along the ~ 6 GHz width (FWHM) of the water-vapor absorption line. The sidebands of the heterodyne spectra from Figure 83 result from feedback at different

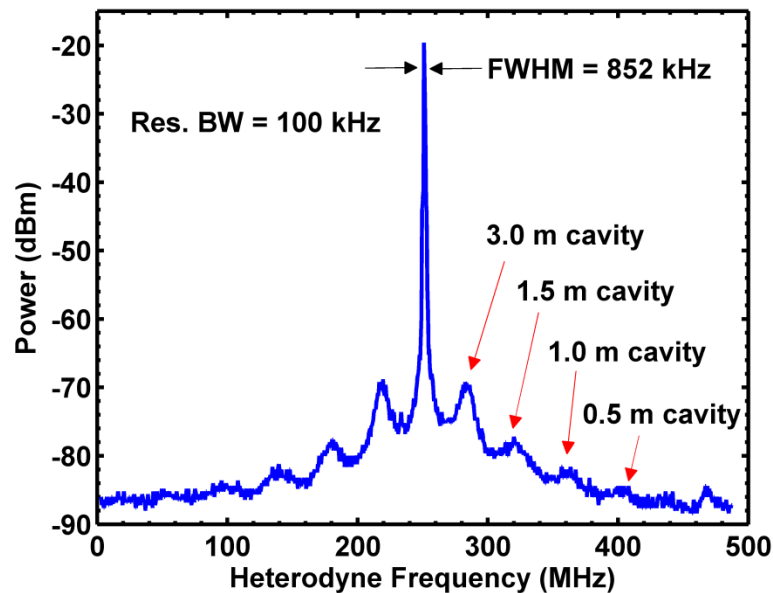


Figure 83 Measured heterodyne spectra from two similar ECDL's.

wavelengths to the ECDL from external cavities formed between the laser diode and the different legs of the 50/50 fiber beam splitter/combiner. Although clearly noticeable, the feedback signals at the different wavelengths from the fiber splitter are ~ 50 -70 dB below the ECDL heterodyne signal and are considered to be negligible to the overall laser linewidth measurement.

Fiber-Optic Switch

The two ECDL's described above have good spectral properties but have low CW output power. The output of the two ECDL's are amplified using a single pulsed TSOA which will be described in further detail in the next section. To minimize the susceptibility of the DIAL retrievals to changes in the atmospheric composition between the online and offline sampling times, a fiber optic switch is used to sequentially deliver the two seed lasers to the single stage pulsed TSOA with ~ 1 -6 second switching times. The collimated output from the two ECDL's are sent through a half wave plate and PBS where a small portion ($\sim 1\%$) of the light that is transmitted through the PBS is fiber coupled for wavelength monitoring and locking. The majority of the light that is rejected by the two PBS's are fiber coupled into the two legs of a 2x1 polarization maintaining electromechanical switch (Agiltron LB Series 2x1 PM Switch). The three ports of the optical switch have angled physical contact (APC) fiber connectors which minimize feedback to the laser source and alleviate the need for optical isolators. Because the TSOA is polarization sensitive, a polarization maintaining (PM) fiber coupled switch was desirable to maintain the high polarization extinction ratio of the ECDL's ($> 100:1$)

through the transmit optics. As shown in Figure 66, the polarization of the two seed lasers are aligned to the fast axis of the PM fiber's using a second half wave plate before the fiber coupler.

A picture of the fiber optic switch and the accompanying electronics driver board is shown in Figure 84. The specified and measured device performance is also presented in Table 7. The switch is housed on a compact ($\sim 2'' \times 3'' \times 0.5''$) electrical driver board. Communication to the switch is achieved using hexadecimal commands over a serial connection. The device is based on a PZT that is used to actuate a light bending prism. A voltage applied to the PZT actuator causes the prism to rotate, which changes the coupling of the light between a common output fiber and two input fibers.

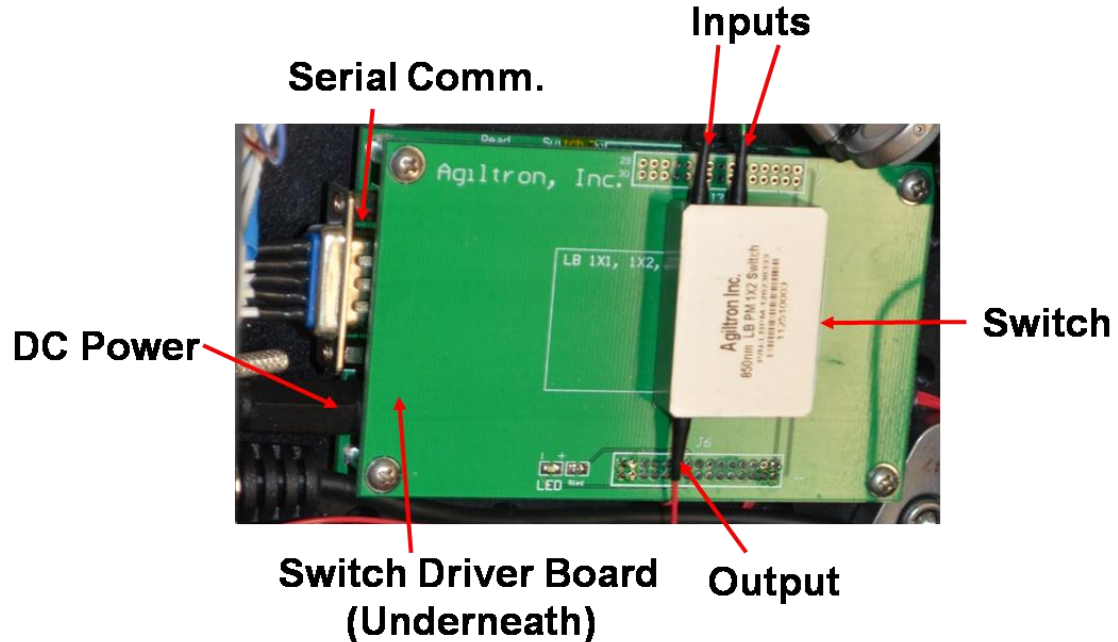


Figure 84 Picture of the 2x1 fiber optic switch. The electronic driver/communications board is mounted underneath the switch housing board.

Table 7 Specified and measured performance of the Agiltron 2 x 1 fiber optic switch.

Parameter	Specified	Measured
Operating Wavelength	850 nm	NA
Insertion Loss	0.8 dB	0.84 dB*
Cross Talk	55 dB	< 80 dB
Switching Time	4 ms	~ 1 ms
Repeatability	± 0.02 dB	± 0.032 dB
Durability	10^7 Cycles	NA
Switching Type	Non-Latching	
Optical Power Handling	300-500 mW	NA

The switch is a non-latching device which acts as a shutter for one of the two ports when the electrical power is either applied or removed. A nanosecond rise time silicon photodetector (Newfocus) was used to measure the switching performance of the fiber optic switch. The time resolved switching behavior of the device for each channel is shown in Figure 85. With no voltage applied to the PZT, channel one, which is coupled to online ECDL transmits to the TSOA. Over a serial bus, a hex signal triggering a constant 5 V signal slightly moves the prism, bending the light path to allow

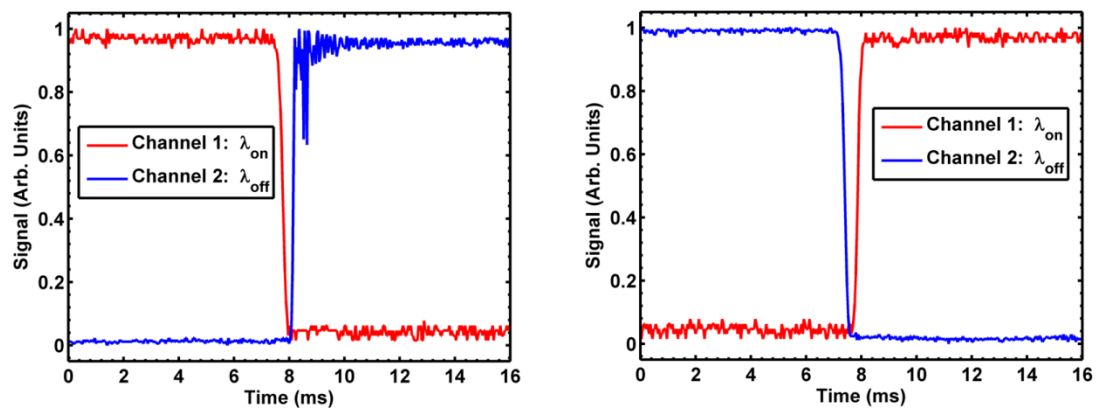


Figure 85 Left) Switching behavior from the default "off" position where channel 1 transmits when no voltage is applied. Same as left except for a voltage applied to the optical switch which transmits channel 2 at the output.

channel 2 which is coupled to the offline ECDL to transmit. Under-damped oscillations can be seen from the figure on the left corresponding to the abrupt switching of the actuating element from the default off position to the on position where channel 2 transmits.

The relaxation from this state back to the default position where channel 1 transmits is shown in the figure on the left and does not show a similar behavior. The switching time (90%) for channel 1 to turn on between the two ECDL's was measured to be ~ 1 ms and is shown in Figure 86. For a third generation DIAL transmitter PRF of 10 kHz, the 1 ms dead time corresponds to the loss of 10 pulses. The relatively short dead time ensures that the backward propagating ASE from the TSOA which has an exponentially growing optical density due to the tapered geometry does not have sufficient time to grow and damage the input facet of the amplifier between the switching

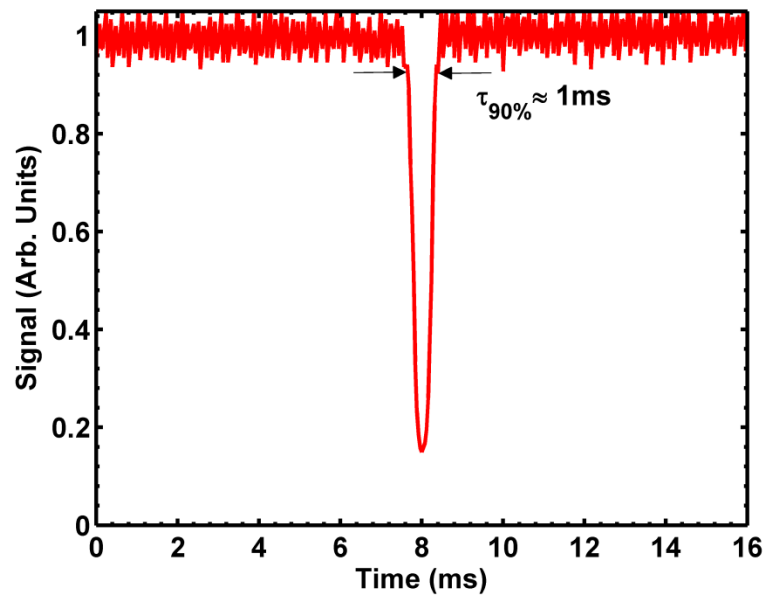


Figure 86 Switching time associated with channel 1 turning on.

of two seed lasers. After the switch, the output is sent through an optical isolator to prevent unwanted feedback from the amplifiers ASE to the ECDL's. A half wave plate is then used to align the polarization of the output of the PM fiber perpendicular to the TSOA junction plane for maximum extraction of the amplifier gain.

Power Amplifier

Pulse Energy

The design of the third generation DIAL transmitter utilized a single stage pulsed TSOA to amplify the cw output from the two high power seed lasers. In talking with the manufacturer of the ECDL laser diodes (Sacher Laser), it was thought that the ECDL's could exhibit output powers exceeding 100 mW with good spectral properties. As explained in the ECDL section of this chapter, the spectral properties of the ECDL's degraded rapidly as the cavity was tuned in order to achieve higher output powers. Hence, a maximum output power of ~ 35 mW was achieved with good spectral properties at the fiber coupling stage. It should also be noted that the beam quality from the ECDL's were not optimal which led to low fiber coupling efficiencies ranging between 20-30% leaving ~ 5 -10 mW of available seed power at the amplifier input. The decrease in the available power would have required a cascaded pre-amplification stage similar to that of the second generation transmitter, but new amplifiers were purchased with a longer gain region.

A 4.0 mm length TSOA (compared to the previously used 3.0 mm) was used as the power amplifier for the third generation DIAL transmitter, providing up to 30 dB

small signal gain, a factor of 50 increase over the amplifiers used in the second generation transmitter. The amplifier is placed in the same housing and utilizes the same pulsed current source described for the TSOA's used in the previous generation transmitter. With $\sim 5\text{-}10\text{ mW}$ of seed power available at the input aperture to the TSOA, peak pulse energies exceeding $7\text{ }\mu\text{J}$ were measured at a PRF and pulse width duration of 10 kHz and $1\text{ }\mu\text{s}$, respectively. The PRF was dropped to achieve a higher maximum anti-aliased range of 15 km . The TSOA pulse energies were measured using the experimental setup shown in Figure 87. To later assess their amplified spectral properties the two seed lasers were fiber coupled into the 2×1 switch where a small portion of the light from the rejection port of each PBS was fiber coupled for locking monitoring of the laser wavelengths. The output of the switch was isolated and coupled into the pulsed TSOA.

The output pulse energy was measured by calibrating the small signal response of a ns rise time photodiode to the response of a power meter using the cw output from the TSOA. The combination of a half wave plate and a PBS (which was characterized for

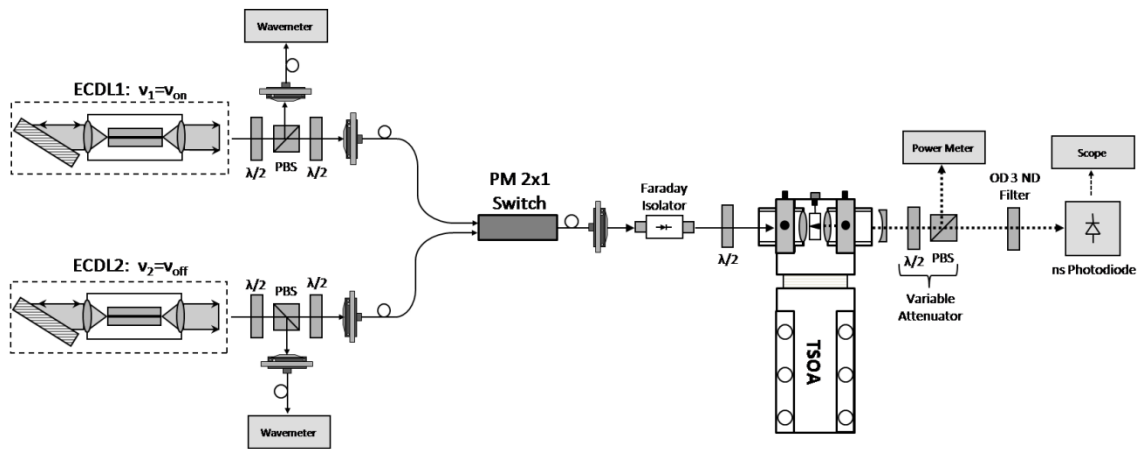


Figure 87 Experimental set up used to measure the amplifier output pulse energy.

minimum and maximum transmission and reflection) was used as a variable attenuator to measure the small signal voltage response from the photodiode over varying cw TSOA output powers (from the PBS transmission port). An OD 3 (Optical density of 1000) filter was used to drop the intensity of the cw light on the photodiode by three orders of magnitude to avoid saturation and to ensure linear operation of the photodiode in both the cw and pulsed regime. The response of the photodiode to the attenuated cw output power of the TSOA is shown in Figure 88. A linear fit to the measurement was used to convert the pulsed voltage output from the photodiode to an optical power. The OD 3 filter was chosen such that the signal level at the photodiode in the cw regime was comparable to the peak powers incident on the detector in the pulsed regime.

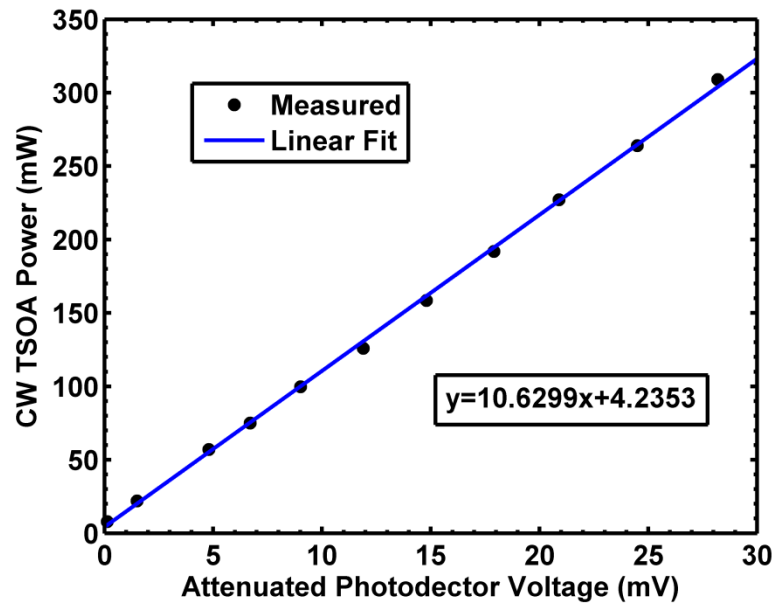


Figure 88 Measured response of the photodiode to the attenuated cw output of the TSOA.

Using the voltage to power relationship from above, the TSOA output pulse energy as a function of the pulsed forward current for the seeded online and offline wavelengths are shown in Figure 89. Output Pulse energies approaching 7 μJ are achieved for 8.0 A pulsed forward currents. A linear response to the pump can be seen above 2.5 amps where the TSOA lasing threshold is passed. Sufficient gain in the amplifier from 2.5-8.0 A results in almost equal output pulse energies between the online and offline wavelengths for a 40% difference between the available seed power from the ECDL's. A time resolved capture from a ns rise time photodetector of the TSOA output pulse power at the online and offline wavelength for an 8.0 A pulsed forward current is shown in Figure 90. A clean square pulse shape can be seen where the output powers over the 1 μs pulse duration are comparable for a 40 % difference in the seeding power. A low inductance flat cable was used to pulse the drive current to the TSOA using a

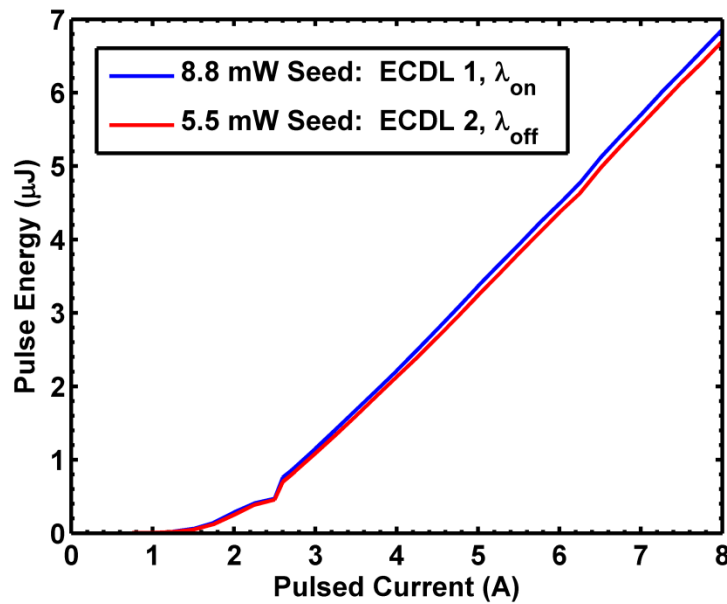


Figure 89 Output pulse energy as a function of the pulsed forward current to the TSOA for the online and offline seed lasers.

Directed Energy Incorporated PCX-7410 pulsed current source. Impedance matching between the TSOA and the drive source was not required as the pulse shape was deemed sufficient for lidar applications.

It should be noted again that extreme care must be taken in assuring good seeding of TSOA as the backward propagating ASE for high pulse currents can cause irreversible damage to the amplifier. Poor or low seeding powers also results in instability of the output power due to gain fluctuations within the amplifier. Small fluctuations in the offline seeded output is visible in Figure 90 and is thought to result from insufficient seeding power. This behavior is exaggerated in Figure 91 where the seeded input (online) was slightly misaligned, moving the TSOA out of a saturation operating region. It is not yet clearly understood the direct mechanism that causes this behavior but it does not seem to be a problem if proper alignment of the seed is assured to the TSOA optical axis. The TSOA alignment was maintained over a 1 month duration where no adjustments were required to maximize the output pulse energies. The 3.5-7 x increase in the output pulse energy over the second generation DIAL transmitter is a major achievement that allowed for measurements of water-vapor and aerosol profiles up to ~ 6 km and 15 km, respectively.

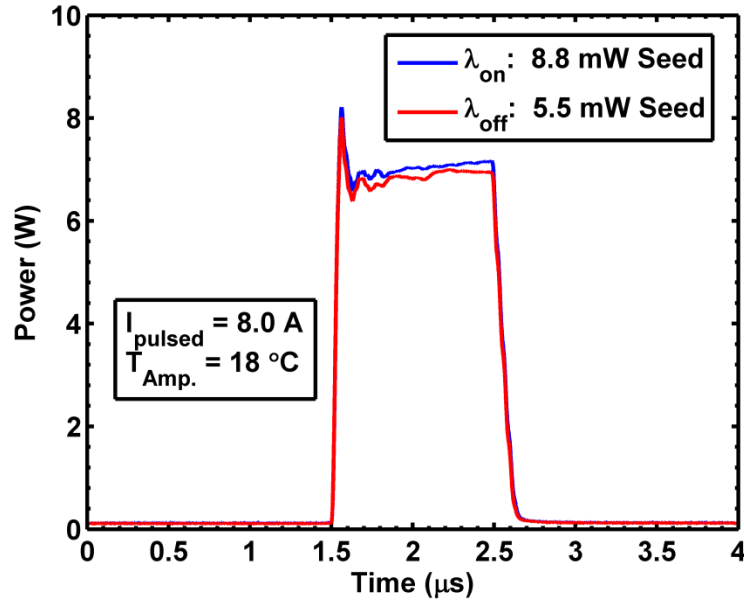


Figure 90 Time dependence of the output power of the injection seeded third generation DIAL transmitter at online and offline wavelengths for an 8.0 A 1 μ s duration forward current pulse. The PRF for this measurement was set at 10 kHz corresponding to a 1% duty cycle.

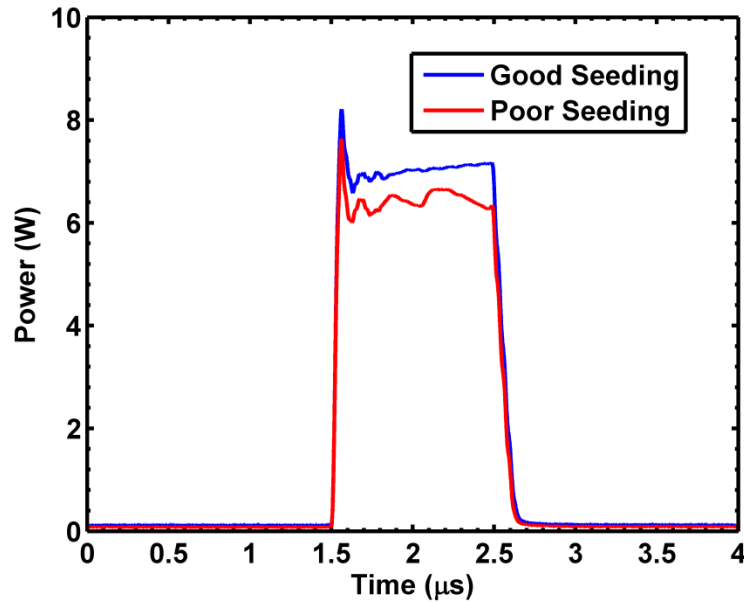


Figure 91 Demonstration of the gain fluctuation within the TSOA for poor seeding from the online ECDL.

Injection Seeding

The enhanced output pulse energy will result in an increased SNR at higher altitudes, allowing for water-vapor and aerosol profiling well into the free troposphere. In the upper atmosphere where the width of the Doppler broadened absorption line decreases, the accuracy of the water-vapor retrievals becomes much more sensitive to the laser transmitter spectral properties, hence the preservation of the good seed laser properties through the TSOA is important. A spectrum of the unseeded and seeded DIAL transmitter at the online wavelength for a maximum pulsed operating current of 8.0 A is shown in Figure 92. For the unseeded case, the broad gain spectrum of the TSOA can be seen. Despite a manufacturer deposited AR coating, lasing within the amplifier cavity can be seen at high operating currents. The injection seeded TSOA spectrum for ~ 8.0

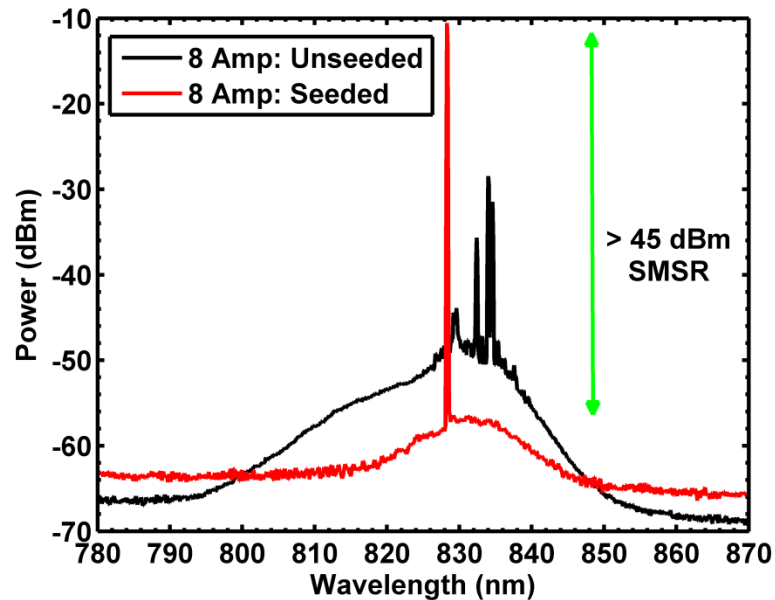


Figure 92 Output spectra of the seeded and unseeded DIAL transmitter at the online wavelength for a maximum operating pulsed current of 8.0 A. Suppression of the TSOA ASE spectrum can be seen when a seed is applied to the traveling wave amplifier, yielding a SMSR > 45 dB.

mW seed power shows good suppression of the broadband ASE while maintaining the narrow linewidth properties of the seed lasers with a measured SMSR > 45 dBm.

Sufficient gain and good injection seeding give way to excellent laser transmitter spectral properties for high peak pulsed currents. The behavior of the ASE-and injection seeded spectrum as a function of varying pulsed forward currents is shown in Figure 93. For the unseeded case, an increase the magnitude of the ASE spectrum can be seen where lasing beginning at approximately 4.0 A. With sufficient seeding (~ 8 mW), good suppression of the ASE spectrum can be seen for pulsed forward currents ranging between 3.0-8.0 A suggesting there is enough gain to allow for operation at both low and high output pulse energies without sacrificing the good transmitter spectral properties.

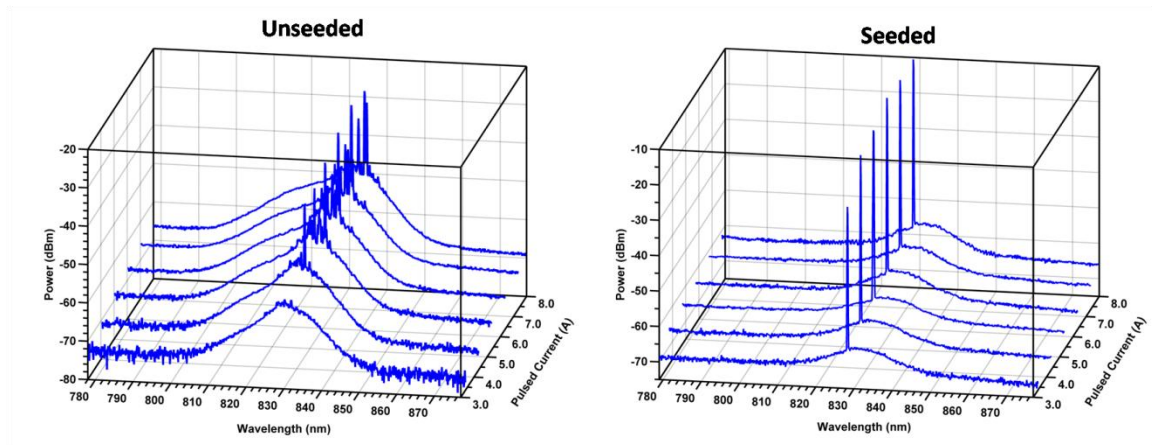


Figure 93 Seeded and unseeded TSOA spectrum as a function of the pulsed forward current at a 10 kHz PRF.

Beam Profile

The output of the pulsed TSOA is collimated using the same two stage beam forming arrangement utilized in the second generation DIAL transmitter. Good beam

quality coupled with sufficient beam expansion is essential for long distance propagation of laser beams through the atmosphere. The beam spatial characteristics were analyzed using a camera to assess the impacts of high current pulsing on the output beam shape of the third generation DIAL transmitter. Figure 94 shows the attenuated beam profiles for the collimated output of the unseeded and seeded TSOA for a maximum 3.0 A cw operating current and an 8 mW seed. When no seed is provided to the amplifier, the ASE

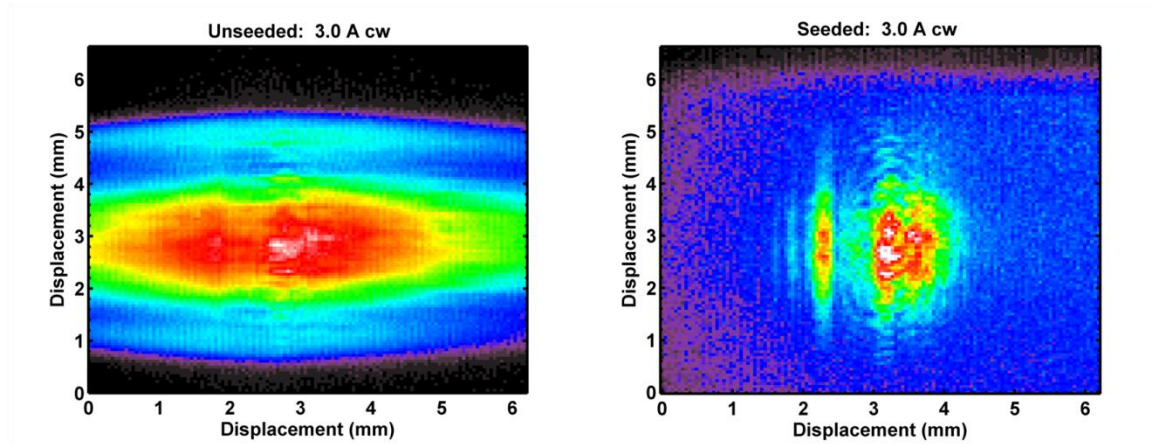


Figure 94 Beam profiles for the seeded and unseeded DIAL transmitter for a 3.0 A maximum cw operating current.

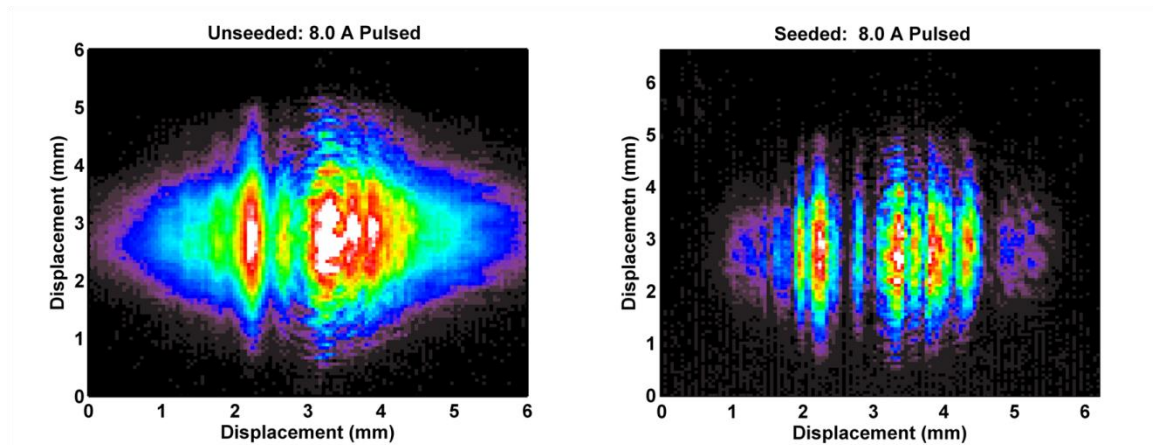


Figure 95 Beam profiles for the unseeded and seeded DIAL transmitter in the pulsed regime. A maximum pulsed forward current of 8.0 A was supplied to the TSOA.

output clearly reveals the astigmatic beam shape resulting from the tapered output facet geometry. When injection seeded at higher cw currents, the ASE is suppressed and a nominally circular beam can be seen although filamentation within the profile is prominent.

An increase in the striations within the beam profile was observed for higher pulsed currents to the TSOA. Figure 95 shows the measured beam profiles for the unseeded and seeded output of the TSOA under pulsed operation for an 8 mW seed. The measurements were acquired using a maximum pulsed current of 8.0 A over a 1 μ s pulse duration to the amplifier. The striations in the beam profile for both the seeded and unseeded cases are more pronounced in the pulsed regime. The suppression of the filamentation also shows less sensitivity to injection seeding. A major obstacle in long range propagation of the pulsed output from TSOA's results from obtaining a spatially coherent beam shape at high output powers in a pulsed current regime. This filamentation behavior has previously been studied and is attributed largely to the dependence of the refractive index of the TSOA gain medium on the carrier density, i.e. the magnitude of the forward current (Bossert, Dente & Tilton 1997). Specifically, the striations are thought to originate from small impurities in the gain region which cause small changes in the local index/carrier density and amplifies to become more prominent as the wave propagates down the amplifier.

The parallel and perpendicular cross sections of the injection seeded output from Figure 95 is shown in Figure 96. The striations are clearly visible in the parallel cross section of the tapered axis of the amplifier where the beam shape envelope nominally fits

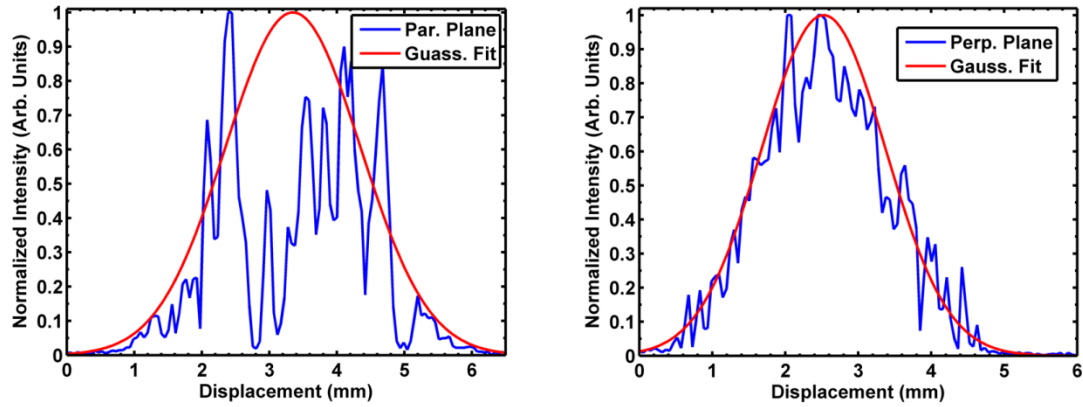


Figure 96 Parallel and perpendicular cross section of the injection seeded pulsed output from the TSOA shown in Figure 95.

a 2.5-3.0 mm diameter Gaussian distribution. The perpendicular axis of the TSOA output which more closely resembles the dimensions of a single mode laser diode shows less evidence of filamentation and more closely overlaps with a Gaussian fit to a 2.5-3.0 mm output beam diameter. Although unattractive, the non uniform output from the TSOA does not seem to pose a significant problem for beam propagation as excellent return signals have been recorded at altitudes approaching 15 km with appropriate beam expansion.

The collimated output from the TSOA is next incident on a $\sim 3\%$ wedge beam sampler used to direct light to a power meter in order to monitor the output pulse energy for shot to shot normalization. Both short and long term DIAL transmitter measured energy fluctuations of $< 1-2\%$ and $< 10\%$, respectively, have been proven to not present a large problem in processing of the lidar returns. The pulse energy output from the injection seeded DIAL transmitter measured over approximately a two day period is shown in Figure 97. The larger pulse energy drifts at the online wavelength result from

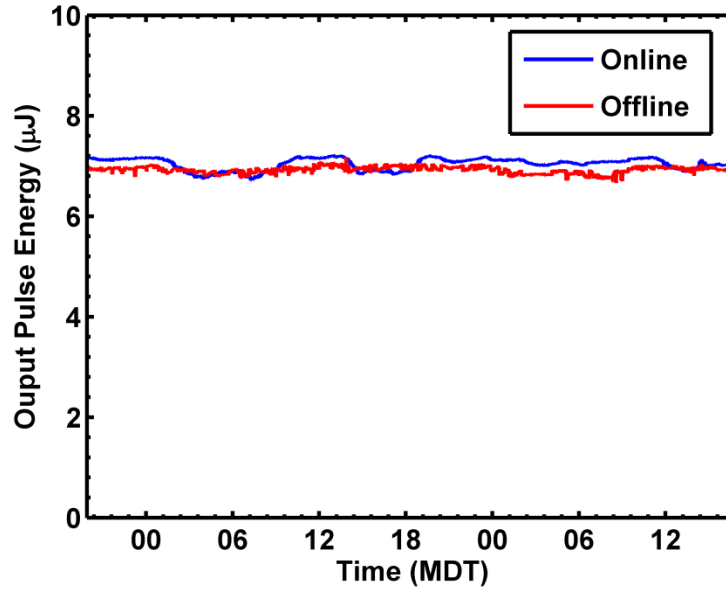


Figure 97 Output pulse energy trends for the third generation injection seeded DIAL transmitter measured over approximately 2 days.

small changes in the seed laser output power as the PZT is used to lock the online seed laser wavelength to the water-vapor absorption line as the ECDL cavity modes drift due to changes in the ambient room temperature.

An optional flipper mirror and fiber coupler can be used for output beam spectral property diagnostics and receiver alignment. The light transmitted by the beam sampler is incident on a 10x Galilean beam expander (Thorlabs BE10M-B) used to increase the beam diameter to 32 mm and decrease the divergence of the transmitted beam to ~ 50 - $100 \mu\text{rad}$. For a $7 \mu\text{J}$ pulse at a 10 kHz PRF and 32 mm beam diameter a pulse energy density of $0.87 \mu\text{J}/\text{cm}^2$ was measured, falling just below the ANSI MPE of $0.9 \mu\text{J}/\text{cm}^2$ which resulted from the eye safety calculations shown in equations (3.1)-(3.3). Hence for a maximum output pulse energy of $7 \mu\text{J}$, the transmitted beam is deemed eye-safe at 0 m

from the third generation DIAL transmitter exit aperture. The output beam is transmitted to the atmosphere coaxially with the telescope via two 45 degree turning mirrors that are directly connected to the beam expander.

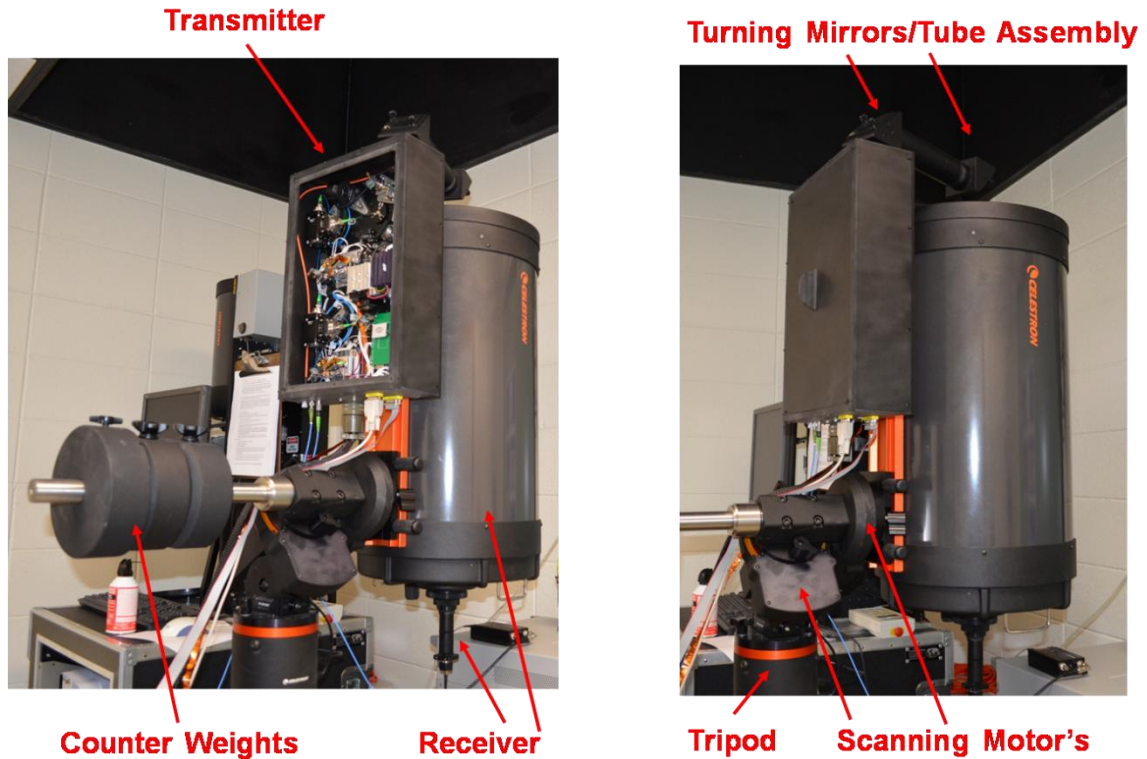


Figure 98 Picture of the third generation DIAL transmitter and receiver housed on a full-sky scanning motorized mount.

Spectral Purity and Pressure Shift

The compact design of the third generation DIAL transmitter coupled with the use of a scanning tripod mount has allowed for the first time for horizontal measurements of saturated absorption spectral purity using a hard target return. For a sufficiently long absorption path length in moist conditions, all of the laser energy will be absorbed due to water-vapor at the online wavelength (828.187 nm in vacuum). For a mid latitude

location such as Bozeman, MT during the winter season, a path length corresponding to 100% extinction of the laser light for the chosen DIAL water-vapor absorption line ranges between 12-15 km. A hard target is used to measure the backscattered signal at the online and offline wavelengths where the ratio of the two returns is referred to as the spectral purity. Any measurable signal at the online wavelength indicates transmission of the laser light in the out of band region relative to the narrow bandwidth around the center of the absorption line and introduces a negative bias in the water-vapor measurements.

The Hyalite mountains were used as horizontal hard target returns for the spectral purity measurements. Figure 99 shows a Google Earth image of the hard target path used for the spectral purity measurements. The red beam denotes the approximate path of the



Figure 99 Google Earth image of the line of site measurement used for the horizontal DIAL spectral purity measurement. The red beam indicates the approximate path of the laser fired out of the Cobleigh Hall roof port room window. The Hyalite mountains are south east of Cobleigh hall.

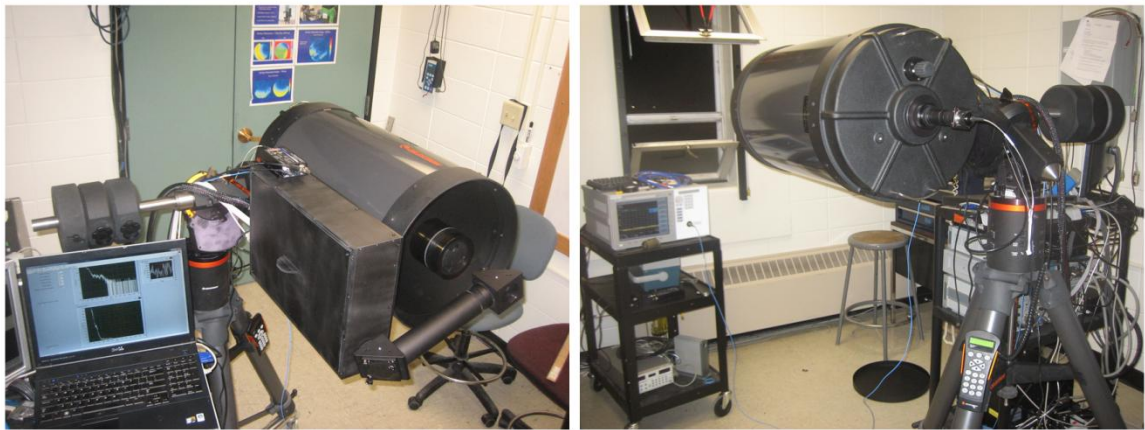


Figure 100 Pictures of the DIAL instrument pointing horizontally out of the lab window for the spectral purity measurements.

laser fired out of the south facing Cobleigh Hall roof port room window. Pictures of the DIAL instrument operating in the horizontal mode for the spectral purity measurements are shown in Figure 100. Hard target returns at the water-vapor absorption line center (828.187 nm) and the offline wavelength (828.287 nm) were collected for ~ 30 seconds at each spectral position.

The horizontal hard target measurements are shown in Figure 101 where the same data is plotted on a linear and log scale in the left and right plots, respectively. The plot on the left clearly shows attenuation of the signal at the online wavelength due to water-vapor absorption although the log plot on the right reveals a small measurable signal. Taking the ratio of the online to the offline hard target returns, a moderate spectral purity 99.59 was measured. For confirmation that the DIAL transmitter was operating at the center of the water-vapor absorption line, the online seed laser wavelength was scanned over ~ 6 -10 GHz and the returns were monitored. A further minimum in the "online" returns signal was measured at 828.1895 nm. It was experimentally verified that the

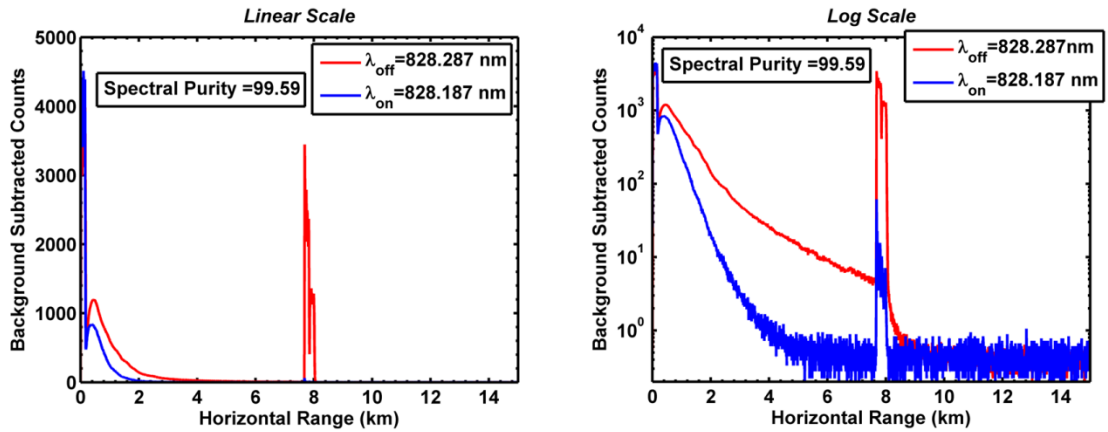


Figure 101 Horizontal hard target measurements at the online and offline wavelengths. The linear scale on the left clearly shows the lack of returns at the online wavelength due to water-vapor absorption. The figure on the right is the same as the data shown on the left except on a log scale. The relative humidity and temperature for the measurement was $\sim 70\%$ and -5°C , respectively.

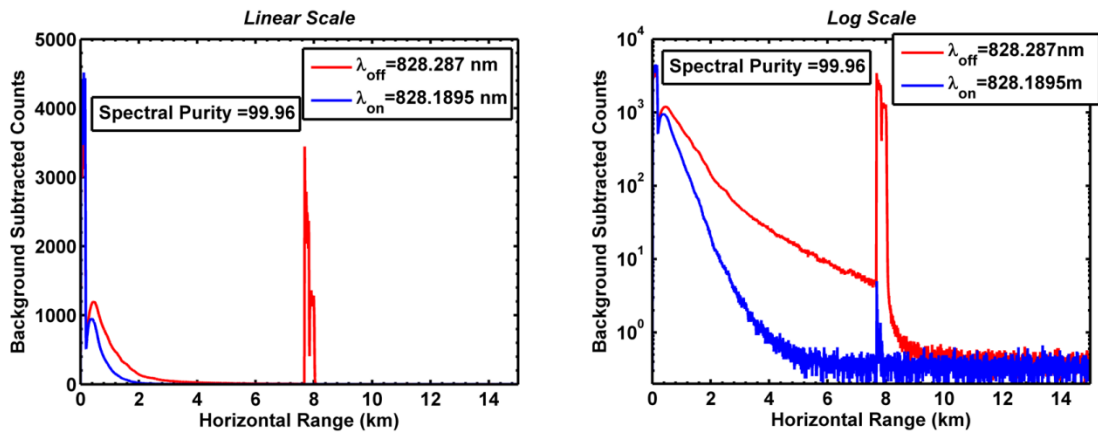


Figure 102 Horizontal hard target measurements at the offline wavelength and the new online wavelength corresponding to the center of the pressure shifted absorption line. A decrease in the measured signal at the new online wavelength significantly increased the spectral purity to 99.96%.

spectral position of the water-vapor absorption line had shifted to a longer wavelength due to the pressure shift described in the theory section. The returns corresponding to the center of the pressure shifted water-vapor absorption line are shown in Figure 102. A significant decrease in the measurable signal can be seen, yielding a much higher spectral purity of 99.96%. The high DIAL transmitter spectral purity also indicates that little or no frequency chirp is encountered resulting from the sharp change in the TSOA carrier density/index as the 1 μ s current pulse is turned on and off to the gain medium. For comparison with the performance specifications of the second generation DIAL transmitter shown in Table 4, the third generation DIAL transmitter specifications is shown in Table 8.

Table 8 Third generation DIAL transmitter specifications.

Parameter	Measured
Laser oscillator	2 Modified Littrow ECDL's
Laser amplifier	Single Stage TSOA
Transmitted wavelengths (vacuum)	3: 828.187 nm (online), 828.193-828.195 nm (sideline), 828.287 nm (offline)
Pulse repetition frequency	10.0 kHz
Pulse length	1 μ s
Pulse energy	7 μ J
Short-term bandwidth	≤ 0.3 MHz
Long-term bandwidth	± 55 MHz
Spectral purity	$\geq .9996$
Beam divergence	50-100 μ rad
Beam diameter	~ 30.0 mm
Eye-safe region	0 m
$t_{on} - t_{off}$	~ 6 s

Receiver

The receiver used for the third generation DIAL instrument is almost identical to the design of second generation DIAL receiver which is shown schematically in Figure 31. A 35 cm diameter Schmidt-Cassegrain telescope (Celestron) is used to collect the backscattered light, increasing the light gathering aperture area by a factor of 1.56 over the 28 cm diameter telescope. This increase in the aperture size allows for more efficient collection of weak backscattered returns at higher altitudes but also extends the initial

overlap range out to a further distance from the telescope. A correction to this disadvantage which also limited the aerosol retrievals of the second generation DIAL instrument will be discussed in the next section. Using the methods presented in the second generation DIAL receiver section as well as in Appendix D, a full angle FOV of $125\ \mu\text{rad}$ was calculated for the 35 cm telescope. Although not in perfect agreement, the ZEMAX full field spot diagram presented in Figure 103 shows that a smaller full angle FOV of $105\ \mu\text{rad}$ is required to completely image the backscattered returns of the larger 35 cm diameter aperture compared to the $125\ \mu\text{rad}$ FOV for the 28 cm diameter telescope. The smaller FOV further limits the influence of background solar radiation but also makes for higher sensitivity of the alignment of the transmitter to the receiver optical axis.

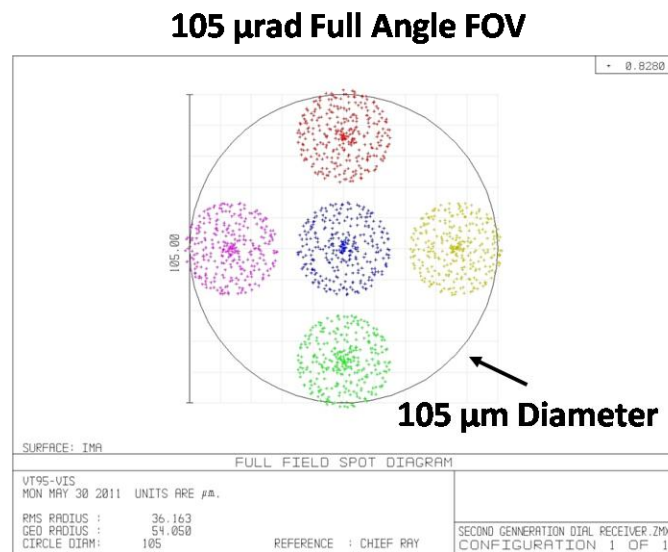


Figure 103 ZEMAX full field spot diagram for the 35 cm diameter telescope. A smaller full angle FOV is required to completely image the backscattered returns from the larger telescope aperture.

Despite the narrow FOV required to fully image the backscattered returns for the larger telescope, the background noise due to solar radiation is expected to increase relative to the second generation instrument by the ratio of the area of the two receivers, approximately a factor of 1.5. To overcome the higher background noise two narrowband optical filter are placed in series. The addition of an extra filter in the receiver drops the peak transmission of the filter from 61 % to 38 % while dropping the out of band transmission by another 4 orders of magnitude from $\sim 10^{-4}$ to 10^{-8} . The transmission spectrum for one and two filters (placed in series) is shown in Figure 104. The addition of a second filter in the DIAL receiver sufficiently blocks the background noise such that daytime water-vapor and aerosol measurements are made possible at higher altitudes. The addition of a light shielded fiber (Coastal Connections) in the

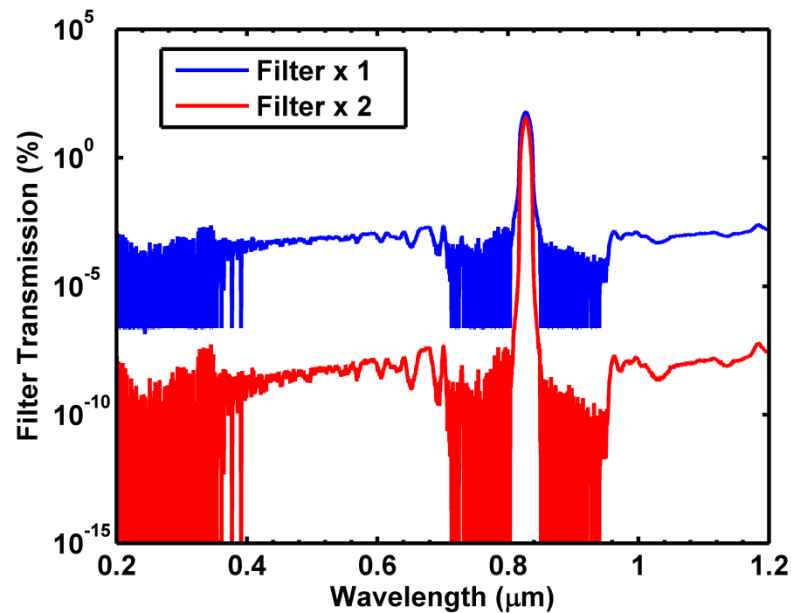


Figure 104 Narrowband optical filter transmission spectrum for normal incidence (BARR Associates) for both 1 and 2 filters in the receiver train. The addition of the second filter drops the peak transmission from 68 % to 38 % while dropping the out of band transmission from $\sim 10^{-4}$ to $\sim 10^{-8}$.

receiver also acts to further increase the SNR by preventing the ambient room background light from leaking into the cladding of the fiber and traveling to the APD detector.

Figure 105 shows histograms of the ambient background noise measurements collected over ~ 5 minutes for the third generation DIAL receiver under varying nighttime conditions. It should be noted that the laboratory room lights were on for all of the subsequent measurements to gauge the light tightness of the back end receiver optical train given no solar background radiation. Sub-figure a shows the measured detector count rate with the transmitter completely turned off and the telescope open to the nighttime sky. Average background count rates of ~ 250 -260 photoelectrons/second can be seen which is in good agreement with the average dark count rate of 250 photoelectrons/second for the APD detector, although lower dark count rates of ~ 210 counts/second have been observed after long periods of operation. Sub-figure b shows the cross talk of the transmitter and receiver due to the small amount of cw leakage light from the seed lasers through the TSOA. Very little evidence of cross talk can be seen where the average count rates do not differ greatly from those of when the transmitter was completely turned off from figure a. Sub-figures c and d show the average dark count rates for the telescope aperture closed and the DIAL transmitter completely off and pulsing at the maximum 7 μJ , respectively. For the lid closed and the transmitter completely off, the average dark count rates with the room lights on fall below the specified APD detector dark count rate of 250 counts/second. Further evidence of a

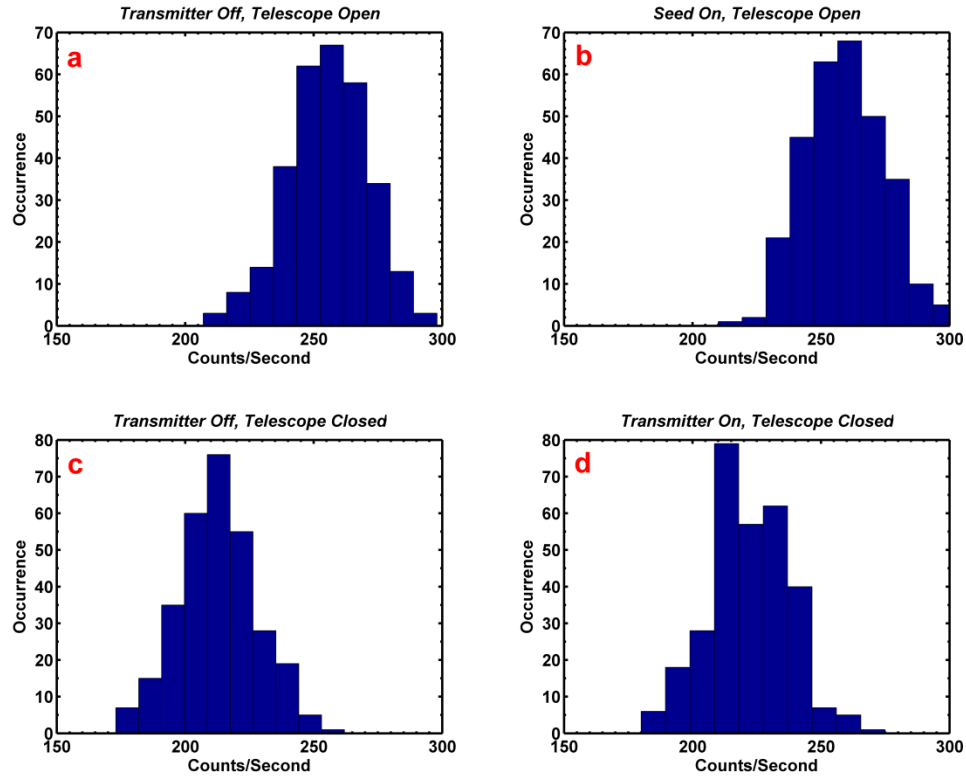


Figure 105 APD detector dark count measurements under varying conditions: a) Transmitter turned off and telescope is exposed to a dark nighttime atmosphere. b) Amplifier off while a small amount of cw seed light is transmitted through the TSOA to measure the receiver cross talk under dark conditions. c) Transmitter off and telescope closed to measure the shielding of the receiver optical train from the ambient room lights (which were on). d) Transmitter on and telescope closed to measure the amount of leakage light into the receiver optical train resulting from the high pulse energy DIAL transmitter flashing in the roof port room.

completely light tight receiver optical train can be seen in sub-figure d where the laser flashes from $7\mu\text{J}$ pulses are completely blocked and the average background count rate is still below the specified APD dark count rate. An example of a typical clear sky diurnal background measurement is shown in Figure 106. Suppression of the daytime background solar radiation resulting from the addition of a second narrowband optical

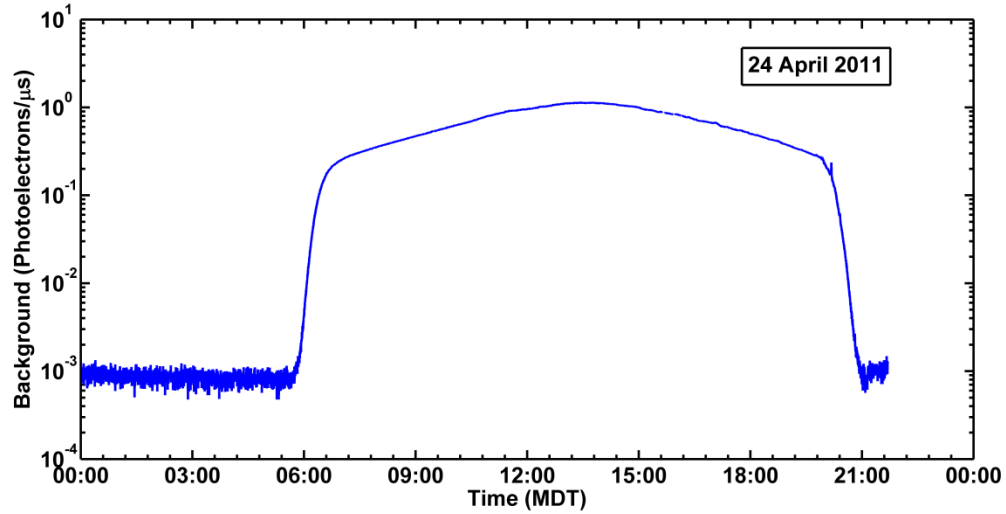


Figure 106 Evolution of the background counts over ~ 22 hours for a clear sky.

filter keeps the daytime APD count rate at ~ 1 MHz (1 photoelectron/ μ s), hence ensuring the APD operates in a linear regime during both daytime and nighttime operation.

Overlap Function Correction

Because of the differential normalization in the DIAL technique, the water-vapor measurements are not subject to the drawbacks of the incomplete near field overlap function where instead the scattering angle incident on the narrowband filter poses as the major limiting factor (Nehrir 2008; Nehrir et al. 2009). Conversely, the incomplete overlap function in the near field returns limits the minimum altitude in which aerosol retrievals can be obtained for most backscatter lidars. The aerosol retrievals from the past generation DIAL instruments have suffered from the incomplete overlap where the aerosol extinction from the initial overlap range to the surface was estimated using a linear interpolation from a scattering nephelometer measurement at the ground. The third generation DIAL instrument was designed to have scanning capabilities so that the

overlap function can be measured using horizontal backscattered returns from a well mixed atmosphere and vertical pointing aerosol retrievals can be extended to the surface.

For a telescope focus set to infinity, the near field returns as a function of range focus to a point behind the field stop (105 μm core fiber) with variable image magnification size whereby the near-field optical efficiency of the DIAL receiver is compromised. The degradation of the near field efficiency is also attributed to the vignetting of the backscattered light due to telescope secondary mirror obscuration. Using the methods presented in Appendix D, the image spot size of the transmitted laser beam at the fiber can be estimated as a function of altitude, thus providing a rough estimate of the minimum range where the scattering object is fully imaged by the 105 μm core fiber. Figure 107 shows the image spot size at the field stop for the specified second

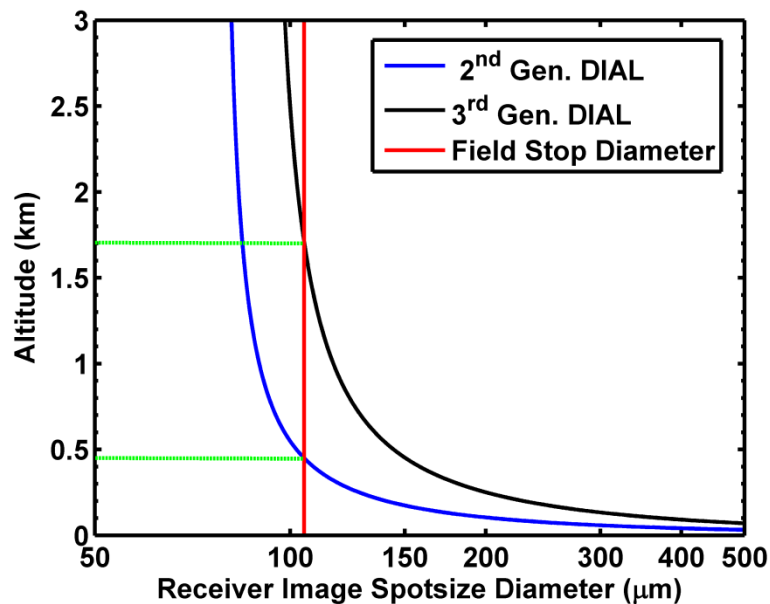


Figure 107 Image spot size at the receiver field stop (fiber) for the transmitted laser beam for the second and third generation DIAL instruments. The altitude in which the transmitted beam is fully captured by the 105 μm core fiber is increased from ~ 0.5 km to ~ 1.7 km from the 2nd to 3rd generation DIAL instrument.

and third generation DIAL instruments. The red line indicates the size of the fiber core diameter which acts as the receiver field stop for the both instruments. An increase in the initial overlap range r_0 from ~ 0.5 km to ~ 1.7 km between the second and third generation receivers can be seen where the full backscattered images from the transmitted laser beams are fully captured by the $105\ \mu\text{m}$ core diameter fiber receiver.

For calibration and inversion of aerosol optical properties from elastic backscatter lidar signals, the overlap function must be computed such that accurate corrections can be made to the returns in the PBL (0-2 km) where most of the atmospheric aerosols reside. Measures (1984) provides a detailed mathematical derivation of the lidar overlap function based on the receiver and transmitter specifications but it is not practical as only optical parameters are provided as inputs. Alternatively the overlap function can be measured experimentally by collecting data from a horizontally pointing lidar in a well mixed boundary layer (Sasano, Takeuchi & Okuda 1979). The collection of sufficiently time averaged horizontal pointing lidar returns in a well mixed boundary with either heavy homogenous- or very little aerosol loading ensures that the extinction of the signal through the horizontal layer is linear with increasing range.

The horizontal pointing lidar equation for a range corrected backscatter signal can be written as

$$S_h(r) = O(r)C\beta(r)T^2(r), \quad (5.13)$$

where $T(r) = e^{-\tau}$ and $\tau = \sigma r$ is the optical depth through a given layer and σ is total extinction coefficient. For the segment of the horizontal backscatter signal where full

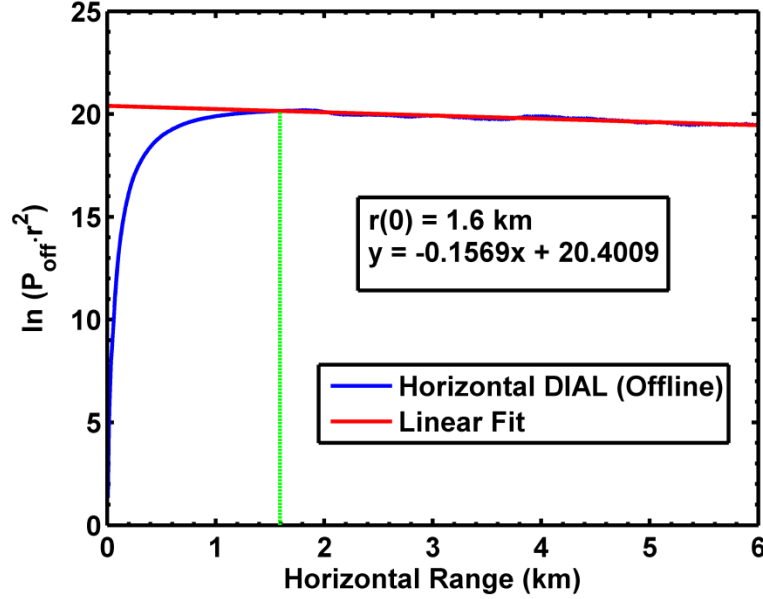


Figure 108 Natural logarithm of the range corrected , background subtracted, APD deadtime corrected data where the instrument is pointed horizontally at the Hyalite hills. Because a well mixed atmosphere was present, the signal falls off linearly proportional to the total extinction beyond the range in which full overlap is achieved. For the 35 cm diameter telescope using a coaxial transmitter/receiver configuration, full overlap is achieved at approximately 1.7 km.

overlap between the transmitter and receiver is achieved, $(r > r_0)$, $O(r > r_0)$ is assumed to be 1.0 and taking the natural log of both sides of equation (5.13) yields

$$\ln [S_h(r)] = \ln [C\beta_h(r)] - 2\sigma r, \quad \text{for } r > r_0. \quad (5.14)$$

If the scattering volume is assumed to consist primarily of homogeneously distributed aerosols , the $\ln [C\beta_h(r)]$ term from equation (5.14) is constant with range and the equation takes the form of a straight line $y = mx + b$ beyond r_0 . An example of the natural log of the range corrected horizontal returns for a very clear and stable atmosphere is shown in Figure 108. The blue curve which denotes the horizontal lidar measurements falls off linearly proportional to the extinction beyond the range in which

full overlap is achieved which approximately 1.7 km for the third generation receiver.

The red solid line represents the expected return signal $S_e(r)$ and is denoted by a linear fit to the region where full overlap is thought to be achieved, $\sim 2-6$ km. The extinction term -2σ corresponds to the slope m of the fitted line and the $\ln[C\beta_h]$ term is solved for the intercept value. The overlap function $O(r)$ is then determined by normalizing the measured horizontal signal $S_h(r)$ by the expected linear fit signal $S_e(r)$, yielding

$$O(r) = \frac{S_h(r)}{S_e(r)r} = \frac{S_h(r)}{C\beta_h e^{-2\sigma r}}. \quad (5.15)$$

The measured overlap function for the third generation DIAL instrument using equation (5.15) is shown in Figure 109. Complete overlap is achieved at 1.63 km where the overlap correction to the data beyond that point is assumed to be 1. An example of

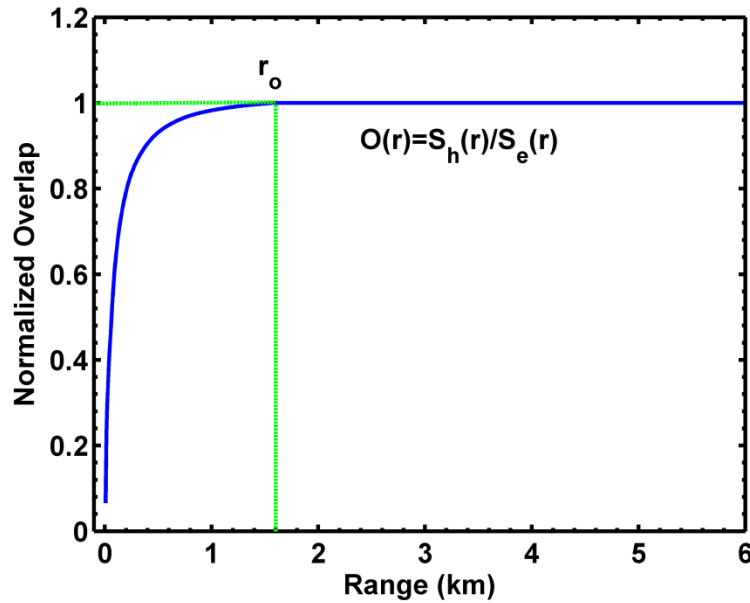


Figure 109 Measured overlap function for the third generation DIAL instrument using horizontal pointing lidar backscatter measurements. The determination of the overlap function is calculated by fitting normalization of the horizontal backscattered returns to the expected linear fit to the returns at $r > r_0$. Once the initial overlap is reached at ~ 1.7 km, the overlap correction factor for all subsequent ranges is considered to be 1.0.

the overlap correction to the vertical pointing range corrected backscattered returns is shown in Figure 110. A significant underestimation of the returns can be seen without the correction factor due to vignetting of the near field returns at the receiver field stop. The inclusion of the near field overlap correction factor will allow for accurate measurements of aerosol optical properties to near the surface.

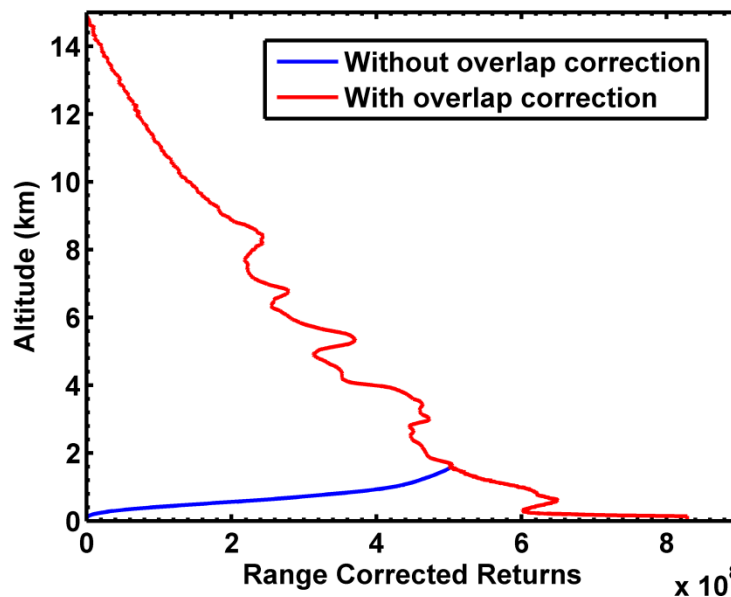


Figure 110 Influence of the near field overlap correction factor to the vertical pointing range corrected backscattered returns. The signal from the ground up 150 m above the instrument which corresponds to the duration of the transmitted pulse is considered to be constant and taken as the value measured at 150 m above the instrument.

Data Acquisition and Real-Time Processing

Similar to the first and second generation DIAL instruments, the third generation DIAL uses the Labview programming environment to control the instrument and collect atmospheric backscattered data. A picture of the Labview based graphical user interface

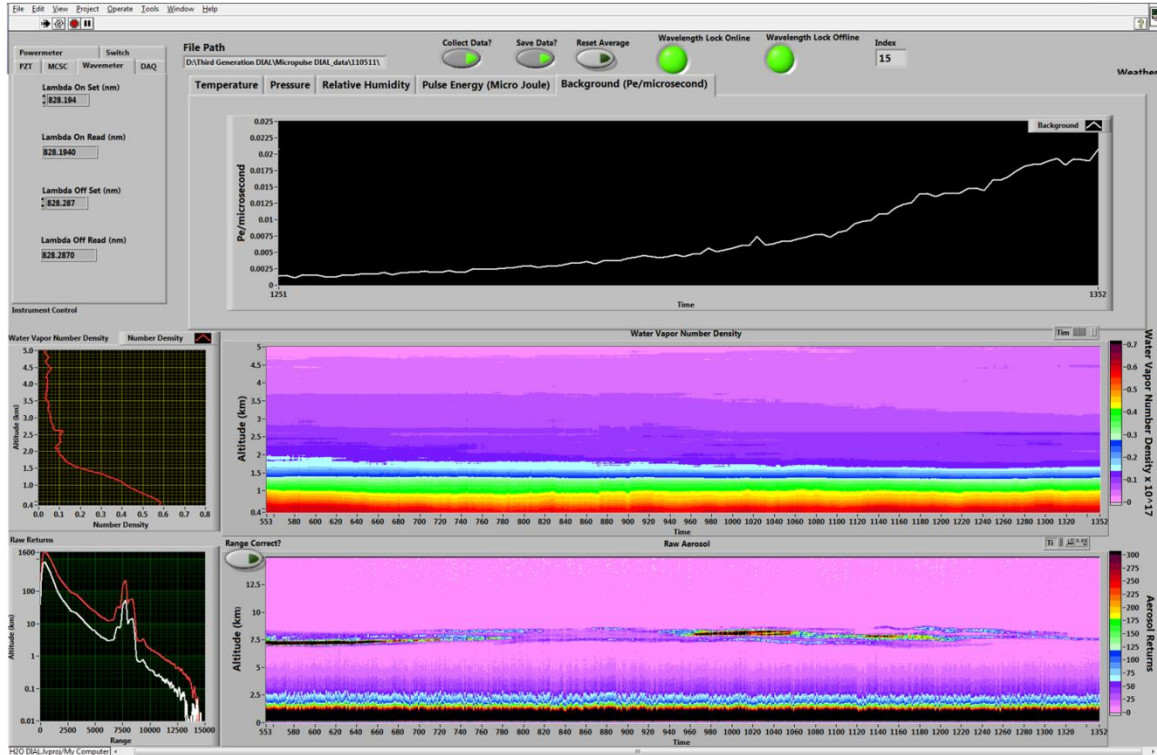


Figure 111 Labview graphical user interface for the third generation DIAL instrument.

(GUI) used to control and process the data from the third generation DIAL instrument is shown in Figure 111. Water-vapor- and attenuated aerosol backscatter profiles are calculated real time, alleviating the need for post processing and allowing for real time monitoring of the lower atmospheric state. The generalized data acquisition flow diagram is shown in Figure 112 where the red and black arrows denote the passing and receiving of optical and electrical signals, respectively. A lap top computer is used to communicate with the DIAL instrument as well as to retrieve ancillary data required for the DIAL calculations and the aerosol inversions. The online ECDL is locked to a given spectral position along the water-vapor absorption feature using wavelength feedback from a 55 MHz resolution wavemeter. The online and offline ECDL's are sequentially

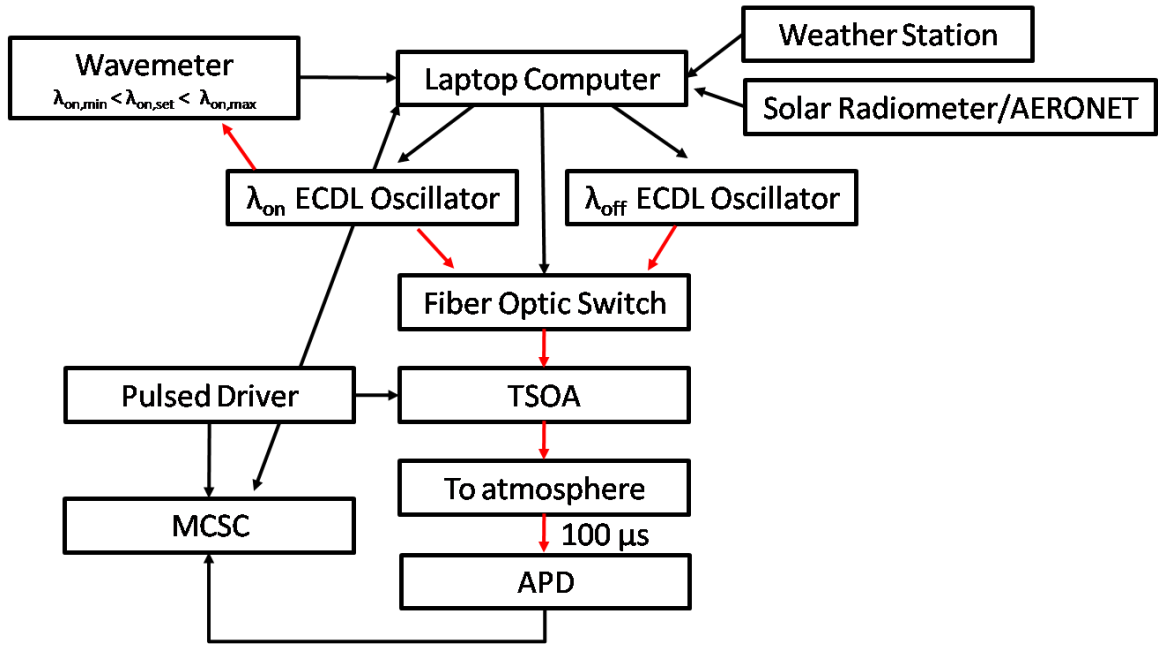


Figure 112 Data acquisition flow diagram for the third generation DIAL instrument. The red and black arrows denote optical and electrical signal, respectively.

injection seeded into the pulsed TSOA using the 2x1 fiber optic switch. The pulsed current source is used to trigger the output pulse from the TSOA with 1 μ s pulse duration at a 10 kHz PRF and is also used to begin the data acquisition process from the MCSC.

Atmospheric backscattered returns from the TSOA output are sampled by the APD over 100 μ s and integrated on a second by second basis with the MCSC with 7.5 m vertical range resolution. The dwelling time at each wavelength is user defined but is typically set to average data over three seconds. To minimize the systematic errors that arises from the spectral cross talk of the backscattered returns, a two second dead time is required between the collection of the online and offline returns due to the time required to clear the buffers of the commercially purchased MCSC, yielding a 60% duty cycle.

Different FPGA development boards are currently being investigated as an alternative to the commercially purchased scaler card.

To streamline the data processing and to minimize user interaction with the instrument, the water-vapor and aerosol data processing is completed in real time using the Matlab and Labview programming environment. The flow diagram for the real time data processing is shown in Figure 113. The DIAL returns at the online and offline wavelengths are summed at 10 kHz using a MCSC and a laptop computer. Several Matlab programs nested in the main Labview data acquisition program are then used to analyze the data. The time averaged data (~ 1 -3 seconds) between the online and offline switching are corrected for instrument and background noise induced biases. Because the third generation DIAL transmitter exhibits substantially higher pulse energies than the

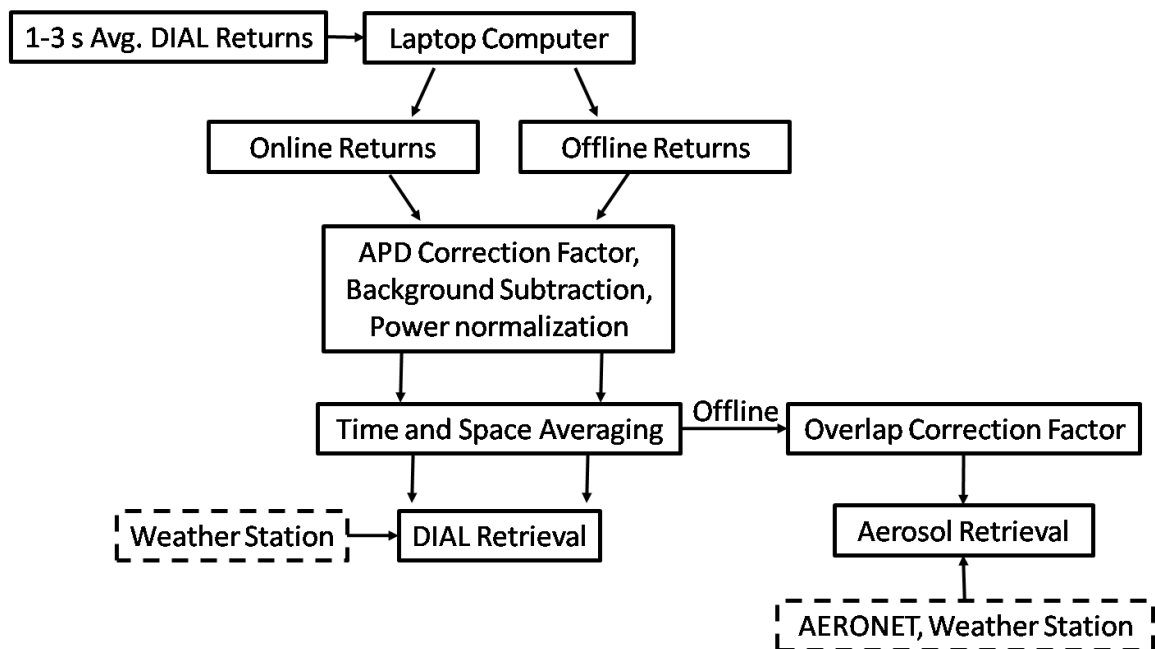


Figure 113 Real time data processing flow diagram for the third generation DIAL instrument. The dashed inputs such as the weather station and AERONET data are auxiliary data and are not necessarily required for the DIAL and aerosol retrievals.

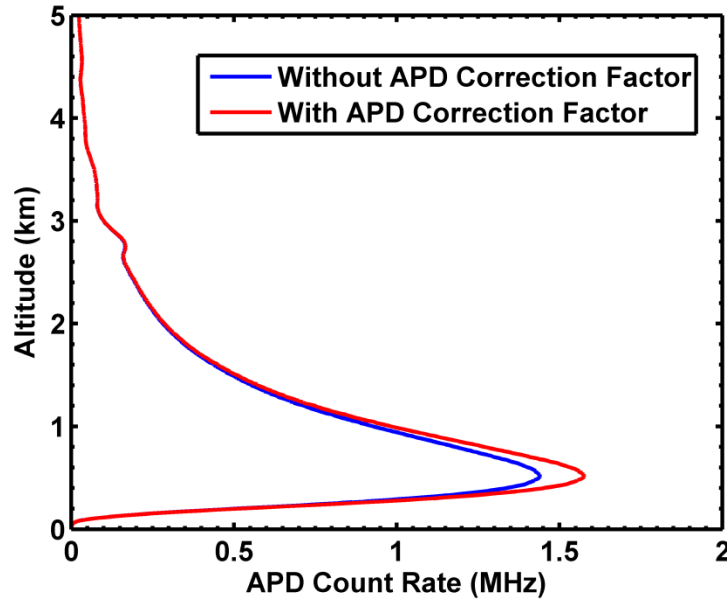


Figure 114 APD dead time correction factor applied to the offline returns. Note that the dead time correction factor is calculated before the overlap correction and background subtraction is applied to the returns.

previous instruments, a near field correction factor is applied to the APD to account for the relatively small near field saturation effects from the transmitted pulse.

Figure 114 shows the affect of the APD correction in the "brighter" near field returns using equation (3.6) to calculate the APD dead time correction factor. The dead time correction factor is calculated using the raw backscattered returns to account for the higher daytime background signal and is applied prior to the energy normalization and the overlap correction factor presented in Figure 110 but after the background subtraction.

Once corrected for instrument and background induced biases, the online and offline data are spatially and temporally averaged appropriately for the water-vapor and aerosol inversions. For the water-vapor retrievals a 10 minute temporal and 150 m

spatial running average over the online and offline returns are used to increase the SNR for the DIAL calculation presented in equation (2.12). The 150 m spatial gliding average is used to increase the SNR of the returns while preserving the 7.5 m sampling rate of the MCSC for the DIAL calculation. It should be noted that there exists a 150 m ambiguity in the exact altitude of the number-density calculated at a given 7.5 m range bin. A second 150 m spatial gliding average is performed over the water-vapor profile to further increase the SNR of the water-vapor profile. If available, the weather station data (courtesy of Dr. Joe Shaw) such as the temperature and pressure are also used to calculate the range resolved differential absorption cross section.

The aerosol inversion is completed using the energy normalized APD corrected-background subtracted offline returns. A 1 minute temporal and 150 m spatial running average is used to increase the SNR for the aerosol inversion technique described in chapter 4. The overlap correction factor described in the previous section is also used to extend the aerosol returns to near the surface. Given that AERONET data is available, the aerosol retrievals are completed using the iterative Fernald inversion technique presented in chapter 4. The weather station temperature and pressure data at the ground are used to model the molecular backscatter profile for inclusion in the aerosol inversion. Considering the solar radiometer data takes ~ 1 -2 hours to process and post on the AERONET website (<http://aeronet.gsfc.nasa.gov>), the aerosol inversions are completed separately at a later time and a qualitative form of the aerosol retrieval is used to monitor the atmospheric backscatter which is often referred to as the normalized relative backscatter (NRB) (Campbell et al. 2002).

Based on the lidar equation (4.1), the raw backscattered returns at the offline wavelength can be expressed as

$$n(r) = \frac{\frac{O(r)CE[\beta_m(r)+\beta_a(r)]T_m^2(r)T_a^2(r)}{r^2} + n_b}{D[n(r)]}, \quad (5.16)$$

where $n(r)$ is the photo-electron counts per second at a range r , E is the output pulse energy in micro joule, n_b is the ambient background signal also measured in photo-electrons per second, and $D[n(r)]$ is the APD dead time correction factor as a function of the raw count rate $n(r)$. The NRB is derived by solving for the attenuated backscatter coefficient times the instrument calibration constant from equation (5.16) and is given as

$$NRB = \frac{[n(r) \cdot D[n(r)] - n_b] r^2}{O(r)E} = C\beta_{total}(r)T_{total}^2(r). \quad (5.17)$$

The units for the NRB are $(photoelectrons \cdot km^2)/(\mu sec \cdot \mu j)$. The NRB is useful for direct lidar comparisons with the well established NASA MPLNET (MicroPulse Lidar Network) which also uses the NRB as the primary level 1.0 output data product.

MPLNET is a federated community of low pulse energy high PRF commercially available single channel elastic backscatter lidars at 532 nm used for full time monitoring of aerosols and clouds. The calibration constant C can be easily obtained when equation (5.17) is constrained with a column AOD measurement from AERONET similar to the calibration method presented in chapter 4. Once C is obtained, the iterative Fernald inversion using the same AERONET AOD as a constraint can be used to arrive at the range resolved aerosol extinction coefficient.

Experimental Results: Initial Data

The third generation DIAL instrument has been operational since February 2011 where very little data has been collected due to the poor weather conditions over the northwestern United States resulting from La Nina driven weather patterns. Favorable comparisons to radiosonde measurements under very dry conditions have been observed for both nighttime and daytime operation under varying atmospheric conditions (i.e. cloudy, partly cloudy, sunny, windy...etc). It should be noted that the radiosonde ground check station used for the water-vapor comparison measurements has not been calibrated in almost five years and is not believed to be in situ truth but is rather used as an indication for general agreement. Water-vapor and aerosol trends are also compared with weathers station data as well as other active and passive sensors such MPLNET, AERONET, and SuomiNET. SuomiNET is an international network of global positioning (GPS) receivers configured to back out the total column precipitable water-vapor as well as other atmospheric properties by analyzing the effective change in the atmospheric refractive index as the atmosphere density changes.

Slant Path Profiling

The performance of the water-vapor retrieval is directly proportional to the strength of the backscatter signal at the online and offline wavelength. To evaluate the maximum range for the water-vapor profiles under optimal scattering conditions the DIAL was operated in a horizontal mode such that the atmospheric density and aerosol concentrations were relatively constant. This was done in conjunction with the spectral

purity and overlap correction measurements where the instrument was pointed at the Hyalite foothills as shown in Figure 99. The horizontal pointing range corrected returns and water-vapor profiles collected on 07 April 2011 are shown in Figure 115. Low level clouds and aerosol are transported from the east to the west as time increases, corresponding to the nighttime down slope winds described in chapters 3 and 4 resulting from the unique meteorology caused by the Gallatin valley and the nearby mountain ranges. The horizontal water-vapor time series also shows good structure out to the hard target range resulting from a good scattering signals at all range bins prior to the mountains. Furthermore, even with 10 minute averaging at each DIAL wavelength, small scale water-vapor features that correlate very well with the rapidly changing aerosol signal can be seen starting at $\sim 20:15$. The good temporal resolution of the water-vapor profiles in the presence of rapidly moving aerosols and thin clouds is attributed to the faster spectral switching time of the third generation DIAL transmitter.

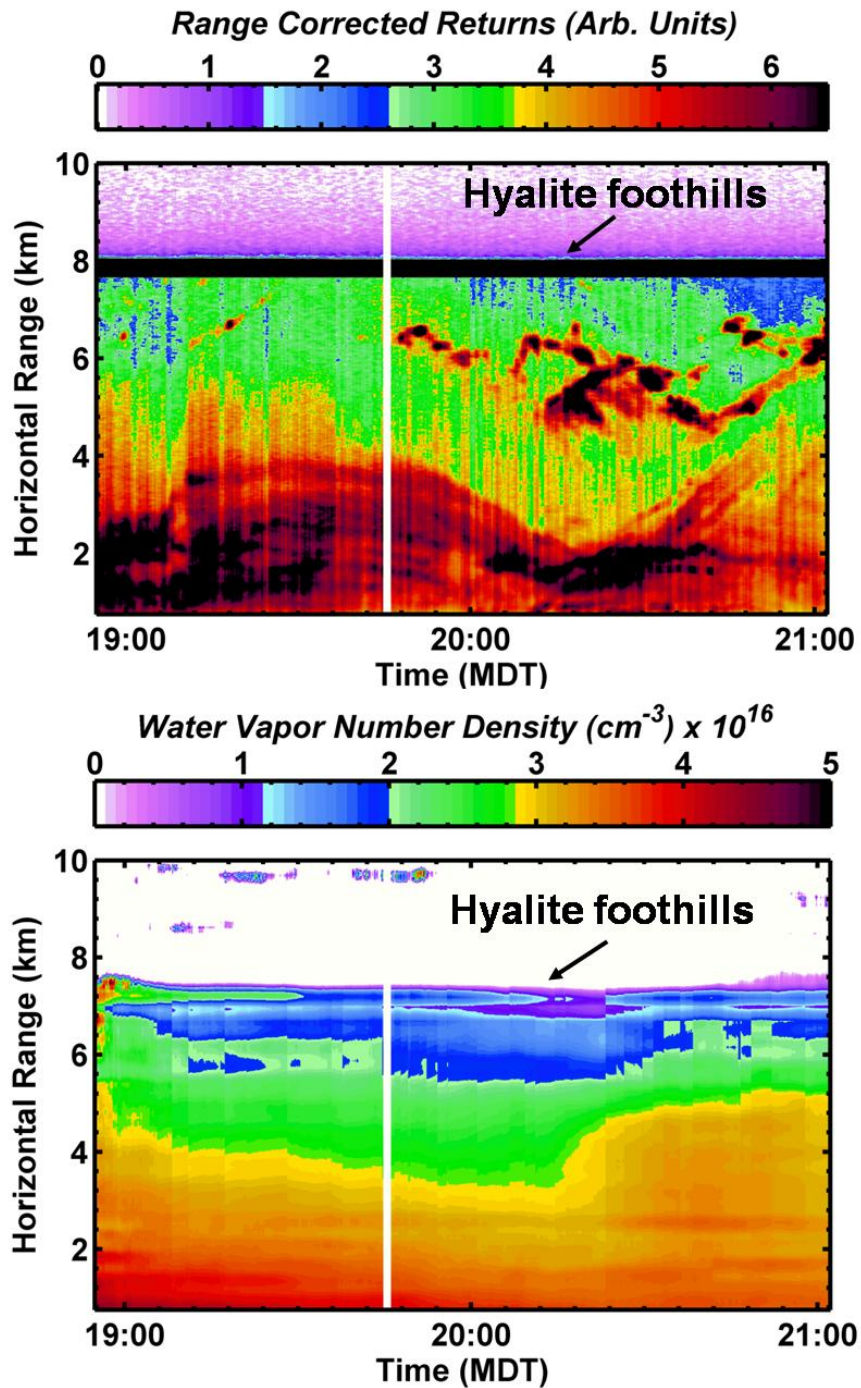


Figure 115 Top) Range corrected returns for the horizontal offline channel backscattered returns collected on 07 April 2011. The data are averaged over 150 m spatial and 30 second temporal running average windows. The hard target returns from the foothills can be seen at ~ 8 km. Bottom) Corresponding water-vapor profiles with 10 minute and 150 m temporal and spatial resolution, respectively. The white artifacts beyond ~ 8 km result from the lack of a signal beyond the hard target.

Nighttime Profiling: Clear Conditions

Initial nighttime data was collected with the third generation DIAL on 15 February 2011 where comparisons were made to a collocated radiosonde measurement. Data was collected over approximately 2 hours where clear skies permitted the comparison to a radiosonde measurement under very dry conditions at $\sim 20:45$. Figure 116 shows the water-vapor time series over the 2 hour period where the black dotted line indicates the launch of the radiosonde measurement from the roof of Cobleigh hall. The two profiles shown below the time series are the DIAL comparisons to the radiosonde measurement for a 300 m (left) - and 150 m (right) gliding average over the calculated water-vapor profile. The water-vapor time series was calculated using a 300 m gliding average. Excellent agreement between the two measurements can be seen in both averaging scenarios between initial overlap at ~ 0.75 km up to 6 km which is well into the free troposphere. The blue shaded patch represents the error in the water-vapor measurement calculated based on photon noise statistics presented in Appendix E. Depending on the application, the 150 m or the 300 m gliding average window can be used to exploit different water-vapor features in the lower and upper atmosphere. The good agreement between the DIAL and radiosonde measurement into the free troposphere is attributed to the increase the output pulse energy of the DIAL transmitter.

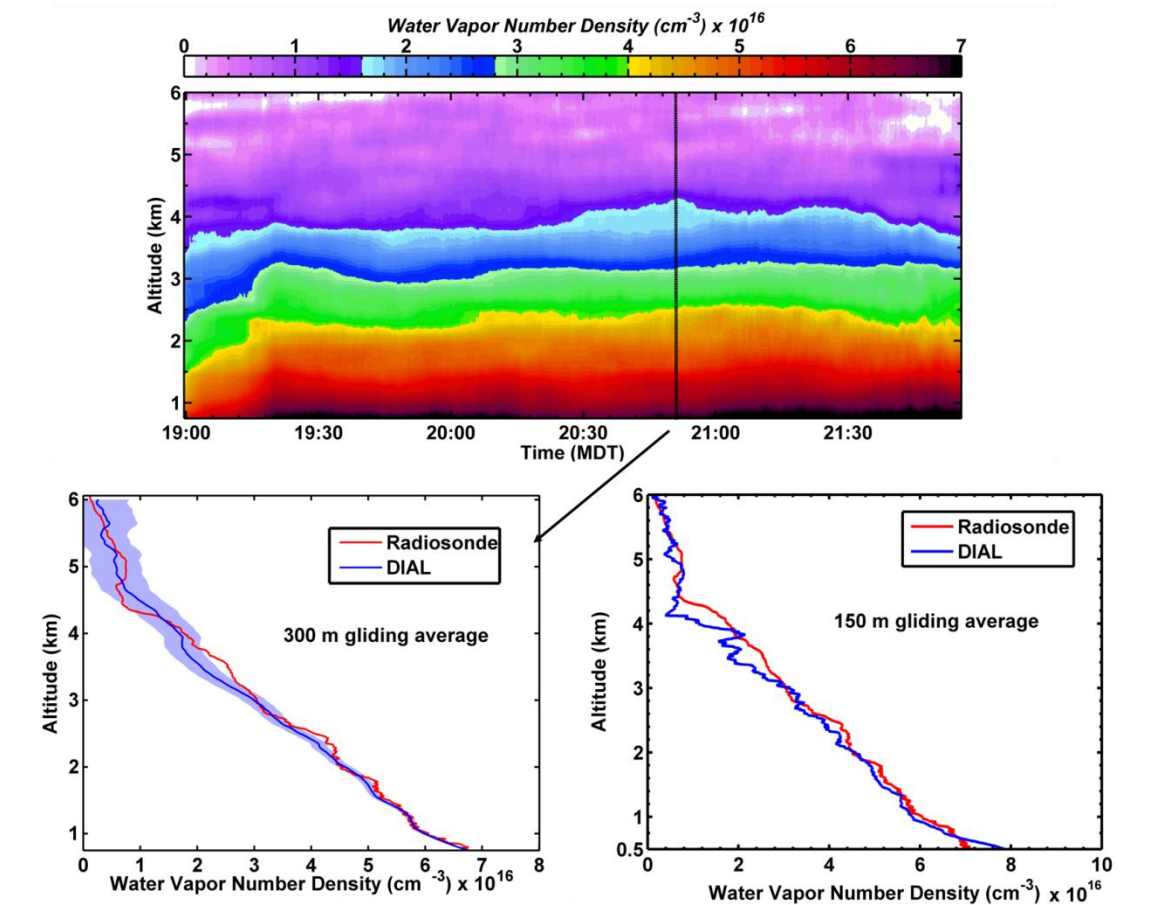


Figure 116 Time series of nighttime water-vapor profiles collected over Cobleigh Hall on 15 February 2011. The black line at $\sim 20:45$ indicates the launch of a collocated radiosonde measurement. The two profiles shown below the time series are the comparisons to the radiosonde measurement using a 300 m (left)- and a 150 m (right) gliding average over the calculated number-density profiles.

Daytime Profiling: Cloudy Conditions

The benefit of the increased spectral sampling time for the DIAL measurement is clearly evident in the water-vapor profiles obtained in the presence of optically thin clouds. NRB and water-vapor profiles for a partly cloudy day on 09 March 2011 are shown in Figure 117. Several stratified cloud layers can be seen in the NRB denoted as

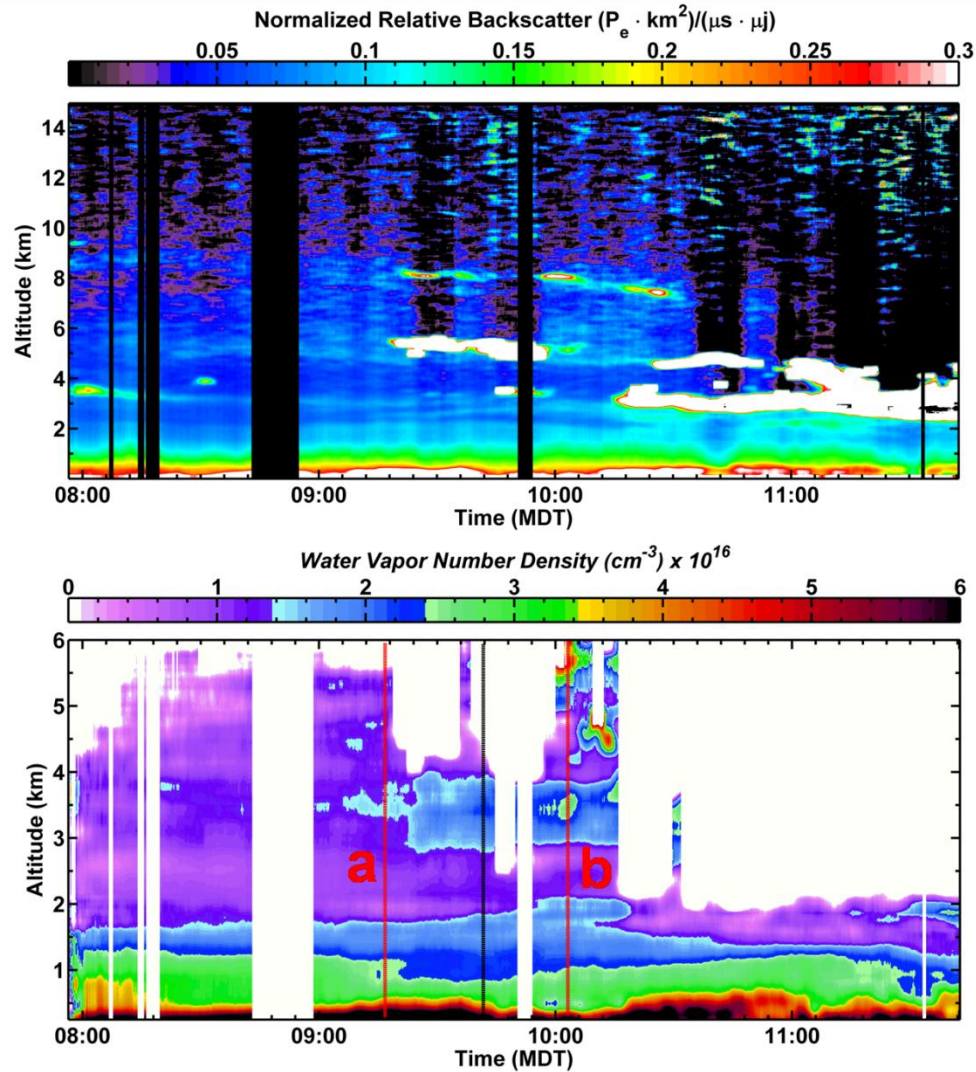


Figure 117 Top) 1 minute temporal and 150 m spatial averaged NRB returns collected on 09 March 2011. Bottom) Water-vapor time series corresponding to the NRB returns from above. The black dotted line indicates the launching time of a collocated radiosonde measurement. The red dotted lines at a and b correspond to the water-vapor profile comparisons before and after the cloud enters the FOV of the DIAL instrument shown in Figure 118.

the white signals that have a NRB magnitude beyond 0.3. Enhanced scattering from the forming of boundary layer clouds at $\sim 1.5\text{--}4$ km can also be seen below the stronger already developed clouds at $\sim 3\text{--}6$ km. The corresponding water-vapor profiles are shown below where the black dotted line indicates the launching of a collocated radiosonde

measurement. It should be noted that it takes approximately 30 minutes for the weather balloon to sample to the lower atmosphere from the ground up to ~ 4 km. Points a and b indicate the DIAL comparisons to the radiosonde measurement before and after the launch of the weather balloon such that temporal overlap between the two measurements is met both below (a) and above the cloud (b). The white omitted areas above the clouds indicate the complete extinction of the signal and no water-vapor profiles are recorded above that altitude. The black and white gaps in the NRB and water-vapor data, respectively, indicate a mode hop at either the online or offline wavelength and no data was retrieved until the wavelengths were corrected.

Figure 118 a and b show the comparison of the DIAL water-vapor retrievals to the radiosonde measurement before and after the launch, respectively. Good agreement between two measurements can be seen below the cloud in profile a prior to the launch of the weather balloon. Due to the use of a larger telescope in the third generation DIAL receiver, the overlap range has been extended to between ~ 0.75 -1.0 km depending on the transmitter alignment. The profile comparison at higher altitudes in part b after the sonde sampled the low level cloud at ~ 3 km also shows good agreement one another. The good agreement between the DIAL water-vapor measurements and the in situ radiosonde measurement in the presence broken clouds indicates that the faster spectral switching time of ~ 6 seconds allows for more accurate sampling of the air masses between the online and offline wavelengths.

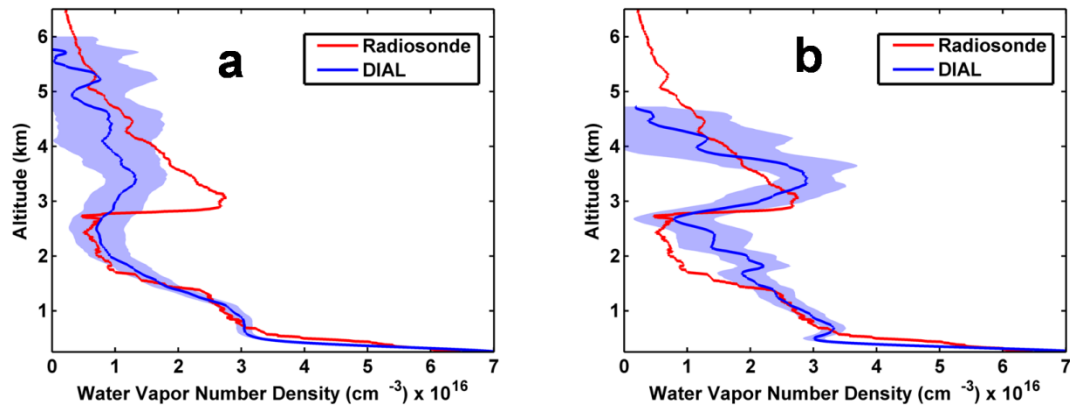


Figure 118 10 minute averaged (at each wavelength) water-vapor profile comparisons to a radiosonde measurement on 09 March 2011. Profiles a and b correspond to the two red lines in Figure 117 where comparisons to the sonde were made before and after the cloud passed over the DIAL instrument.

Diurnal Measurements: Varying Conditions

Once the weather permitted, several longer duration experiments were conducted to measure the diurnal boundary layer trends against other active and passive measurements of aerosols, water-vapor, and meteorological data such as wind speed and direction. The first example of a longer duration data set is shown in Figure 119 where the NRB and water-vapor profiles were monitored over a ~18 hour period on 23 March 2011. Lots of structure in the aerosol returns can be seen both in the boundary layer as well as in the free troposphere over the 18 hour period. Low level clouds limited the maximum altitude for water-vapor and aerosol retrievals during the early morning and mid day by causing severe extinction of the laser light. However water-vapor and aerosol profiles were successfully retrieved up to cloud bases given that they were above the initial overlap range of ~ 1 km. A daytime water-vapor comparison to a collocated

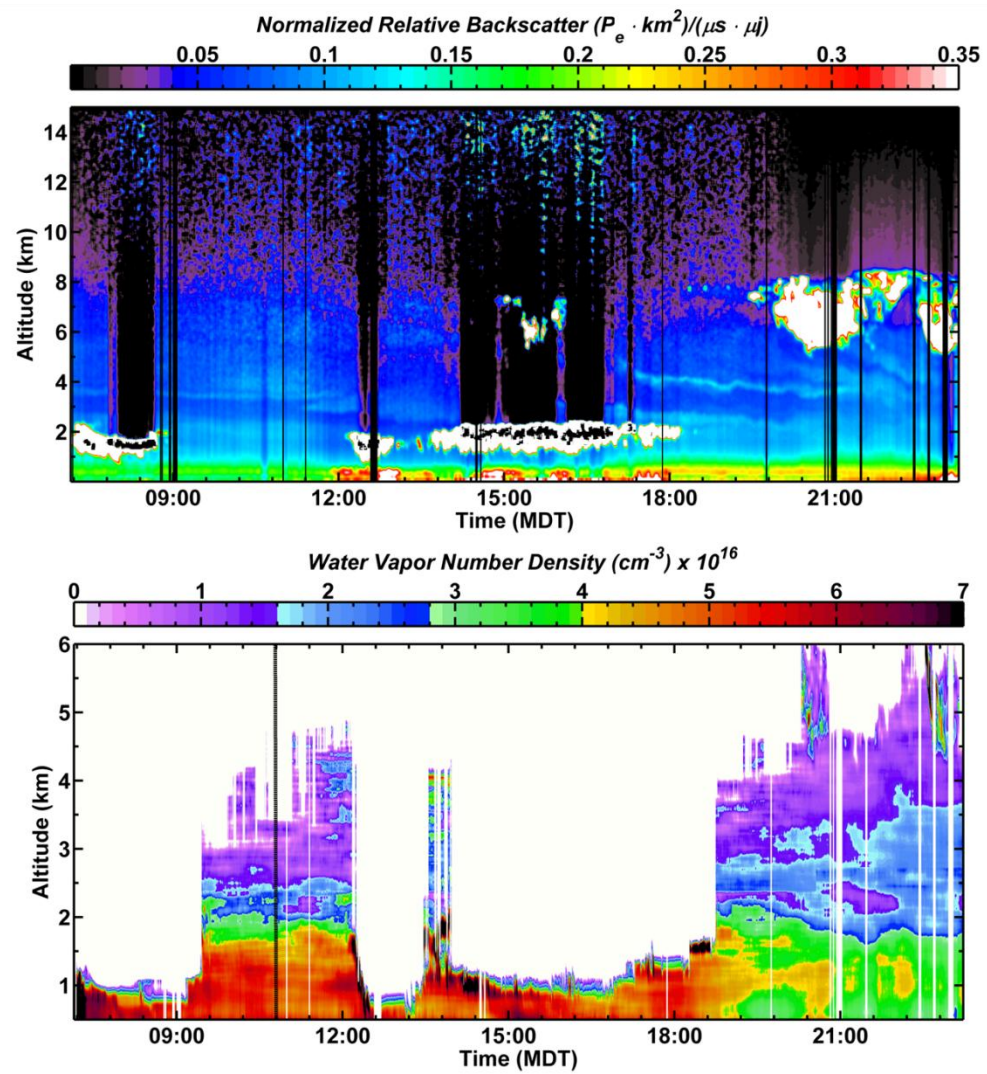


Figure 119 NRB and water-vapor profiles measured over ~ 18 hours on 23 March 2011. The black line indicates the launch of a collocated radiosonde measurement .

radiosonde measurement is shown in Figure 120 indicated by the black dotted line at ~10:40 from the water-vapor time series. Good agreement can be seen from initial overlap at ~ 1 km up to the top of the PBL. Several daytime inversion layers are well resolved by the DIAL at ~ 1.6 and 1.8 km. A large decrease in the PBL water-vapor content can be seen at ~ 19:00 which corresponds well with the increase in wind speed and change in wind direction from the Cobleigh hall weather station (Joe Shaw) data shown in Figure 121. The change in wind direction at ~ 17:00 to the east corresponds nicely with the typical evening down slope winds experienced in the Gallatin valley.

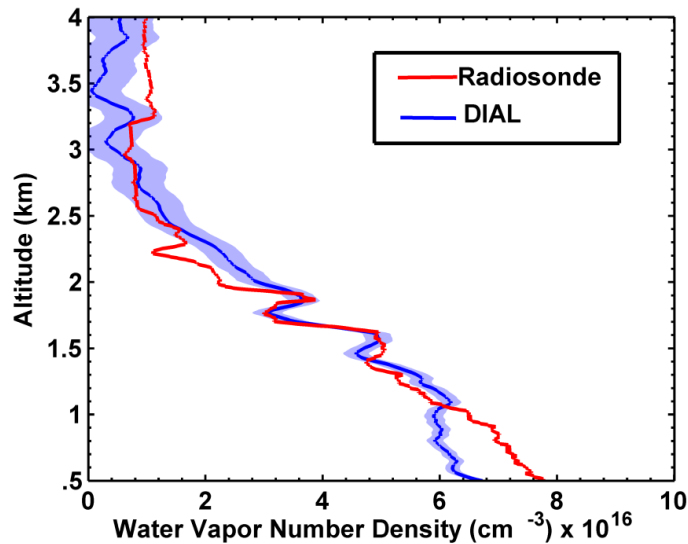


Figure 120 Daytime comparison between the radiosonde and DIAL water-vapor profiles at 10:40 on 23 March 2011. Good agreement between the two measurements can be seen above the overlap region where several temperature inversion layers at ~ 1.6 km and 1.8 km were captured by the DIAL. Initial overlap was achieved at ~ 1 km.

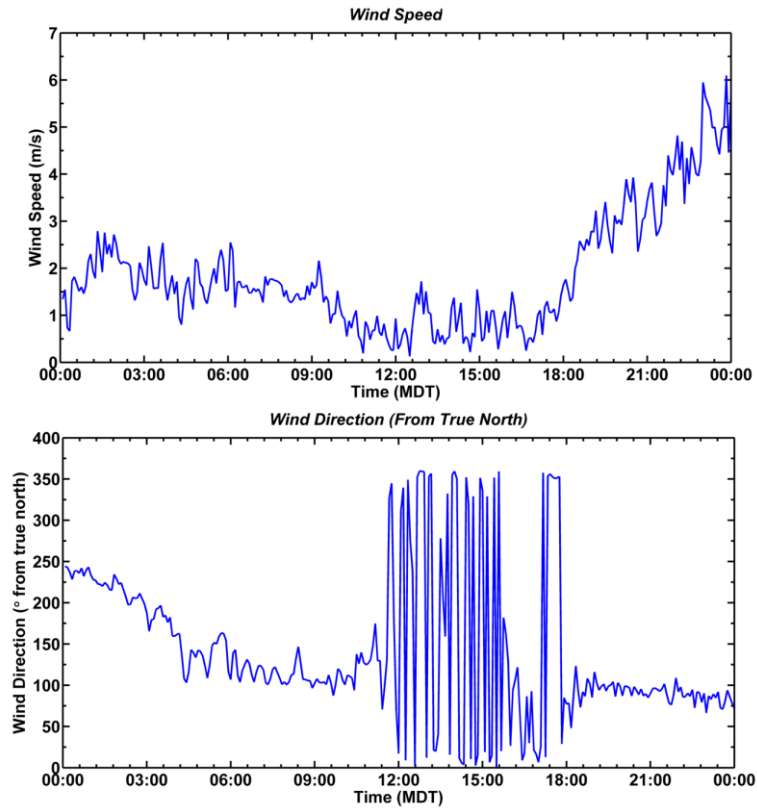


Figure 121 Wind speed- and direction measured on the rooftop of Cobleigh Hall on 23 March 2011. The change and increase in the wind direction and speed at $\sim 17:00$, respectively, indicates the start of the nighttime easterly down slope winds from the mountains.

A second longer duration time series of the NRB and water-vapor profiles measured on 20 April 2011 is shown in Figure 122. Once again, fine aerosol structure can be seen in the NRB returns which correlates well with the spatial confinement of the water-vapor as the PBL decays throughout the night to form into a stable nocturnal boundary layer before sunrise. Enhancement of the aerosol loading as well as an increase in the water-vapor content near the surface can be seen starting at approximately 11:00 where heating of the surface begins to cause convective mixing of the boundary layer. The discontinuity in the water-vapor time series at ~ 2.5 km is an

artifact resulting from the change in the width of the spatial averaging window. Another favorable nighttime DIAL comparison against a radiosonde measurement launched at 04:50 is shown in Figure 123. Good agreement between the two measurements can be seen from initial overlap up to 5 km. A weak capping inversion layer at the top of the PBL at ~ 2.5 km is moderately resolved with the DIAL instrument where the abrupt change in the water-vapor concentration is attributed to the change in the width of the spatial averaging window used to smooth the profiles above the PBL.

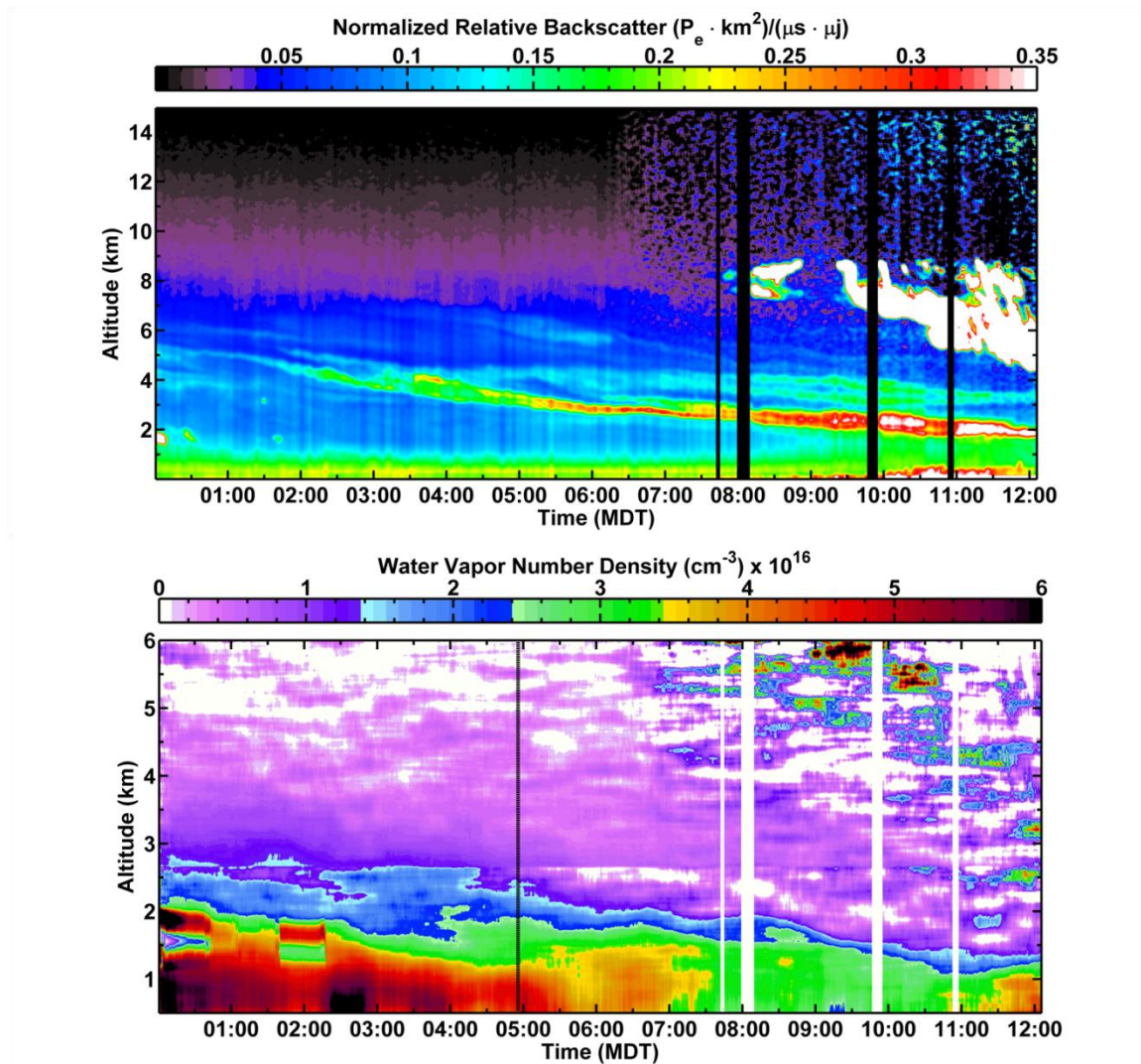


Figure 122 NRB and water-vapor profiles measured on 20 April 2011. The black dotted line indicates the launch of a radiosonde measure for water-vapor comparisons shown in Figure 123.

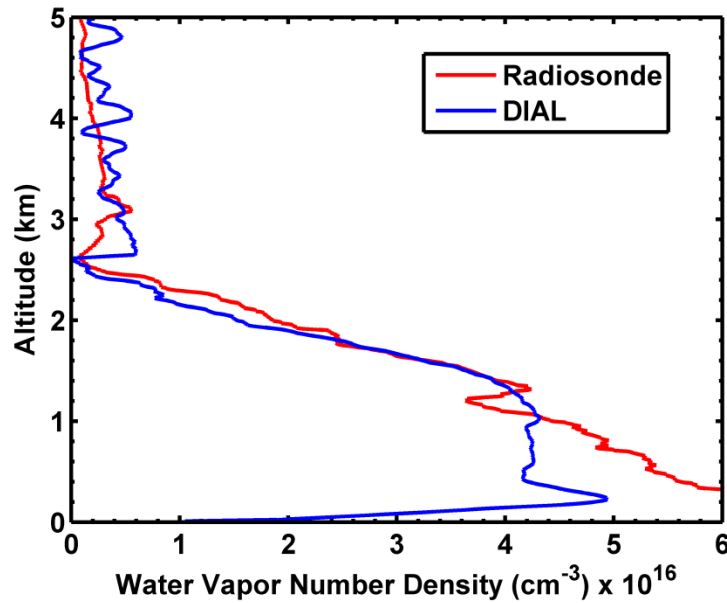


Figure 123 Water-vapor profile comparison with a collocated radiosonde measurement launched at 04:50 on 20 April 2011. Good agreement between the two measurements can be seen from an initial overlap range of ~ 1 km up to 5 km.

Total Precipitable Water-Vapor: A Comparison

Comparisons of the total integrated water-vapor from the third generation DIAL instrument have been made against passive measurements of the total precipitable water-vapor (PWV) using SUOMINET and AERONET data. NRB and water-vapor profiles as well as the PWV were collected over a 1.5 day period starting on the morning of 23 April 2011 and are shown in the top and middle parts of Figure 124. From the NRB returns convective mixing can be seen in the PBL late in the daytime as the surface begins to heat up due to solar heating. The PBL begins to decay at night as the atmosphere cools through molecular conduction. The diurnal cycle of the PBL shows a strong correlation with the mountain plains wind system and can be seen from the auxiliary weather station data measured on top of Cobleigh hall as shown in Figure 125.

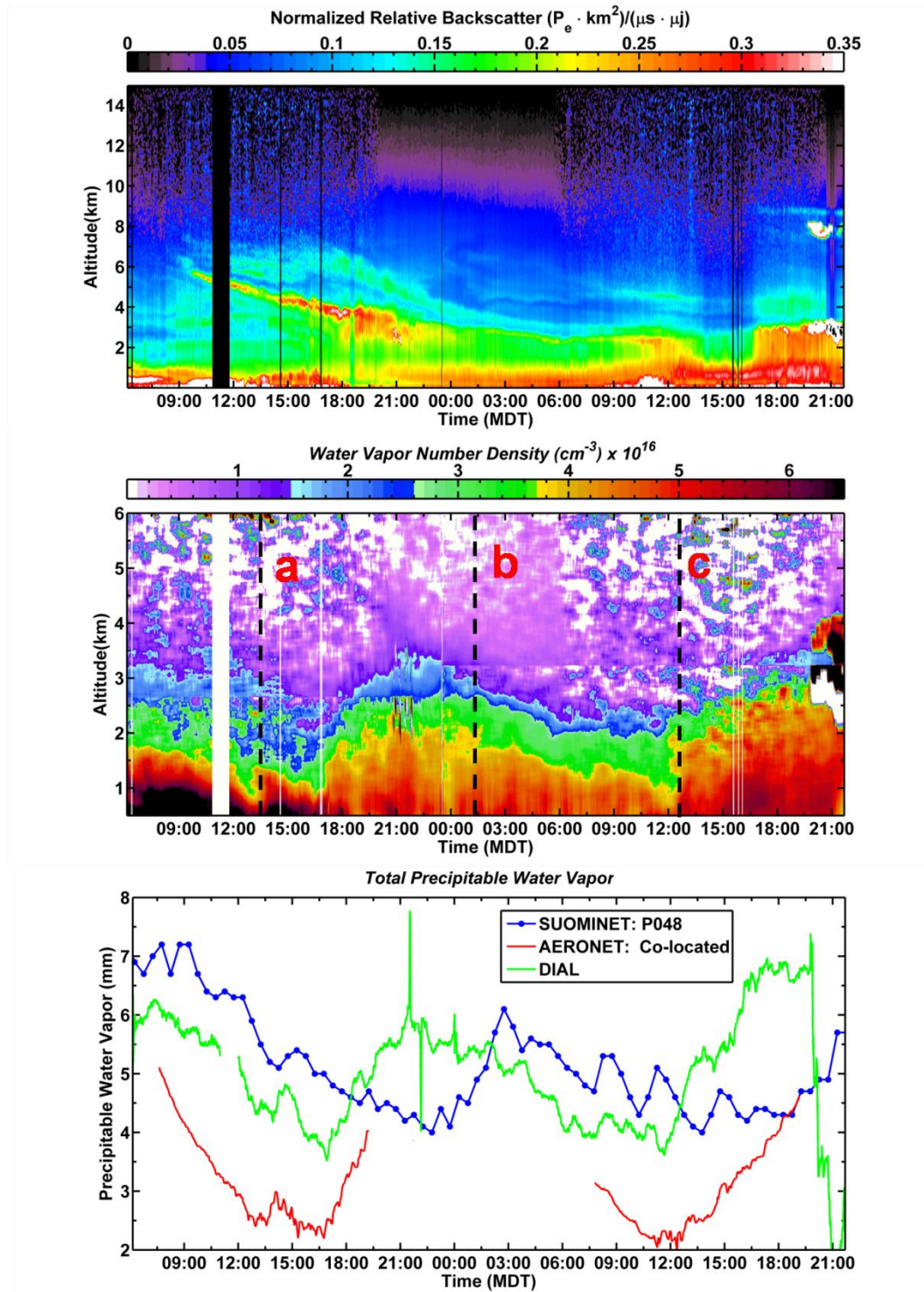


Figure 124 NRB profiles, water-vapor number-density profiles, and total precipitable water-vapor from the DIAL, SUOMINET, and AERONET in the upper, middle, and lower plots, respectively measured over 23-24 April 2011.

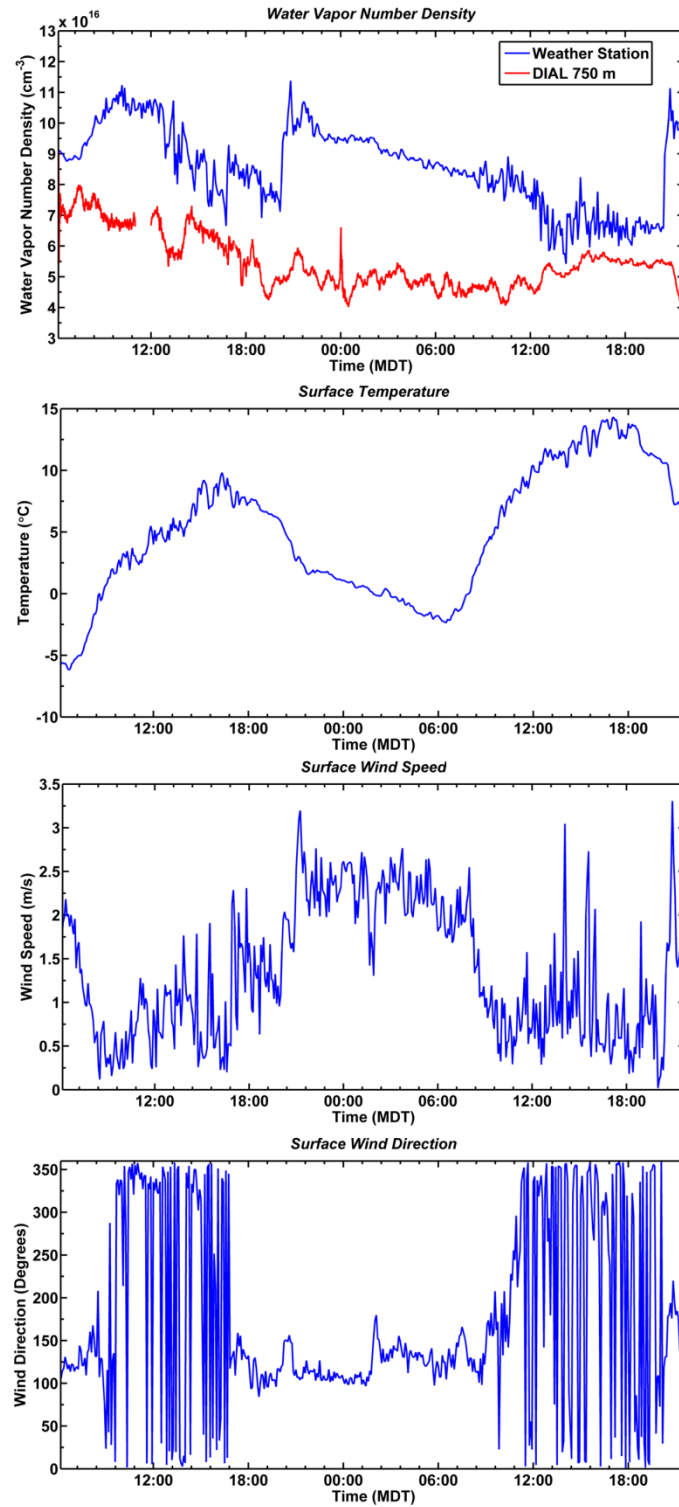


Figure 125 Auxiliary weather station data measured on top of Cobleigh Hall. The water-vapor number-density measured at the initial overlap ~ 0.75 km using the DIAL is also presented in the top figure for reference.

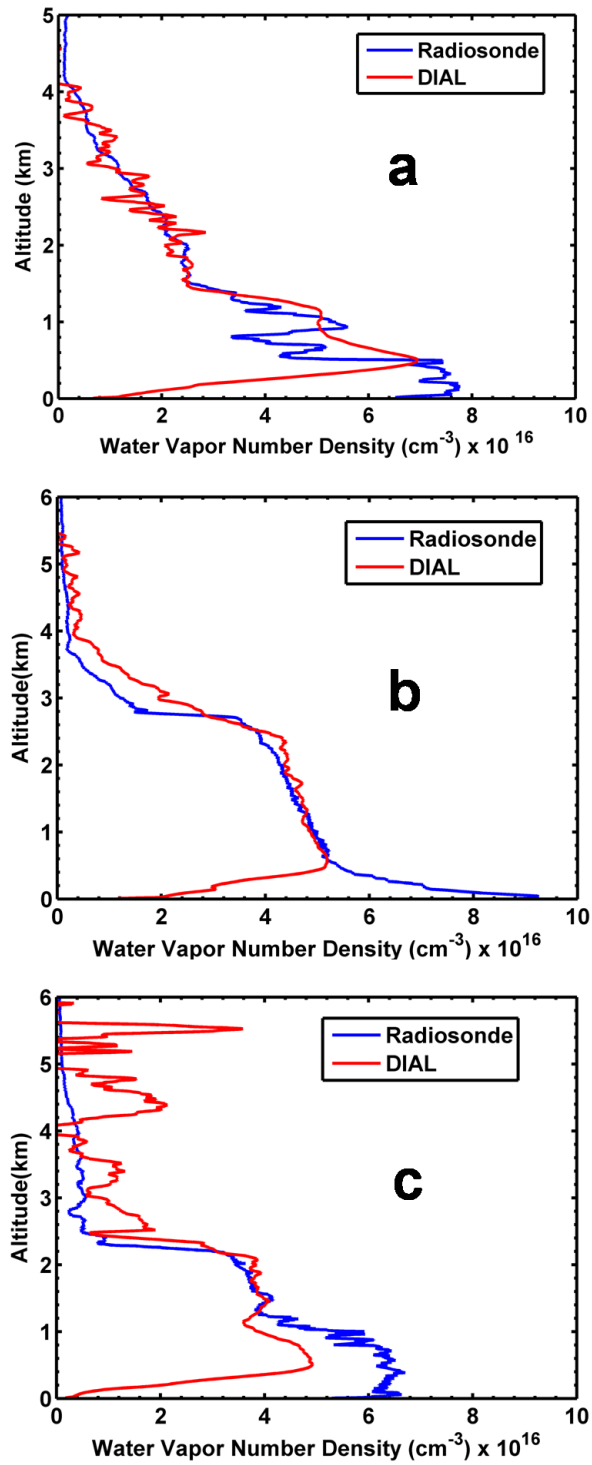


Figure 126 Water-vapor profile comparisons with colocated radiosonde measurements indicated by the three dashed lines marked a, b, and c in the water-vapor time series from Figure 124.

Moistening of the PBL is also evident with the intrusion of the evening easterly down slope winds which begin to mix the aerosols in the lower atmosphere. Three radiosonde weather balloons were launched corresponding to times a, b, and c in the water-vapor time series shown in the middle part of Figure 124. The calibration of all three radiosondes were off by more than 12% at the ground check station during launch, hence no strong conclusions were made about the comparisons with the DIAL measurements which are shown in Figure 126. Moderate agreement between the collocated sonde and the DIAL measurements can be seen in all three cases where the general trends are observed from both independent measurements.

The total PWV was used as another quantity to measure the overall accuracy of the DIAL measurements relative to different well established and mature technologies in the field. The PWV from the MSU NASA solar radiometer AERONET site which is located approximately 0.5 km to the south-east of Cobleigh hall was used as a direct comparison for the total column integrated water content. The total PWV from a SUOMINET (<http://www.suominet.ucar.edu>) GPS receiver station located in Four Corners Montana which is approximately 12 km directly to the west was also used for comparing general trends between AERONET and the DIAL measurements. The PWV measurements from the DIAL as well as the two passive sensors described are shown in the bottom part of Figure 124.

As would be expected, the DIAL measurements underestimate the total PWV compared with the GPS measurements due to the instrument blind region in the near field where a large fraction of the moisture resides. Unexpectedly though the AERONET solar

radiometer measurements of the total PWV read significantly lower than both the DIAL and SUOMINET measurements. Because the solar radiometer makes column integrated retrievals based off of the attenuation of direct sun radiance measurements, all of the AERONET data retrieval algorithms are susceptible to very low AOD conditions where a good measurable signal cannot be obtained. The average AOD measured by AEROENT for 23-24 April 2011 was ~ 0.02 at 870 nm which is at the lower bound of the instruments sensitivity range, hence the dry biased PWV measurements are thought to be attributed to systematic errors resulting from the very low AOD's.

Although dry biased, the DIAL and AERONET measurements of the PWV show very good agreement in the general diurnal/anomalous trends. The trends of the DIAL and AERONET PWV measurements track with the SUOMINET retrievals during the morning and early evening hours where then SUOMINET underestimates the atmospheric water content as measured from the Cobleigh hall area. The dry bias in the afternoons shows a strong correlation with the increase and change in the wind speed and direction shown in Figure 125 which results from the evening easterly down slope winds. Because the GPS receiver is ~ 7 miles directly to the west, it is believed that the effects of the down slope winds in the center of the Gallatin valley are not as strong, hence causing the large discrepancy in the PWV trends between SUOMINET and DIAL/AEROENT.

MP-DIAL-MPL Aerosol Comparison: Design Draw Backs

The third generation DIAL instrument has retrieved nighttime and daytime water-vapor and aerosol profiles under varying atmospheric conditions. Although initial data shows favorable agreement with independent measurements of both range resolved and

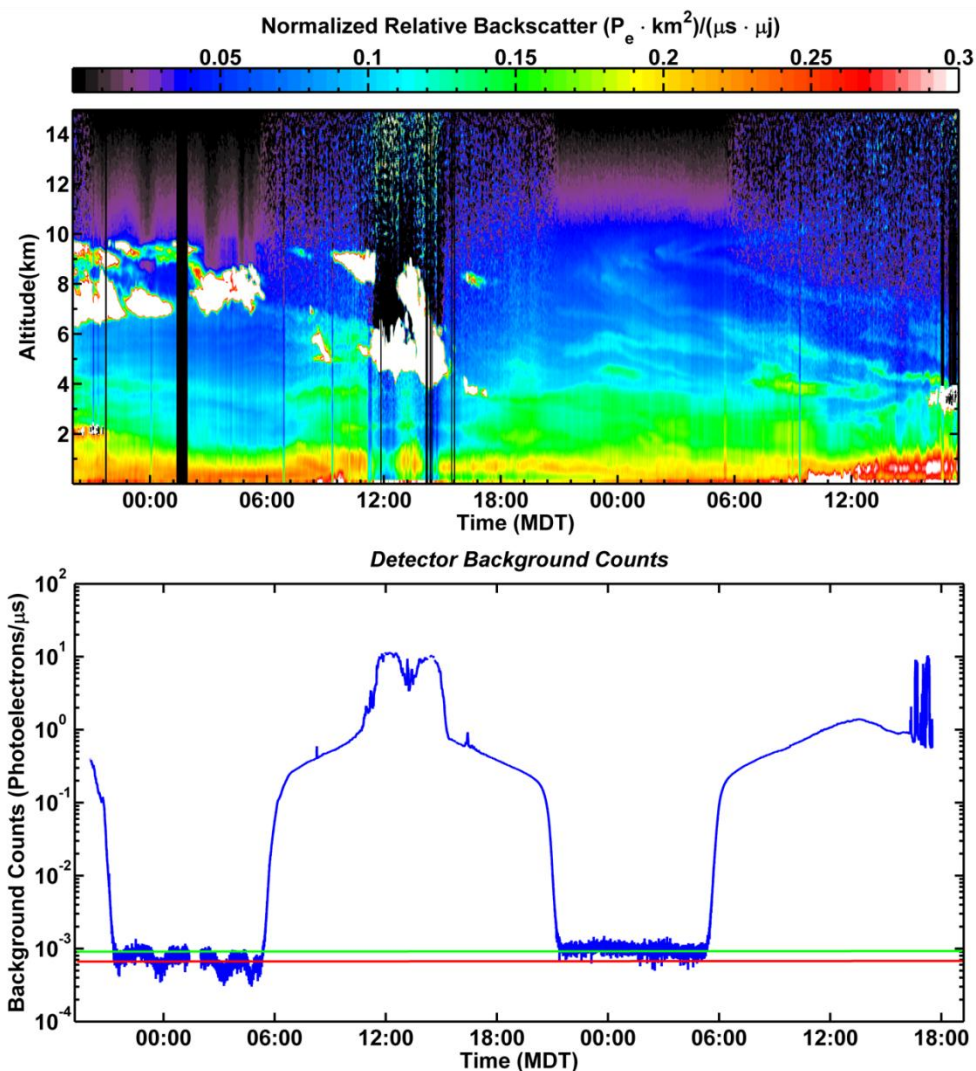


Figure 127 Top) NRB returns collected starting on 10 May 2011. The spectrally bright clouds above the DIAL instrument at $\sim 12:00$ causes artifacts in the backscattered returns due to the saturation of the APD detector. Bottom) The background measurements for the NRB returns shown above. The influence of the bright clouds at $\sim 12:00$ on 11 May 2011 and $\sim 17:00$ on 12 May 2011 can be seen where the daytime background increases from ~ 1 MHz to greater than 10 MHz, causing the detector to go into complete saturation.

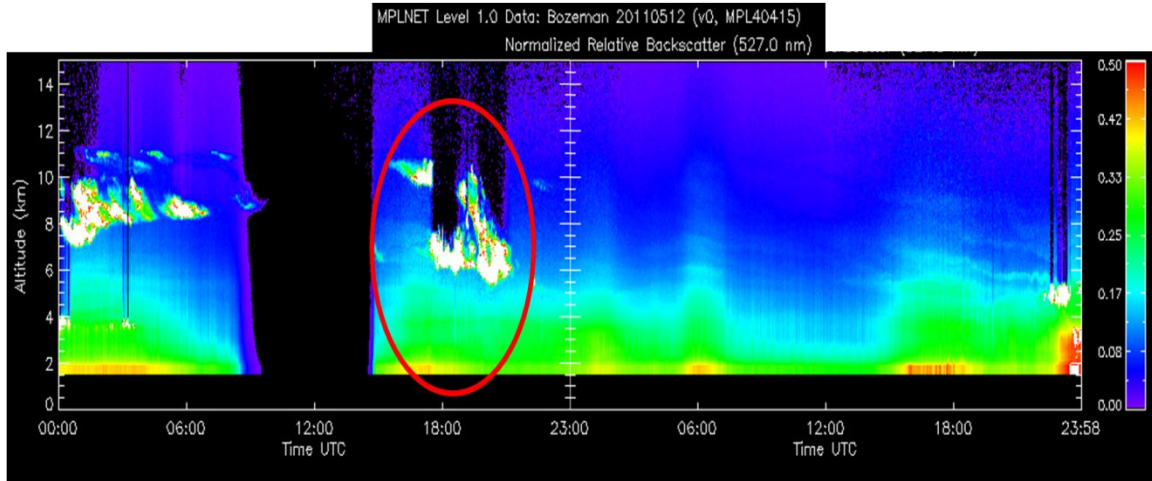


Figure 128 NRB returns from a collocated MPL instrument shown in UTC time. The red circled area corresponds to the bright clouds seen with the DIAL instrument at ~ 12:00 MDT shown in Figure 127. Because of the uniaxial design of the MPL, full overlap is not achieved until ~ 3-4 km. The void in the data at 12:00 UTC is due to frost on the MPL housing window.

column integrated water-vapor, the third generation DIAL is still not able to accurately profile aerosols and water-vapor in the presence of daytime spectrally bright clouds that cause the APD detector to go into saturation. An example of this is shown in Figure 127 where NRB and background measurements were collected from 10-12 May 2011 under varying atmospheric conditions. NRB returns from a collocated commercially purchased MPL instrument are also shown in

Figure 128. Comparing the NRB returns from the two instruments shows that the DIAL outperforms the MPL during nighttime and clear sky conditions where finer structure in the aerosol and sub visual cloud returns can be seen at higher altitudes.

Although the FOV of the two instruments are almost identical, the influence of the daytime background noise is greater for the DIAL. The sensitivity of the DIAL instrument to daytime background noise can be seen where the background counts at ~

12:00 on 11 May 2011 significantly increase in the presence of bright clouds, causing the detector to go into saturation. The saturation effect results in under sampling the aerosol returns up to the cloud base causing artifacts in the NRB returns. The same saturation behavior is not seen in the MPL instrument in the presence of bright clouds and is attributed to the robust receiver design

The MPL receiver field stop consists of a 200 μm pinhole placed at the focus of a ~ 2.0 m focal length f/10 telescope. The hard pinhole field stop ensures that the full angle FOV of 100 μrad is maintained in the receiver. On the other hand, the third generation DIAL utilizes a 105 μm core fiber optic cable at the back end of the receiver optical train as the system field stop. The fiber optic cable has a 150 μm diameter glass cladding region which can guide light to the APD that is trapped between the core and the outer buffer region and effectively increase the system FOV. The coupling of the daytime background light into the cladding mode of the fiber optic cable is thought be the primary reason for the degradation of the instrument performance in the presence of daytime spectrally bright clouds. This drawback can be solved by placing a pinhole at the telescope focus which will act as the system field stop.

Ending on a positive note, the analysis of the instrument nighttime background noise shown in Figure 127 indicates that the increase in the output pulse energy of the third generation DIAL transmitter has allowed for measurable offline signals at 15 km with relatively short integration periods. The DIAL background measurements are calculated at the end of each set of returns where the signal from ~ 14.5 -15 km is assumed to be 100 % extinct and the measured signal is due to primarily to background

noise. The red and green lines shown in Figure 127 indicate the background levels during cloud and clear sky nighttime conditions, respectively. The increase in the clear sky nighttime background counts indicates that lidar offline returns from 14.5-15 km are actually measured and being used as an indication of the background signal level. During cloudy conditions such as the first part of the data set shown in Figure 127, the laser light is completely extinct and the measured signal from 14.5-15 km is attributed to background noise, hence the apparent nighttime background noise decreases in the presences of optically thick clouds. This is considered to be a good problem to have and future solution would most likely entail the decrease of the transmitter PRF to increase the maximum range of the instrument to ~ 20 km.

CONCLUSIONS

Two compact, eye-safe DIAL instrument were developed to demonstrate the for the first time ever the feasibility of using low pulse energy high PRF all diode based laser based transmitters for measuring daytime and nighttime tropospheric water-vapor and aerosol profiles. A first generation DIAL instrument based on commercially available cw TSOA's was described in Nehrir (2008). The transmitter was passively pulsed yielding ~ 150 nJ pulses over a $1 \mu\text{s}$ pulse duration at a 20 kHz PRF, yielding nighttime water-vapor profiles that showed good agreement with radiosonde measurements up to ~ 2.5 with 1 hour averaging times. The main goal of this project was the implementation of custom built TSOA's to increase the output pulse energies, decrease the transmitter footprint, and to decrease the required averaging time needed for lower tropospheric water-vapor retrievals.

The second generation DIAL instrument utilized a single Littman-Metcalf configured ECDL as the seed source for a MOPA configured transmitter. A preamplifier stage TSOA was used to increase the cw output power of the seed laser in order to saturate the gain of a second actively current pulsed 3.0 mm length TSOA which was used as the output of the DIAL transmitter. The second generation transmitter produced up to $2 \mu\text{J}$ pulse energies over a $1 \mu\text{s}$ pulse duration at a 20 kHz PRF. The increase in the output power allowed for nighttime and daytime water-vapor profiling up to ~ 4.5 and 2.5 km, respectively. Aerosol retrievals were completed based on an iterative Fernald solution to the lidar equation that allowed for classification and radiative impacts of different aerosol types based on the retrieved aerosol optical properties.

A third generation DIAL instrument was developed to overcome the limitation of the slow spectral switching time of the second generation DIAL instrument. Two high powered Littrow configured ECDL's were designed and built as the dedicated online and offline seed sources for the DIAL transmitter. A fiber coupled optical switch was used to decrease the atmospheric spectral sampling time between the online and offline wavelengths such that water-vapor retrievals could be made in the presence of clouds and heterogeneous aerosol layers. The spectrally varying output from the switch was used to seed a single actively current pulsed 4.00 mm length TSOA chip, yielding up to 7 μJ pulse energies over 1 μs pulse durations at a 10 kHz PRF. Water-vapor profiles from the third generation DIAL instrument showed good nighttime and daytime agreement with collocated radiosonde measurements from near the surface up through the PBL. Column integrated PWV retrieved from the DIAL also compared favorably with column integrated measurements obtained from nearby AERONET and SUOMINET sites.

Aerosol s retrievals were also completed based on the iterative Fernald approach where the increase in the transmitter pulse energy allowed for aerosol and cloud monitoring up to the tropopause, $\sim 10\text{-}15$ km. The compact design of the third generation transmitter allowed for the integration of a commercially available full-sky-scanning tripod mount into the system. This allowed for horizontal and slant path measurements of boundary layer aerosols and water-vapor. The transmitter spectral purity which was previously unknown was measured using horizontal hard target returns to be greater than 99.96 %. The receiver overlap function which was also previously unknown was

measured using horizontal backscattered returns which allowed for the extension of the offline aerosol retrievals to the ground.

Future Work

Although successfully demonstrating nighttime and daytime water-vapor and aerosol retrievals, the performance of the third generation DIAL instrument can be greatly improved by addressing several key points. 1) For full-time autonomous operation, fiber coupled DFB laser diodes would be needed to replace the two ECDL's which would decrease the temperature sensitivity of the seed lasers to spectral mode hops. 2) In order to field harden the instrument for rapid deployment and minimize the effects of mechanical shock, the input stage to the pulsed TSOA would need to be fiber coupled similar to that of butterfly packaged laser diodes. This would also significantly decrease the footprint of the DIAL transmitter as all of the lasers would be fiber coupled, hence allowing for the transmitter size to approach $\sim 4'' \times 4''$ and allow for easy and rapid deployment. 3) Decrease the size of the receiver telescope to $\sim 8\text{-}10''$ diameter in order decrease the initial overlap range for the DIAL retrievals. The relocation of the field stop to the focus of the telescope would also significantly decrease the effects of background noise at the APD detector. 4) Although the inline design of the third generation DIAL transmitter minimized the pointing error of the transmitted beam with changes in the ambient temperature, the inclusion of quadrature detector measurement using a four section pie shaped fiber bundle in the receiver and 4 APD detectors would allow for long term active alignment of the transmit beam to the receiver optical axis. 5) Decrease the

MCSC buffer read/write dead time to increase the measurement duty cycle. This will most likely involve reverse engineering the current Sigma Space MCSC digital counter or programming a digital counter from scratch on an FPGA board. Taking into account the modifications state above, the development of a next generation DIAL instrument could be a viable candidate for an autonomous full-time lidar as a part of a multi-point network of active remote sensing instruments for weather and climate forecasting applications.

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APPENDICES

APPENDIX A

ACRONYMS

Acronym	Description	First Used
AERONET	Aerosol Robotic Network	116
AIRS	Atmospheric Infrared Sounder	8
AOD	Aerosol Optical Depth	95
APC	Angled Physical Contact	161
APD	Avalanche Photodiode	68
APP	Anamorphic Prism Pair	47
AR	Anti-Reflection	48
ASE	Amplified Spontaneous Emission	48
CCN	Cloud Condensation Nuclei	7
COTS	Commercial Off The Shelf	10
CW	Continuous Wave	16
DBR	Distributed Bragg Reflector	16
DFB	Distributed Feedback	16
DIAL	Differential Absorption Lidar	9
ECDL	External Cavity Diode Laser	16
FAA	Federal Aviation Administration	124
FAR	Fourth Assessment Report	6
FC	Fiber Connector	74
FOV	Field of View	18
FPGA	Field Programmable Gate Array	80
FSR	Free Spectral Range	140
FWHM	Full Width Half Maximum	30
GPIB	General Purpose Interface Bus	80
GPS	Global Positioning System	199
GRIN	Gradient Index Lens	69
GUI	Graphical User Interface	193
HALOE	Halogen Occultation Experiment	8
HITRAN	High Resolution Molecular Transmission	12
HR	High Reflective	139
HWHM	Half Width Half Maximum	28
HWP	Half Wave Plate	52
IPCC	Intergovernmental Panel on Climate Change	6
LASE	Lidar Atmospheric Sensing Experiment	75

LIDAR	Light Detection and Ranging	8
MCSC	Multi-Channel Scaler Card	80
MIPAS	Michelson Interferometer for Passive Atmospheric Sounding	8
MODIS	Moderate Resolution Imaging Spectrometer	120
MODTRAN	Moderate Resolution Atmospheric Transmission	13
MOPA	Master Oscillator Power Amplifier	57
MPE	Maximum Permissible Energy	64
MPLNET	Micro-Pulse Lidar Network	199
NA	Numerical Aperture	69
NBF	Narrow Band Filter	18
NIR	Near Infrared	14
NRB	Normalized Relative Backscatter	197
OD	Optical Depth	25
PBL	Planetary Boundary Layer	1
PBS	Polarizing Beam Splitter	53
PI	Power vs Current	138
PM	Polarization Maintaining	161
PMT	Photomultiplier Tube	68
PRF	Pulse Repetition Frequency	62
PWV	Precipitable Water Vapor	212
PZT	Piezo Electric Transducer	45
RF	Radio Frequency	160
RH	Relative Humidity	92
SMSR	Side Mode Suppression Ratio	151
SNR	Signal to Noise Ratio	16
TEC	Thermoelectric Cooler	45
TSOA	Tapered Semiconductor Optical Amplifier	10
UTLS	Upper Troposphere Lower Stratosphere	8
UV	Ultra Violet	2

APPENDIX B

TSOA COLLIMATION

Collimation of the Tapered Amplifier System

From the manufacture's data, the input and output aperture of the gain region is 3 μm and 190 μm respectively. We assume the index of refraction of the gain medium $n_1 \approx 3$ and index of the refraction of the air is $n_2 = 1$.

Figure B-1 is the top view of the tapered amplifier diode. From the basic geometry, $\theta_1 = \tan^{-1}(\frac{190/2}{2750}) = 1.978^\circ$. Then from the Snell's law $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$,

we have $\theta_2 = \sin^{-1}[\frac{n_1 \sin(\theta_1)}{n_2}] = 5.9^\circ$ or $2\theta_2 = 11.8^\circ$ and $h_1 = \frac{190/2}{\tan(\theta_2)} = 912.3 \mu\text{m}$. The

manufacture's data shows the parallel divergence angle is 7-13°, which is consistent with our calculation of 11.8°. The perpendicular divergence angle from the datasheet is approximately 28°. Since these two divergent angles differ a lot, it is impossible to collimate the beam with just one spherical lens. An extra cylindrical lens is needed after the spherical lens.

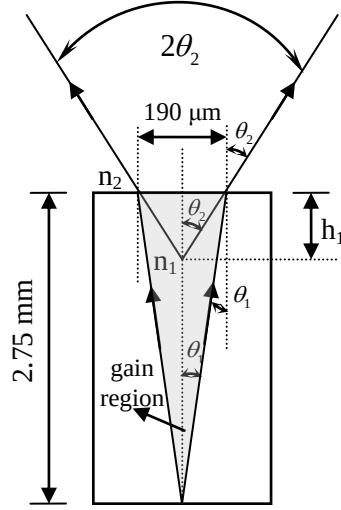


Figure B-1. The top view of the tapered amplifier diode. The shadowed area represents the gain region. The parallel divergent angle is approximately 11.8° .

1. Collimating the Divergent Beam in the Perpendicular Direction

A spherical lens with $f_s = 4.5 \text{ mm}$ was chosen to collimate the perpendicular divergent beam first. The height of the gain region is not given from the datasheet, but based on the single slit diffraction limit, we assume the height is about 2.4 μm , which is comparable with the input aperture, but much smaller than the output aperture in the parallel direction. The spherical lens is positioned approximately 4.5 mm away from the output aperture. The perpendicular divergent angle as shown in figure B-2 is 28° and we can calculate the collimated beam radius $R_l = 4.5 \times \tan(14^\circ) = 1.122 \text{ mm}$ based on simple geometry.

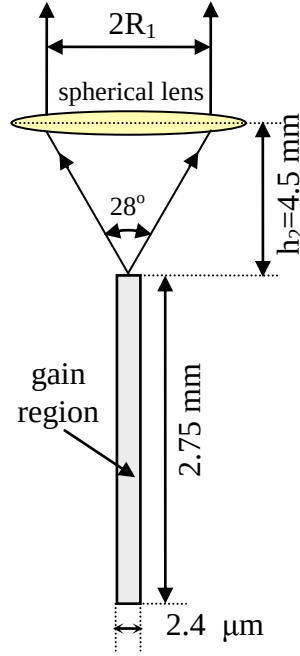


Figure B-2. The side view of the tapered amplifier diode. A spherical lens with focal length of 4.5 mm is used here to collimate the perpendicular divergent beam. The resulting collimated beam radius is 1.122 mm.

2. Collimating the Divergent Beam in the Parallel Direction

Now we need to collimate the divergent beam in the parallel direction to the same size as in the perpendicular direction. Unlike the perpendicular one, after a spherical lens, the beam does not collimate as shown in figure B-3, so an extra cylindrical lens is placed after the spherical lens.

From the earlier discussion, we know $h_1 = 912.3 \text{ }\mu\text{m}$, $h_2 = 4.5 \text{ mm}$ and

$f_s = 4.5 \text{ mm}$. The Gaussian Lens Formula $\frac{1}{(h_1 + h_2)} + \frac{1}{h_3} = \frac{1}{f_s}$ gives $h_3 = 26.703 \text{ mm}$.

Based on the figure B-3, $R_3 = (h_1 + h_2) \tan(\theta_2) = 1.121 \text{ mm}$ and $\frac{R_3}{R_1} = \frac{h_3}{h_4}$, then

$h_4 = 52.537 \text{ mm}$, which also should be focal length of the cylindrical lens $f_c = 52.537 \text{ mm}$.

3. Summary of the Collimating the Tapered Amplifier Output Beam

In order to collimate the output beam from the tapered amplifier diode, we need to put a spherical lens ($f_s = 4.5 \text{ mm}$) 4.5 mm away from the diode and a cylindrical lens ($f_c = 52.537 \text{ mm}$) 7.9 cm after the special lens. With these parameters, the final collimated beam radius is 1.122 mm.

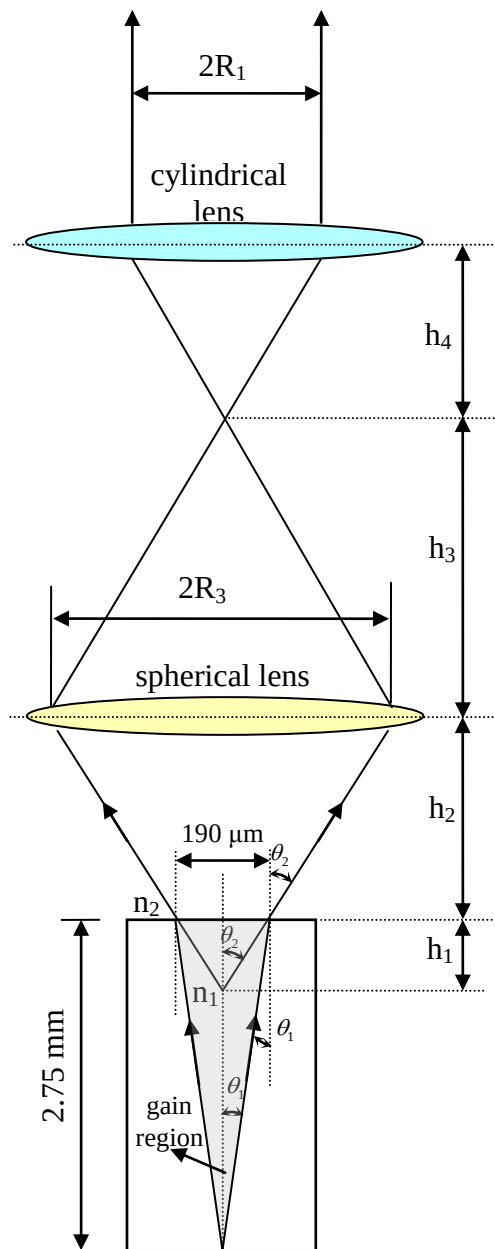


Figure B-3. Optical design of how to collimate the parallel divergent beam.

APPENDIX C

APD SPECIFICATIONS

Table 1. Specifications SPCM-AQR-WX at 22°C, all models, unless otherwise indicated

Parameter	Minimum	Typical	Maximum	Units
Supply current		0.5	1.9	Amps
Supply voltage: (1)	4.75	5.0	5.25	V
PerkinElmer power cable total resistance		0.2		Ω
Case operating temperature (1.3)	5	40		°C
Active area (diameter) at minimum Pd	170	175		μm
Photon detection efficiency (Pd) at 400 nm	2	5		%
650 nm	50	65		%
830 nm	35	45		%
1060 nm	1	2		%
Pd variation at constant case temperature (2hrs at 25°C)		± 1	± 3	%
Pd variation 5°C to 40°C		± 4	± 10	%
Dark count (4,5,6) = SPCM-AQR-12		—	500	Counts/Sec.
SPCM-AQR-13		—	250	Counts/Sec.
SPCM-AQR-14		—	100	Counts/Sec.
SPCM-AQR-15		—	50	Counts/Sec.
SPCM-AQR-16		—	25	Counts/Sec.
Average dark count variation at constant case temperature (6hrs at 25°C) for (4,5,6); SPCM-AQR-12 & 13			± 10	%
SPCM-AQR-14 & 15 & 16			± 1	σ
Average dark count variation at 5°C to 40°C case temperature for (4,5,6); SPCM-AQR-12 & 13			± 20	%
SPCM-AQR-14 & 15 & 16			± 2	σ
Single photon timing resolution		Contact factory for availability		
Dead time (Count rates below 5 Mc/s)		50	60	ns
Output count rate before saturation	10	15		Mc/s
Linearity correction factor: (7) at 200 kc/s		1.01		
at 1 Mc/s		1.08	1.15	
at 5 Mc/s		1.40	1.67	
Afterpulsing probability		0.5		%
Settling time following power up (1% stability) at 1 meg counts/sec and 25°C		15	30	s
Threshold setting required on counter for digital output pulse (terminate in 50 Ω)	0.75	1.0	2.0	V
Output pulse width		35		ns
Gating turn on/off: (50 Ω output)				
Disable = TTL Low		2	4	ns
Enable = TTL High		45	55	ns
Gating threshold voltage: (at V supply = 5 V)				
Low level (sink current >90mA)		0	0.4	V
High level (sink current >30mA)		3.5	5.25	V

Table 2. Absolute maximum ratings

Supply voltage (1)	5.5 V
Mean count rate	5 Mc/s (Above this point, dead time will increase due to diode self-heating)
Peak light intensity	10 ⁴ photons per pulse and pulse width less than 1 ns.
Case temperature (3)	50°C storage, 40°C operating

Operating instructions

1. Connection to incorrect voltage or reverse voltage may destroy the module. The warranty is invalid where such damage occurs.
2. These modules are not qualified for shock or vibration other than normal instrumentation environments.
3. The module dissipates a mean power of 2.5W and a maximum power of 6.5W at high count rate and 40°C. Adequate heat sinking must be provided by clamping the module to a suitable heat sink via the holes in the module base. For the specification performance, the module case temperature must not exceed 40°C.
4. Bi-stability of the dark count:
On a small percentage of delivered modules, bi-stability of the dark count has been observed. Research indicates this bi-stability is probably due to transitions at a single impurity site between a low energy and a high energy state. The phenomenon is seen as an abrupt change in the dark count rate, e.g., 350 to 390 c/s., and the dark count switches between the two states at a rate dependent upon the detector temperature. Multilevel switching has also been observed, where more than one impurity site is switching.
5. Long-term bi-stability is related to fundamental semiconductor physics and is beyond PerkinElmer's control. Warranty claims will not be considered against bi-stability alone. Warranty claims will only be considered if the high level of the dark count exceeds the maximum level in the specification.
6. In the dark, the module generates random counts that follow a Poisson distribution. In a Poissonian process, the standard deviation is equal to the square root of the average count. In this specification the "dark count variation" refers to the stability of the average count of the module.
7. The actual photon rate could be calculated using the following equation, as indicated below:

$$ACTUALCOUNTRATE_{Photons} = \frac{(OUTPUT_{ModuleCountRate} \times CORRECTIONFACTOR @ the Module CountRate) - DARK COUNT Module}{PHOTON DETECTION EFFICIENCY Module}$$

The theoretical value, at low count rate, of the Correction Factor follows this equation:

$$Correction Factor = \frac{1}{1 - (t_d \times C_R)} \quad \text{Where: } t_d = \text{Module Dead Time}$$

$$C_R = \text{Output Count Rate}$$

The deviation from an ideal linear system is another way of looking at the saturation effect. The following equations show how to calculate this departure from the linearity:

$$LINEARITY = \left[\frac{OUTPUT_{ModuleCountRate}}{(PHOTONS_{Actual Count Rate} \times PHOTON DETECTION EFFICIENCY Module) + DARK COUNT Module} \right]^{-1}$$

$$= \left[\frac{1}{Correction Factor} \right]^{-1}$$

Figure 1. Block diagram of module

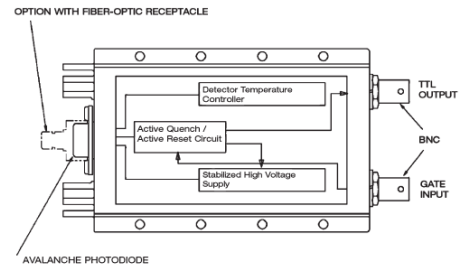


Figure 2. Electrical connections

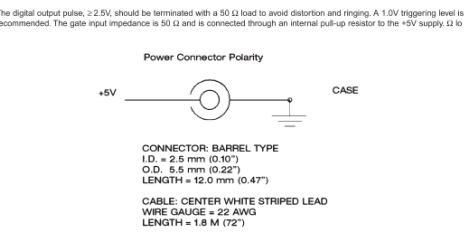


Figure 3. Detector scan

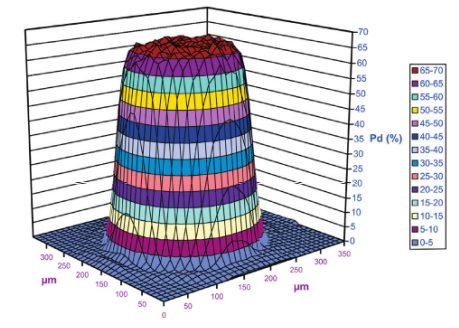


Figure 4. Photon detection efficiency (pd) vs. wavelength

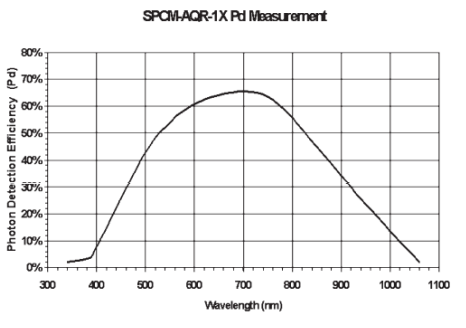


Figure 5. Typical afterpulse probability

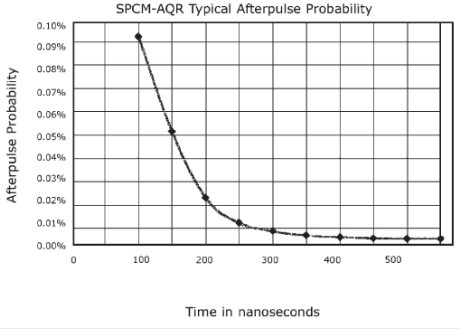


Figure 6. Typical correction factor

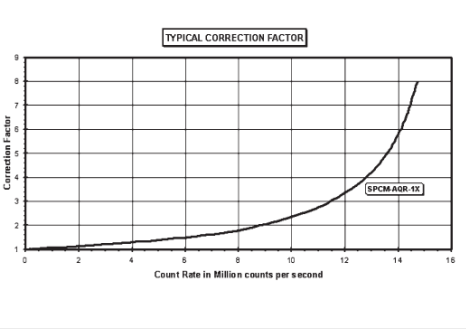


Figure 7. Dimensional Outline

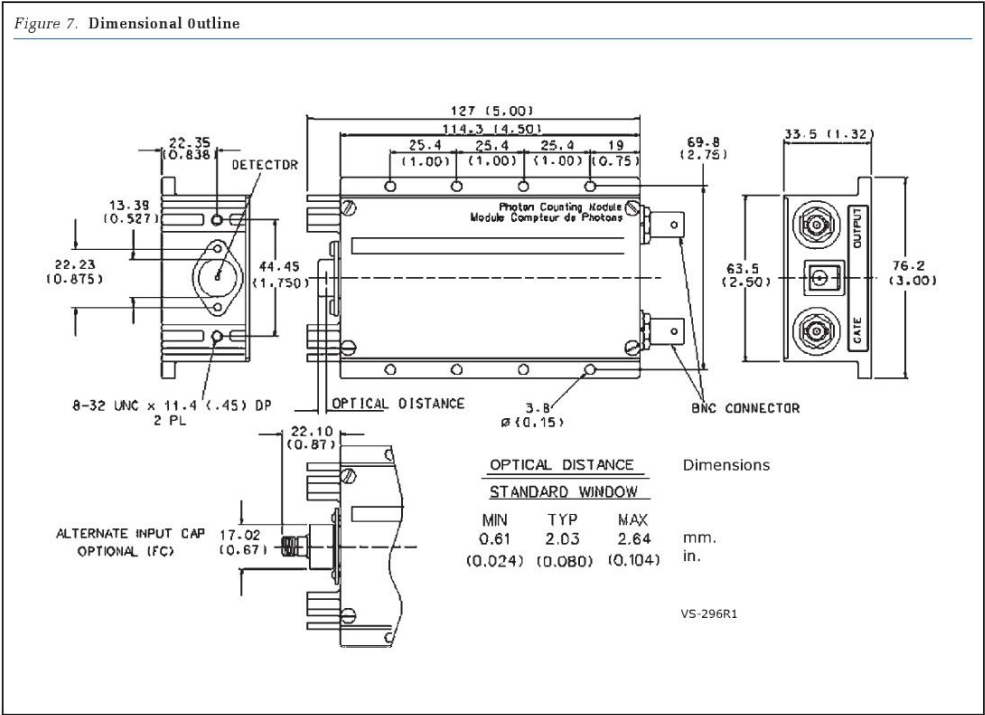
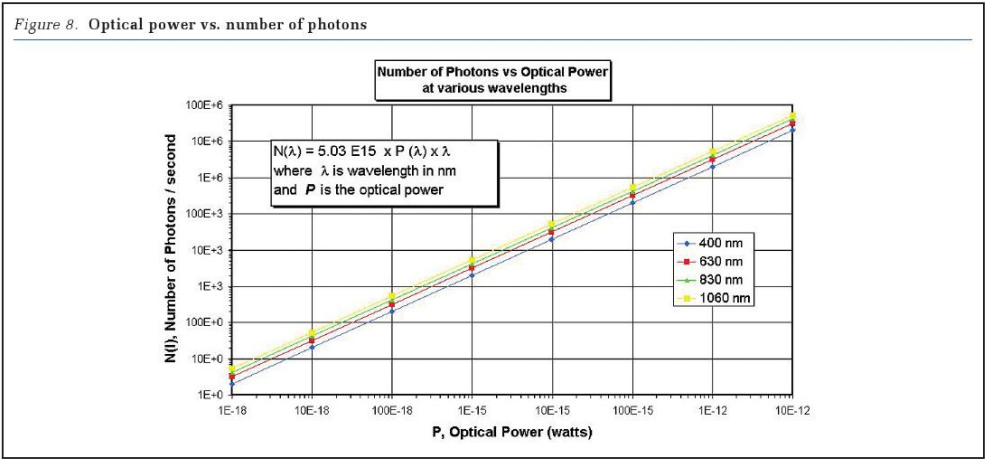


Figure 8. Optical power vs. number of photons



APPENDIX D

TELESCOPE FIELD OF VIEW CALCULATIONS

For a given laser transmitter beam diameter D_t and full angle divergence θ at the ground, the beam diameter at an altitude z has a diameter

$$D_z = D_t + \tan \theta \cdot z \approx D_t + \theta \cdot z \quad (5.18)$$

for small angles. The spot illuminated at an altitude z from the laser transmitter subtends an angle

$$\Phi = \frac{D_z}{z}. \quad (5.19)$$

At a distance ν behind the telescope primary mirror, the image of the spot also subtends the same angle

$$\Phi = \frac{D_i}{\nu}, \quad (5.20)$$

where the image diameter D_i is expressed as

$$D_i = \frac{\nu D_z}{z}. \quad (5.21)$$

If the receiver telescope is modeled as a single element refractor, the thin lens approximation can be used where the image distance ν can be related to z by

$$\frac{1}{z} + \frac{1}{\nu} = \frac{1}{f}, \quad (5.22)$$

where f is the telescope focal length. Rearranging and solving for ν yields

$$\nu = \frac{zf}{z - f}, \quad (5.23)$$

where for large values of z , $\nu = f$. Combining equations (5.18), (5.21), and (5.23), the image diameter at the telescope focal plane can be expressed as

$$D_i = \frac{(D_t + z\theta) f}{(z - f)}. \quad (5.24)$$

If z is large compared to f , the image size at the focus is approximated as

$$D_i \approx f \left(\frac{D_t}{z} + \theta \right), \quad (5.25)$$

where for very large values of z ,

$$D_i \approx f\theta. \quad (5.26)$$

For large values of z where $\nu \rightarrow f$, a fiber with diameter D_f at the telescope focus will capture the image of the far field illuminated spot if $D_f \geq D_i$ and $NA_{fiber} \geq NA_{telescope}$. Conversely, if the fiber core diameter is known, for a given illuminated spot at an altitude z , then the full angle FOV is given by

$$\theta_{fullangle} = \frac{D_{fiber}}{f_{telescope}} \quad (5.27)$$

APPENDIX E

DIAL ERROR ANALYSIS

The precision of the DIAL retrievals can be determined by propagating the independent errors for each signal (online and offline) over adjacent range bins (R to $R+\Delta R$). The total number of photoelectrons N_t created by an APD for any elastic direct-detection lidar system is

$$N_t = N_s + N_b + N_{dc}, \quad (5.28)$$

where N_s , N_b , and N_{dc} are the photon counts due to the backscattered signal, the solar background and leakage light, and the detector dark counts, respectively. The total photocurrent measured after amplification resulting from impact ionization (McIntyre 1966) is given by

$$I_t = (N_s + N_b + N_{dc}) B e \eta G + I_{dc,0}, \quad (5.29)$$

where B , e , η , and G are the detector bandwidth, electron charge, quantum efficiency, and detector gain factor, respectively. $I_{dc,0}$ is the unamplified dark current resulting from surface leakage current. The SLiK APD used in the DIAL receiver is integrated into a commercially purchased photon counting module with back end electronics that allow for photon counting via thresholding and active quenching circuitry, hence the raw photocurrent from the APD is not directly sampled. The output signal from the Geiger mode APD resulting from a measurable signal is comprised of TTL pulses corresponding to photoelectrons created at the detector junction as well as intrinsic APD dark counts, and these will be the measurable quantities used in the DIAL error analysis. Taking into account the measured backscattered signal at the online and offline wavelengths between adjacent range bins, the propagation of the uncorrelated errors due to background noise in

the DIAL retrievals resulting in an rms error Δn of the water-vapor number-density n_{H_2O} is given as (Wulfmeyer & Walther 2001)

$$\begin{aligned} \Delta n = & \left[\frac{1}{(2\sigma\Delta R)} \left\{ \frac{1}{(mk)^2} \sum_{i=1}^m \sum_{j=1}^k \left[\frac{\Delta I_{s,on,j}(R_{1,i})}{I_{s,on,j}(R_{1,i})} \right]^2 \right. \right. \\ & + \frac{1}{(mk)^2} \sum_{i=1}^m \sum_{j=1}^k \left[\frac{\Delta I_{s,on,j}(R_{2,i})}{I_{s,on,j}(R_{2,i})} \right]^2 \\ & + \frac{1}{(mk)^2} \sum_{i=1}^m \sum_{j=1}^k \left[\frac{\Delta I_{s,off,j}(R_{1,i})}{I_{s,off,j}(R_{1,i})} \right]^2 \\ & \left. \left. + \frac{1}{(mk)^2} \sum_{i=1}^m \sum_{j=1}^k \left[\frac{\Delta I_{s,off,j}(R_{2,i})}{I_{s,off,j}(R_{2,i})} \right]^2 \right\} \right]^{\frac{1}{2}}. \end{aligned} \quad (5.30)$$

The i and j subscripts denote averaging over m bins and k sample times, respectively.

R_1 and R_2 represent adjacent range bins over which the DIAL measurement is calculated.

ΔI_s is the measurement error resulting from uncorrelated contributions from the background noise in the measurement I_s . Assuming the measured signal is sufficiently averaged in space and time, I_s can be replaced by its a mean and is given by

$$I_{s,j}(R_{1,2,i}) = \overline{I_s(R_{1,2})}. \quad (5.31)$$

Furthermore, assuming that the range bins are sufficiently small, the signal can be approximated as

$$\overline{I_s(R)} = \frac{[\overline{I_s(R_1)} + \overline{I_s(R_2)}]}{2} \approx \overline{I_s(R_1)} \approx \overline{I_s(R_2)}. \quad (5.32)$$

If the sum over $[\Delta I_{s,j}(R_i)]^2$ is replaced by the variance $\sigma_{I_s}^2 = \Delta I_s^2$, the relative error in the water vapor number density measurement due uncorrelated background noise is given as

$$\frac{\Delta_n}{n} \approx \left(\frac{2}{mk} \right)^{1/2} \frac{1}{2\Delta\tau} \left[\left(\frac{\sigma_{I_{s,on}}(R)}{I_{s,on}} \right)^2 + \left(\frac{\sigma_{I_{s,off}}(R)}{I_{s,off}} \right)^2 \right]^{1/2}, \quad (5.33)$$

where τ is the bin optical depth.

Systematic errors introduced in the DIAL equation resulting from the slow spectral switching time are difficult to extract from the backscattered signal and are considered to be negligible in the presence of a well mixed atmosphere. Doppler broadening of the backscattered DIAL returns have also been shown to introduce errors in the DIAL retrievals of water vapor profiles (Ansmann 1985; Wulfmeyer & Walther 2001). The spectral broadening of the scattered light at the online wavelength can decrease the spectral purity of the measurement and introduce errors in the water vapor profiles. Although a narrow FOV was designed for the DIAL receivers to eliminate the possibility of multiple scattering events, the effects of Rayleigh Doppler-broadening at the online wavelength can still introduce errors in the DIAL measurements. A Rayleigh model can be used to estimate the Doppler-broadening of the backscattered returns, but an absolute measurement is difficult to make and is beyond the scope of the study.

APPENDIX F

SOLIDWORKS DRAWINGS

