WATER VAPOR PROFILING USING A COMPACT WIDELY TUNABLE DIODE LASER DIFFERENTIAL ABSORPTION LIDAR (DIAL)

by

Amin Reza Nehrir

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering

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Dr. Kevin S. Repasky

Approved for the Department of Electrical and Computer Engineering

Dr. Robert C. Maher

Approved for the Division of Graduate Education

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Atmospheric water vapor is an important driver of cloud formation, precipitation, and cloud microphysical structure. Changes in the cloud microphysical structure due to the interaction of aerosols and water vapor can produce more reflective clouds, resulting in more incoming solar radiation being reflected back into space, leading to an overall negative radiative forcing. Water vapor also plays an important role in the atmospheric feedback process that acts to amplify the positive radiative forcing resulting from increasing levels of atmospheric CO$_2$. In the troposphere, where the water vapor greenhouse effect is most important, the situation is harder to quantify. A need exists for tools that allow for high spatial resolution range resolved measurements of water vapor number density up to about 4 km. One approach to obtaining this data within the boundary layer is with the Differential Absorption Lidar (DIAL) that is being developed at Montana State University.

A differential absorption lidar (DIAL) instrument for automated profiling of water vapor in the lower troposphere has been designed, tested, and is in routine operation. The laser transmitter for the DIAL instrument uses a widely tunable external cavity diode laser (ECDL) to injection seed two cascaded semiconductor optical amplifiers (SOA) to produce a laser transmitter that accesses the 824-841 nm spectral range. The DIAL receiver utilizes a 28-cm-diameter Schmidt-Cassegrain telescope, an avalanche photodiode (APD) detector, and a narrow band optical filter to collect, discriminate, and measure the scattered light. A technique of correcting for the wavelength-dependent incident angle upon the narrow band optical filter as a function of range has been developed to allow accurate water vapor profiles to be measured down to 225 m above the surface. Data comparisons using the DIAL instrument and co-located radiosonde measurements are presented demonstrating the capabilities of the DIAL instrument.
INTRODUCTION

Water Vapor, Aerosol’s, and Earth’s Radiation Budget

The Earth’s climate is driven by incoming solar radiation that is distributed and eventually re-emitted back into space [1, 2] as shown schematically in figure 1.1 [3]. Understanding how the incoming solar radiation is distributed and re-emitted back into space provides insight into and understanding of the Earth’s complex climate system.

Figure 1.1: The Earth’s annual and global mean energy balance. The yellow indicates the short wave incoming solar radiation and the red indicates the long wave radiation emitted [3].
Climate models and observational studies are being used to understand the effects of anthropogenic radiative forcing on the climate system. The rising level of atmospheric carbon dioxide (CO$_2$) due to burning fossil fuels and land use changes results in the enhanced greenhouse effect and is responsible for the largest anthropogenic radiative forcing. Observational studies determined that the average rate of increase in atmospheric CO$_2$ from 1960 to 2005 is 1.4 ppm/yr [2], leading to a global average value of 379 ppm in 2005 [2]. Atmospheric concentrations of CO$_2$ result in a radiative forcing of 1.66±0.17 W/m$^2$ [2] with a high level of scientific understanding according to the Fourth Assessment Report (FAR) from the intergovernmental panel on climate change (IPCC) [2].

Atmospheric aerosols produce an important negative radiative forcing on the climate system through reflection and absorption of short and long wave radiation, leading to the aerosol direct effect [4, 5]. The aerosol direct effect produces a radiative forcing of -0.5±0.4 W/m$^2$ [2] with a medium-low level of scientific understanding according to the FAR of the IPCC [2]. Atmospheric aerosols also produce a negative radiative forcing through their influence on clouds, leading to the aerosol indirect effect [4, 5, 6, 7, 8, 9]. Modeling the aerosol indirect effect is difficult because of the incomplete picture of the underlying physics and the insufficient observational data needed for model verification. The aerosol indirect effect produces an average radiative forcing of -0.7 W/m$^2$ [2] with a low level of scientific understanding according to the FAR of the IPCC [2]. The aerosol direct and indirect effects depend on three coupled components of the climate system, including atmospheric aerosols, clouds and atmospheric water vapor.

Aerosols and atmospheric water vapor can influence cloud microphysical properties affecting the climate system. Twomey [10] suggested that an increased concentration of atmospheric aerosols results in a higher concentration of cloud condensation nuclei
(CCN). A small subset of atmospheric aerosols serve as particles upon which water vapor condenses to form supersaturated cloud droplets. The increased concentration of CCN leads to a higher cloud droplet concentration that will suppress drizzle formation [7] and lead to more reflective clouds. However, as noted by Eichel et al [11] and Wulfmeyer and Feingold [12], this chain of events is not a foregone conclusion but rather 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 incoming solar radiation being reflected back into space, leading to an overall negative radiative forcing. The influence on the climate system due to changes in cloud microphysical properties is termed the aerosol indirect effect and produce a negative radiative forcing ranging from -1.8 W/m² to -0.3 W/m² [2].

Water vapor also provides a positive feedback to the Earth’s climate system. As the atmospheric concentration of CO₂ rises from combustion of fossil fuels, the Earth’s temperature begins to increase, causing more water vapor to be present in the atmosphere. 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. 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 [2].

Water vapor is mostly contained in the lower part of the atmosphere, called the troposphere. 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. To better understand and model the effects of atmospheric water vapor on the climate system, new observational instruments and techniques are needed.
Water Vapor Instrumentation

Water vapor in the lower troposphere plays an important role in many Earth system processes associated with the radiation budget and climate, moisture transport and the hydrologic cycle, and weather [13, 14]. Water vapor is primarily contained within the lowest 3-4 km of the troposphere with high temporal and spatial fluxes [14, 15]. Radiosonde launches are currently used to obtain water vapor profiles, but this measurement technique can only provide information at one location at one point in time and cannot easily be used to monitor the spatial and temporal changes associated with atmospheric water vapor [16].

Recognizing the importance of accurate measurements of water vapor profiles in the lower atmosphere for understanding, modeling, and predicting both climate and weather, research in developing instruments for retrieval of water vapor profiles is ongoing [16-29]. Passive remote sensing instruments such as the Atmospheric Emitted Radiance Interferometer (AERI) [17] and the Atmospheric Infrared Sounder (AIRS) [18] show great utility for monitoring atmospheric water vapor, but measure column integrated and or low spatial resolution water vapor profiles.

Active remote sensing techniques such as light detection and ranging (lidar) can produce range resolved measurements of atmospheric water vapor. Raman lidar instruments [16, 19, 20] are capable of making range-resolved measurements of atmospheric water vapor using high-power pulsed lasers. The range information is determined by the time of flight of the light, while the molecular species information is determined by the characteristic Raman shift to longer wavelengths associated with the inelastic Raman scattering process. Raman lidar instruments typically require high peak powers due to the small Raman scattering cross sections [21], and
furthermore, Raman lidar’s need to be accurately calibrated for range-resolved water vapor retrievals [22].

Differential absorption lidar (DIAL) is a second lidar method capable of obtaining range-resolved profiles of atmospheric molecular densities [23, 24, 22, 25, 26, 27, 28, 29, 30, 31, 32]. DIAL instruments use a pulsed tunable laser transmitter that can be tuned to an on-line wavelength associated with an absorption feature for the molecule of interest and then tuned to an off-line wavelength with no molecular absorption, or significantly less absorption in the case of a continuum, like ozone. The wavelengths of the DIAL transmitter are chosen so that the ratio of the return signals from the on-line and off-line wavelengths is directly related to the absorption from the molecules of interest. Because the DIAL transmitter uses a ratio of the return signals from the closely spaced on-line and off-line wavelengths, the DIAL instrument avoids the difficult calibration faced by Raman lidar instruments.

The high spatial and temporal flux of water vapor is hard to capture from a single location. The deployment of an array of low cost, eye safe, automated DIAL instruments for water vapor profiles could be useful for measuring water vapor transport, which is important for better forecasting of precipitation and understanding long-term trends needed for climate studies [13]. Many water vapor lidar instruments currently operating are large, complex, expensive, and are not automated [19, 24, 29]. However, in recent years, work has begun on developing smaller automated water vapor lidar instruments [23, 30, 31, 32]. One promising avenue of research toward development of DIAL instruments for water vapor studies is to use semiconductor laser transmitters. Diode lasers are compact, inexpensive, can be tuned, and have good spectral coverage in the near infrared spectral region where water vapor has many absorption lines. Several numerical studies of diode-laser-based transmitters and photon-counting-avalanche-photodiode-based receivers have been performed [33, 34],
but few systems have been built. Rall et al. [23] built a DIAL instrument based on a diode laser near 811.6 nm, while Machol et al. [30] reported initial water vapor DIAL measurements using a laser transmitter based on a distributed feedback (DFB) laser diode used to injection seed a flared amplifier. Comparisons between their DIAL retrieval and radiosonde data showed agreement up to a height of 2.5 km. Machol et al. noted that new laser transmitter designs are needed for better spectral coverage and larger tuning ranges, calling for “a new laser with a tuning range that accesses a larger selection of good water vapor lines” [30].

A laser transmitter for a water vapor DIAL based on a widely tunable external cavity diode laser (ECDL) that can access many water vapor lines has been built at Montana State University [35, 36, 37, 38, 39]. In his thesis work, Obland used this laser transmitter to demonstrate initial column integrated water vapor profiles in which he tuned a cw laser across a water vapor absorption feature [31, 32]. Further improvements to this water vapor DIAL instrument and water vapor profile retrieval based on the DIAL equation allow the low power diode-laser-based DIAL instrument to accurately retrieve water vapor profiles in the lower troposphere from 225 m to ≈ 3.0 km, allowing for routine night time measurements.

The compact diode-laser-based DIAL instrument for water vapor profiling constructed and tested at Montana State University is described in this thesis. The laser transmitter is based on a tunable ECDL with a tuning range from 824 nm to 841 nm. This ECDL is used to injection seed two cascaded semiconductor optical amplifiers (SOA). The output from the second SOA is pulsed using the first-order beam from an acousto-optic modulator. Light is collected using a commercial telescope and is monitored using an avalanche photodiode (APD). Water vapor profiles collected using this DIAL instrument demonstrate good agreement with data collected using co-located radiosonde measurements.
This thesis is organized as follows. In chapter 2, the theory used to measure water vapor profiles based on the DIAL measurement is presented. The water vapor DIAL instrument built at Montana State University is described in chapter 3. Experimental measurements and results are presented and described in chapter 4. Finally, some brief concluding remarks are presented in chapter 5.
Lidar, an acronym for LIght Detection And Ranging, is a useful method for probing the atmosphere. A schematic of a typical lidar instrument is shown in figure 2.1.

Figure 2.1: A schematic of a lidar instrument including basic principles and components.
A coherent illumination source, typically a laser ranging in wavelength from UV to near infrared (NIR), repeatedly sends short, collimated pulses of light into the atmosphere. Typical pulse widths, repetition frequencies (PRF), and 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 it 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 typically configured in one of two layouts. The first layout, the bi-static configuration, uses a laser transmitter located away from the lidar receiver. The second layout, the co-linear configuration, the laser transmitter and lidar receiver have a common optical axis, 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 multiple scattering events and stray background light are prevented from reaching the detector. The light is then collimated and passes through a narrow band filter (NBF) to ensure that only the backscattered light from the laser transmitter makes it to the detector. The light is then focused onto a detector where a data acquisition (DAQ) card digitizes the analog output from the optical detector. The time of flight of each scattering event from a single laser pulse is directly proportional to the distance to the scattering volume(s) along the entire illuminated path, and the manner in which the light is scattered back reveals information about the scattering volume’s microphysical structure and spectroscopic features.

This chapter is organized as follows. The DIAL equation which is used to derive the range-resolved number density is derived. In this derivation, care is taken to include the effects of the narrow-band transmission filter in the receiver that plays an
important role in accurate measurements at lower elevations. Next, the selection of
the water vapor absorption line is briefly discussed. This selection of the water vapor
absorption feature is based on the work of Browell et al. [28] and Obland [31].

The DIAL Equation

The optical power, $P(\lambda, r)$, collected at wavelength $\lambda$ from a range $r$ can be
calculated using the lidar equation [40]

$$P(\lambda, r) = P_t(\lambda) \frac{A}{r^2} \Delta r \beta(\lambda, r) T_A^2(\lambda, r) \epsilon_0(\lambda, r) \epsilon_R(\lambda, r) \epsilon_D(\lambda, r) T_F(\lambda, r)$$  \hspace{1cm} (2.1)

where $P_t(\lambda)$ is the transmitted optical power and has units of [W]. $P_t(\lambda)$ can also be
written in terms of transmitted photons by using the conversion $P_t(\lambda) = n_t h c / (\lambda \tau)$
where $n_t$ is the number of transmitted photons, $h = 6.626 \times 10^{-34}[J \cdot s]$ is Plank’s
constant, and $c = 2.998 \times 10^8$ m/s. $A[m^2]$ is the entrance pupil area of the tele-
scope receiver, $\Delta r = \tau c / 2[m]$ is the range bin size, $\tau$ [s] is the laser pulse duration,
$\beta(\lambda, r) = \beta_m(\lambda, r) + \beta_a(\lambda, r)[km^{-1}sr^{-1}]$ is the total atmospheric backscatter coefficient
comprising of both molecular $\beta_m$ and aerosol $\beta_a$ backscatter coefficients, $T_A^2(\lambda, r)$
[unitless] is the round-trip atmospheric transmission factor, $\epsilon_0(\lambda, r)$ [unitless] is the
lidar receiver geometric overlap factor, $\epsilon_R(\lambda, r)$ [unitless] is the receiving optics trans-
mission factor not including the narrowband optical filter, $\epsilon_D(\lambda, r)$ [unitless] is the
optical detectors efficiency, and $T_F(\lambda, r)$ [unitless] is the transmission of the narrow
band filter. The round-trip atmospheric transmission factor from equation 2.1 is given
by the Beer Lambert relationship and can be written as

$$T_A^2(\lambda, r) = \exp\left(-2 \int_0^r \alpha(\lambda, r')dr'\right)$$  \hspace{1cm} (2.2)
where $\alpha[m^{-1}]$ is the total atmospheric extinction coefficient taking into account the extinction due to aerosol and molecular absorption and scattering. The atmospheric extinction coefficient can be expanded into two terms

$$\alpha(\lambda, r) = \kappa(\lambda, r) + \sigma(\lambda, r)N(r),$$

(2.3)

where $\kappa(\lambda, r)[km^{-1}]$ is the atmospheric extinction factor due to scattering and $\sigma(\lambda, r)N(r)[km^{-1}]$ is the atmospheric extinction factor due to absorption, where $\sigma(\lambda, r)[m^{-3}]$ is the absorption cross section of the atmospheric constituent of interest and $N(r)$ is the number density of the same absorbing constituent. Substituting equation 2.3 into equation 2.2 yields the round-trip atmospheric transmission factor

$$T_A^2(\lambda, r) = \exp\left(-2 \int_0^r \kappa(\lambda, r)dr\right) \exp\left(-2 \int_0^r \sigma(\lambda, r)N(r)dr\right).$$

(2.4)

The total receiver efficiency is defined as the product of the receiver overlap factor, the receiver optics transmission factor excluding the narrow-band optical filter, and the detector efficienc, and can be written as

$$\epsilon(\lambda, r) = \epsilon_0(\lambda, r)\epsilon_D(\lambda, r)\epsilon_r(\lambda, r).$$

(2.5)

The DIAL technique uses the return signal from two different wavelengths that are closely spaced to determine a vertical profile of the number density of a particular molecule. The first wavelength, $\lambda_{on}$, is the wavelength corresponding to the center of an absorption feature of the molecule of interest, while the second wavelength, $\lambda_{off}$, is the wavelength corresponding to significantly less molecular absorption. The DIAL equation is found by considering the return signal from adjacent range bins for both $\lambda_{on}$ and $\lambda_{off}$. Using equations 2.1 and 2.2, the following equation can be written
\[
\ln P(\lambda_{on}, r) - \ln P(\lambda_{on}, r + \Delta r)] - [\ln P(\lambda_{off}, r) - \ln P(\lambda_{off}, r + \Delta r)] = \\
[\ln \frac{1}{r^2} - \ln \frac{1}{r + \Delta r^2} - 2 \int_{0}^{r} \kappa(\lambda_{on}, r')dr' - 2 \int_{0}^{r} \sigma(\lambda_{on}, r')N(r')dr'] \
+ 2 \int_{0}^{r+\Delta r} \kappa(\lambda_{on}, r')dr' + 2 \int_{0}^{r+\Delta r} \sigma(\lambda_{on}, r')N(r')dr' + \ln \beta(\lambda_{on}, r) - \ln \beta(\lambda_{on}, r + \Delta r) \\
+ \ln \epsilon(\lambda_{on}, r) - \ln \epsilon(\lambda_{on}, r + \Delta r) + \ln T_F(\lambda_{on}, r) - \ln T_F(\lambda_{on}, r + \Delta r) \\
-[\ln \frac{1}{r^2} - \ln \frac{1}{r + \Delta r^2} - 2 \int_{0}^{r} \kappa(\lambda_{off}, r')dr' - 2 \int_{0}^{r} \sigma(\lambda_{off}, r')N(r')dr'] \
+ 2 \int_{0}^{r+\Delta r} \kappa(\lambda_{off}, r')dr' + 2 \int_{0}^{r+\Delta r} \sigma(\lambda_{off}, r')N(r')dr' + \ln \beta(\lambda_{off}, r) - \ln \beta(\lambda_{off}, r + \Delta r) \\
+ \ln \epsilon(\lambda_{off}, r) - \ln \epsilon(\lambda_{off}, r + \Delta r) + \ln T_F(\lambda_{off}, r) - \ln T_F(\lambda_{off}, r + \Delta r)]. \\
\] (2.6)

For the DIAL technique, the wavelengths \(\lambda_{on}\) and \(\lambda_{off}\) are chosen to be close enough such that

\[
\kappa(\lambda_{on}, r) = \kappa(\lambda_{off}, r) = \kappa(r) \\
\beta(\lambda_{on}, r) = \beta(\lambda_{off}, r) = \beta(r) \\
\epsilon(\lambda_{on}, r) = \epsilon(\lambda_{off}, r) = \epsilon(r). \\
\] (2.7a, b, c)

For \(\lambda_{on}\) and \(\lambda_{off}\) closely spaced so that the atmospheric extinction, backscatter and receiver efficiency are equal for the two wavelengths, equation 2.7 can be substituted into equation 2.6 to yield
\[
\begin{align*}
[\ln P(\lambda_{on}, r) - \ln P(\lambda_{on}, r + \Delta r)] & - [\ln P(\lambda_{off}, r) - \ln P(\lambda_{off}, r + \Delta r)] = \\
2 \int_{r}^{r+\Delta r} \sigma(\lambda_{on}, r')N(r')dr' & - 2 \int_{r}^{r+\Delta r} \sigma(\lambda_{off}, r')N(r')dr' + \\
\ln T_F(\lambda_{on}, r) - \ln T_F(\lambda_{on}, r + \Delta r) & + \ln T_F(\lambda_{off}, r) - \ln T_F(\lambda_{off}, r + \Delta r)
\end{align*}
\]

(2.8)

Assuming the absorption cross section of the molecule of interest is constant across a range bin, we can assume that for the range bin located at \(r\),

\[
\begin{align*}
\sigma(\lambda_{on}, r) &= constant = \sigma(\lambda_{on}) \quad \text{(2.9a)} \\
\sigma(\lambda_{off}, r) &= constant = \sigma(\lambda_{off}). \quad \text{(2.9b)}
\end{align*}
\]

The number density is also assumed to be constant over each range bin, allowing the integrals in equation 2.8 to be simplified as

\[
\begin{align*}
2 \int_{r}^{r+\Delta r} \sigma(\lambda_{on}, r')N(r')dr' &= 2\sigma(\lambda_{on})N(r + \Delta r)\Delta r \quad \text{(2.10a)} \\
2 \int_{r}^{r+\Delta r} \sigma(\lambda_{off}, r')N(r')dr' &= 2\sigma(\lambda_{off})N(r + \Delta r)\Delta r. \quad \text{(2.10b)}
\end{align*}
\]

The assumptions made in equation 2.10 are only valid for small range bin sizes that capture the micro-structure scale of the atmospheric constituent of interest. The range-dependent absorption cross section in equations 2.9 and 2.10 will be discussed further in section 4 on page 53. Using the assumption that the absorption cross section and number density are constant across a range bin, the dial equation, which provides the range-dependent number density profile of the atmospheric constituent of interested, simplifies to
\[
N(r + \Delta r) = \frac{1}{2(\sigma(r)_{on} - \sigma(r)_{off})} \Delta r \left[ \ln \left( \frac{P(\lambda_{on}, r) P(\lambda_{off}, r + \Delta r)}{P(\lambda_{on}, r + \Delta r) P(\lambda_{off}, r)} \right) \right] - \left[ \ln \left( \frac{T_F(\lambda_{on}, r)}{T_F(\lambda_{on}, r + \Delta r)} \frac{T_F(\lambda_{off}, r)}{T_F(\lambda_{off}, r + \Delta r)} \right) \right] \] (2.11)

The transmission through the narrow-band filter as a function of wavelength and range adds a correction factor to the DIAL equation defined as

\[
- \ln \left( \frac{T_F(\lambda_{on}, r)}{T_F(\lambda_{on}, r + \Delta r)} \frac{T_F(\lambda_{off}, r)}{T_F(\lambda_{off}, r + \Delta r)} \right) . \] (2.12)

The correction factor plays an important role in accurately retrieving the number density for the molecule of interest and will be discussed in detail in section 4 on page 47.

Water Vapor Absorption Line Selection

Three main criteria must be considered when choosing a water vapor absorption line to achieve accurate measurements of water vapor profiles. The three primary criteria for selection of the water vapor absorption line include the line strength, temperature sensitivity, and absence of nearby absorption features [30, 31, 32, 35]. To arrive at the temperature-sensitive line strength parameter of the water vapor absorption line of interest, the Beer-Lambert relationship is used to describe the transmission, \( T \), through the atmosphere. The Beer-Lambert relationship can be written as

\[
T = \frac{I}{I_0} = e^{-2\alpha L} \] (2.13)
where \( I \) is the attenuated optical intensity after traveling a path of length \( L \), \( I_0 \) is the initial transmitted optical intensity, and \( \alpha \) is the absorption per unit length which is referred to as the linear absorption coefficient and has units of [1/cm]. The squared term in the exponent takes into account the round-trip transmission through the atmosphere and back to the receiving unit via a molecular or aerosol scattering event. The water vapor absorption feature is described by a unique linear absorption coefficient, \( \alpha \), that can be written as

\[
\alpha = S \, g(\nu - \nu_0) \, N \, P_a
\]  
(2.14)

where \( S \) is the molecular line intensity and includes information about both the partition function of the molecule and the Boltzmann population factor. Values for the line intensity, \( S \) with units of length per number of molecules [cm/molecule], are listed in the HITRAN database developed by the U.S. Air Force Research Lab (AFRL) for many molecules, including water vapor [41]. \( N \) is the number density of the molecule of interest with units of [molecule/cm\(^3\)] and is a function of both ambient temperature and barometric pressure. \( g(\nu - \nu_0) \) is the normalized line shape and has units of length [cm]. \( \nu \) is the wavenumber in cm\(^{-1}\) and \( \nu_0 \) is the wavenumber corresponding to a line center vibrational resonance transition resulting in photon absorption [41]. For a given path length and water vapor absorption line intensity from the hitran database, the round-trip atmospheric transmission can be calculated to approximate the attenuation in the backscattered signal due to water vapor absorption through the lower troposphere. A round-trip signal attenuation of approximately fifty percent should be the target for the majority of DIAL instruments [31]. Picking a water vapor absorption feature that yields the appropriate round trip signal transmission will optimize the water vapor absorption optical depth such that there is enough signal attenuation due to water vapor absorption to distinguish between the on-line and off-
line returns while having enough of a return signal at the receiver to make a reasonable measurement. Once an appropriate line strength has been chosen to optimize for the water vapor optical depth for the climate at a given geographical location [31], a temperature sensitivity analysis must be conducted to assess the temperature induced error in the water vapor number density measurement. Accurate measurements of water vapor profiles require care in selecting an absorption line that is insensitive to variations in the atmospheric temperature [30, 31, 32, 42]. The evaluation of the temperature sensitivities of water vapor absorption lines in the 820-840 nm spectral region were studied [30, 31] using the methods presented by Browell et al. [42], leading to the selection of a water vapor absorption line for number density profiles. The temperature dependence of the line strength, $S \left[ cm^{-1}/(mol \cdot cm^{-2}) \right]$, associated with an absorption feature is given by [42]

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

where $S_0$ is the reference line strength at temperature $T_0$ [K], $T$ [K] is the temperature at which the line strength $S(T)$ is being calculated, $h$ is the Planck constant, $c$ is the speed of light, $k$ is the Boltzmann constant, $\nu_0$ [cm$^{-1}$] is once again the line center position, and $E''$ [cm$^{-1}$] is the ground state energy of the transition.

Because the Earth’s atmosphere is not homogeneous, different broadening processes occur at different altitudes. For low altitudes $\leq 2km$, pressure broadening is the dominant effect and can be described by a Lorentzian line shape. The half width at half maximum (HWHM) value of the water vapor absorption line of interest is dependent on both atmospheric pressure and temperature and can be described as

$$\gamma_L = \gamma_0 \left( \frac{P}{P_0} \right) \left( \frac{T_0}{T} \right)^\alpha, \quad (2.16)$$
where $\alpha$ is the linewidth temperature dependence parameter, and $\gamma_0$ is the initial HWHM line center value of the absorption line of interest at standard temperature $T_0$ and pressure $P_0$. To calculate the temperature and pressure-dependent linestrength, $S(T)$, and linewidth, $\gamma_L$, the line strength $S_0$ and the linewidth $\gamma_0$ are first obtained from the HITRAN database for the water vapor absorption line of interest [41].

In the limiting case where pressure is the dominant broadening process, the line-center water vapor line strength can be derived by integrating the Lorentzian line shape absorption cross section over all frequencies. This process reveals a relationship between the line strength and cross section that can be described as

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

Using a mathematical look up table [43] 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 one to write the water vapor line strength as

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

From equation 2.19 the line center absorption cross section $\sigma_0$ [cm$^{-2}$] can be expressed as $\sigma_0 = \frac{S}{\gamma_L \pi}$.

In the other limiting case where measurements are taken at altitudes $\geq 50$ km, the Lorentzian line shape no longer accurately describes the water vapor absorption line.
shape due to infrequent molecular collisions as a result of lower atmospheric pressures and temperature. The dominant line broadening mechanism for these altitudes is a Doppler-broadened line shape and can be described by a Gaussian profile where the Doppler-broadened linewidth can be expressed as

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

(2.20)

where \( m \) [kg/molecule] is the molecular mass of water vapor. Using a similar approach as the Lorentzian line shape and cross section analysis and equation 2.20, the temperature dependent Doppler broadened Gaussian line shape absorption cross section can be written as

\[ \sigma(\nu) = \frac{S}{\gamma_D} \left( \ln 2 \pi \right)^{1/2} \exp \left[ -\frac{\ln 2(\nu - \nu_0)^2}{\gamma_D^2} \right]. \]  

(2.21)

Evaluated at line center, the Doppler-broadened absorption cross section reduces to

\[ \sigma_0 = \frac{S}{\gamma_D} \left( \ln 2 \pi \right)^{1/2}. \]

Although the DIAL instrument in this thesis focuses on obtaining water vapor profiles up through the lower troposphere (2-4 km), the effects of both broadening mechanisms must be accounted for between the upper and lower bounds of the atmosphere. A convolution of the Lorentz and Doppler line shapes, associated with a water vapor absorption feature at different altitudes yields a Voigt profile for the absorption cross section

\[ V(x, y) = \frac{\sigma(x, y)}{K} = \frac{y}{\pi} \int_{-\infty}^{\infty} \frac{\exp \left[ -\frac{t^2}{y^2 + (x-t)^2} \right]}{y^2 + (x-t)^2} dt, \]  

(2.22)

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 \( K = \left( \frac{S(T)}{\gamma_D} \right) \left( \ln 2 \pi \right)^{1/2} \). Once again, values of \( \gamma_0, S_0, \) and \( E^\pi \) were obtained from
Figure 2.2: Temperature sensitivity of water vapor DIAL number density measurement errors at 1.0 and 0.25-atm pressure for a range of $E^\prime$ values.

the HITRAN database [41]. The temperature sensitivity for the number density measurement is calculated using the expression [42]

$$\frac{1}{\sigma_0} \frac{d\sigma_0}{dT} \approx \frac{1}{T - T'} \frac{\sigma_0(T) - \sigma_0(T')}{\frac{\sigma_0(T) + \sigma_0(T')}{2}}. \tag{2.23}$$

where $\sigma(T)$ is found using equation 2.15 on page 16 and equation 2.22 on the preceding page. A plot of the number density error as a function of temperature for various ground state energies is shown in figure 2.2 for a pressure of 1 atm and 0.25 atm respectively. The absorption cross section, $\sigma(T)$, is temperature independent at the temperature neutral point when $\frac{d\sigma}{dT} = 0$.

To emphasize again, the three primary criteria for selection of the water vapor absorption line include the temperature sensitivity, line strength, and absence of nearby absorption features [30, 31, 32, 35]. The on-line wavelength chosen for the water vapor DIAL instrument has a wavelength of 828.187 nm (828.0069 nm) in vacuum (air) while the off-line wavelength was chosen to be 828.287 nm (828.1069 nm) in vacuum (air) as seen in figure 2.3 on the following page. The temperature
Figure 2.3: HiTRAN derived atmospheric absorption spectrum near 828.00 nm. The indicated on-line and off-line wavelengths corresponding to 828.0069 nm and 828.1069 nm respectively are the final on and off-line wavelengths selected for the DIAL measurement.

neutral point for this absorption feature, as seen in figure 2.2 on the previous page for the ground state energy of 212.2 cm\(^{-1}\) ranges from 275 K at 0.25 atm to 350 K at 1 atm. At a temperature of 296 K and a pressure of 1 atm, the line strength associated with the water vapor absorption feature used for the DIAL measurements presented in this thesis is \(S = 1.477 \times 10^{-23} \text{cm}^{-1}/(\text{mol} \cdot \text{cm}^{-2})\), the full width at half maximum linewidth is 0.1937 cm\(^{-1}\), the ground state energy is \(E'' = 212.2 \text{ cm}^{-1}\), and the linewidth temperature dependence parameter \(\alpha\) is 0.68.
A schematic of the DIAL instrument is shown in figure 3.1 on the following page. A tunable external cavity diode laser (ECDL) is used to injection seed a tapered semiconductor optical amplifier (SOA). The operating wavelength of the ECDL is determined by both the wavelength of the optical feedback and the external cavity resonance condition. An ECDL in the Littman-Metcalf external cavity configuration [44] is shown schematically in figure 3.2 on page 23. Light from the diode laser is incident on an optical grating that spatially separates the different wavelength components shown schematically as $\lambda(1)$ and $\lambda(2)$ in figure 3.2 on page 23 [45]. A retro-reflector is used to pick one of these wavelength components and direct it back to the laser diode via a second reflection from the optical grating. The optical feedback will be maintained by the external cavity provided that the resonance condition of an integer number of half wavelengths fits within the external cavity optical path length. The schematic drawing on the left of figure 3.2 on page 23 shows the ECDL operating at $\lambda(1)$. Continuous tuning of the ECDL is achieved by first rotating the retro-reflector to provide optical feedback at a different wavelength while simultaneously changing the external cavity optical path length so that the same integer number of half wavelengths is maintained within the cavity at the new wavelength. This is shown schematically by the drawing on the right in figure 3.2 on page 23. If the retro-reflector is rotated to change the wavelength of the light fed back into the diode laser but the optical path length changes so that a different integer number of half wavelengths fits within the optical cavity, a mode hop will occur. Mode hops prevent truly continuous tuning of the ECDL to approximately the free spectral range of the
Figure 3.1: Schematic of the DIAL instrument used for studying water vapor number densities in the lower troposphere.
Figure 3.2: 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 grating 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.

The ECDL constructed for the DIAL instrument in the Littman-Metcalf configuration can be seen in figure 3.3 on page 25. 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 next incident on a 1600 line/mm grating 15 mm wide by 60 mm long by 10 mm thick (Spectrogon) at a grazing angle of three degrees. The first order reflection for the diffraction grating is found from $\cos \theta_{\text{out}} = \cos \theta_{\text{in}} - \frac{\lambda}{d}$ to be 109 degrees where $\theta_{\text{in}}(\theta_{\text{out}})$ is the angle between the incoming (outgoing) beam and the
plane of the diffraction grating, \( \lambda \) is the wavelength, and \( d \) is the 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 of 3.9 GHz corresponding to a 3.8 cm long external cavity. The roof prism rotates so that the cavity length 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. Fine rotation of the roof prism is achieved by applying a voltage to a piezoelectric stack (Thor Labs AE0505D16) giving mode-hop free tuning of over 20 GHz at a fixed temperature. The maximum voltage that can be applied to the PZT is 100 V. The pivot point was chosen using the results from McNicholl et al.[46] to synchronize the cavity mode and optical feedback as the grating is rotated. However, machining tolerances of 127 \( \mu \)m (0.005 inches) and uncertainty of the location of the semiconductor chip in the 9 mm can can limit the accuracy of the location of the pivot point.

The ECDL is placed on a thermo-electric cooler (TEC) for temperature stabilization. A 10 k\( \Omega \) thermistor is used to monitor the temperature of the ECDL and a commercial temperature controller (ILX LDD3722) is used to stabilize the temperature to within 0.1 C. A commercial current controller (ILX LDD3722) is used to supply a drive current to the diode laser. The ECDL is operated in a continuous wave (cw) mode of operation and its performance is summarized as follows. The coarse tuning ranges from 824 nm to 841 nm with a mode-hop free tuning range of approximately 10-20 GHz and a full width half maximum line-width of less than 200 kHz. The maximum output power is 20 mW with a side-mode suppression of greater than 45 dBm. A plot of the 830 nm water vapor absorption band accessible by the coarse tuning range of the ECDL can be seen in figure 3.4 on page 26.
Figure 3.3: Photograph of the tunable ECDL built in the Littman-Metcalf external cavity configuration used to injection-seed a flared amplifier for the DIAL transmitter.

The output of the ECDL is sent through a Faraday isolator to prevent unwanted feedback from affecting its performance. After the Faraday isolator, the light is next incident on a waveplate and polarizing beamsplitter (PBS). The light rejected by the PBS is used to monitor the cw output of the ECDL, while the light passing through the PBS is used to seed an optical pre-amplifier. The ratio of the light passing through the PBS to the light rejected by the PBS can be controlled by rotating the waveplate. The output from the ECDL has the narrow linewidth and broad tunability needed for the DIAL transmitter but has low cw output power. To increase the optical power while maintaining the spectral properties of the ECDL, the ECDL is used to injection seed an SOA. Since the output of the ECDL was unable to saturate the gain of the SOA, a pre-amplifier was first used (Sacher Lasertechnik TA830). The output of the pre-amplifier passed through a Faraday isolator and was then used to injection seed
Figure 3.4: 830 nm water vapor absorption band including several variable strength absorption features accessible by course tuning the ECDL.

A second SOA (Sacher Lasertechnik TA830). The second SOA produced a cw output power of up to 500 mW. The output of the second SOA was then incident on an acousto-optic modulator (AOM) (Isomet 1205C-2). The first order diffraction from the AOM was used to create a pulsed output for the DIAL instrument. After the AOM, a wedged window was used to direct a small portion of the output beam to a reference energy detector to monitor and divide out any fluctuations in output power.

A plot of the optical power as a function of wavelength for the DIAL laser transmitter is shown in figure 3.5 on the following page [35]. This plot shows the DIAL laser transmitter can be tuned from 824 nm to 841 nm, a 17 nm tuning range. The laser transmitter is capable of accessing many water vapor absorption lines, however
Figure 3.5: Output power as a function of wavelength for the injection-seeded tapered amplifier. Good side mode suppression ratio and high optical power are maintained through the amplifier while still maintaining the spectral properties of the seed laser.

care must be taken in choosing an appropriate absorption line to obtain accurate water vapor profiles, as discussed in chapter 2.

External cavity diode lasers (ECDL’s) have proven to be very useful laboratory tools because of their spectral coverage and tunability. The typical performance of an ECDL using a standard Fabry-Perot diode laser as the laser source from above include 20 nm of non-continuous tuning, a line width of approximately 200 kHz, and output powers of 20 mW-50 mW. However, one limiting factor to the usefulness of ECDL’s is the limited continuous tuning range due to mode hops.
Extended Tuning

One method used to increase the continuous tuning range of an ECDL is to choose the pivot point around which the retro-reflector is rotated so that changes in frequency of the light fed back into the diode laser is matched to the change in the optical cavity length of the external optical cavity [44] [45]. This method requires very precise tolerances for the mechanical parts of the ECDL and is hard to implement. An error in locating the pivot point by as little as 20 $\mu$m is enough to cause the ECDL to mode hop [47]. This is well below typical machining tolerances of less than 50 $\mu$m for any given part [47]. A second method to increase the continuous tuning range involves always maintaining the resonance condition within the optical cavity while the ECDL is tuned [45]. This can be achieved by making small corrections to the optical path length of the external cavity by applying a small correction current to the diode laser. The small correction current adjusts the carrier density and temperature of the laser diode, which affects the index of refraction and physical path length of the diode laser and allows for the small changes to optical path length of the external cavity. An electronic feedback scheme is introduced in this thesis allowing one to continuously make small corrections to the optical path length of the external cavity through a small correction current so that the resonant condition is always maintained as the laser is tuned. In this way the mode hops can be eliminated and the continuous tuning range of the ECDL can be extended.

The optical feedback from the external cavity will be highest when the ECDL is operated in the resonance condition. As the ECDL is tuned and the external cavity no longer maintains a resonance condition, the amount of feedback is less due to destructive interference in the external cavity. With less feedback to the diode laser to suppress the spontaneous emission within the diode, the power in the side modes
will begin to grow causing the side mode suppression ratio to lessen. This fact implies that as the external cavity no longer maintains the resonance condition, optical power in the side modes causes the overall output power of the ECDL to grow. Thus, one way to monitor how well the external cavity is maintaining the resonance condition as the ECDL is tuned is to monitor the output power of the ECDL.

A current controller was built based on the low-noise current controller described by Libbrecht and Hall [48]. The current controller serves three purposes. First, it provides a stable dc current to the diode laser. Second, a small signal high-speed sinusoidal modulation can be added to the dc set point to modulate the wavelength of the ECDL. The current controller converts a modulated voltage signal into a modulated current signal and adds this signal to the dc set point. Third, a small signal current can be added to the dc current set point to correct the optical path length of the external cavity. The small signal correction to the dc set point is proportional to the voltage applied to the small signal dc input port.

Original testing of the extended tuning method was conducted for diatomic oxygen absorption spectroscopy near 760 nm and was later applied to extending the continuous tuning range of an already existing water vapor DIAL transmitter. For the duration of this section, tuning characteristics of a 760 nm Littman-Metcalf configured ECDL will be presented to illustrate the method for extending the continuous tuning range for spectroscopic laser applications. Tuning of the laser can be achieved by changing the laser drive current, producing a small change in the external cavity length. The measured current tuning response for this ECDL is 1.25 GHz/mA. Tuning the ECDL is also achieved electronically by applying a voltage to the PZT and is shown in figure 3.6 on the next page. This measurement used a computer to first set a voltage supplied to the PZT and then the operating frequency of the ECDL was measured with a Burleigh WA-1500 Wavemeter with a 10 MHz resolution. As
the voltage is applied to the PZT, the laser begins tuning with a tuning rate of 0.4 GHz/V. However, once the laser has tuned 1 GHz, the changing frequency of the light fed back to the diode laser can no longer maintain the same number of half wavelengths associated with the optical cavity length and the ECDL goes through a mode hop. A plot of the tuning as a function of voltage for the ECDL is shown in figure 3.7 on the following page for a larger applied voltage range. In this figure we see the mode hops associated with the external cavity laser as well as two mode hops associated with the cavity formed by the front and back facets of the diode laser. The facet mode hops cause the ECDL to jump approximately 26 GHz. One very clear problem with tuning an ECDL is that mode hops limit the actual frequency ranges in which the ECDL can be operated. This becomes a problem, for example, if one wants

Figure 3.6: A plot of the operating frequency of the ECDL as a function of voltage applied to the PZT. This plot shows the ECDL will tune approximately 1 GHz before an external cavity mode hop occurs.
Figure 3.7: A plot of the operating frequency of the ECDL as a function of voltage applied to the PZT. This plot shows the external cavity mode hop of approximately 1 Ghz occurring for every 2.5 V applied to the PZT. The laser diode facet modes hops of approximately 26 GHz are seen for every 24 V applied to the PZT. The available operating wavelengths for the ECDL are limited due to both the external cavity and facet mode hops.

The output power of the ECDL will change as the laser is tuned. When the external cavity maintains a resonance condition, the optical feedback to the diode laser is a maximum. In this case, the optical feedback will allow suppression of the spontaneous emission yielding a high side mode suppression ratio. When the ECDL is tuned and the external cavity no longer maintains a resonance condition, the optical feedback to the diode laser will decrease due to destructive interference within the external cavity. This will cause less power to be fed back into the diode and the spontaneous emission will no longer be suppressed. The growth of the spontaneous emission will
have two measurable effects including the growth of side modes thus decreasing the side mode suppression ratio and an increase in the output power of the ECDL. Using a Burleigh wavemeter, an optical spectrum analyzer, and a photodetector, the output of the ECDL was studied in the following way. First, a computer set a voltage to the PZT used to tune the ECDL. Next, the operating frequency, an optical spectrum, and the voltage of an external photodiode were recorded. A new voltage was applied to the PZT and these measurements were repeated. A plot of the operating frequency and photodiode voltage as a function of the applied voltage to the PZT is shown in figure 3.8. The solid line represents the

![Plot of operating frequency and photodiode voltage](image)

Figure 3.8: A plot of the operating frequency shown as the solid line and photodiode voltage shown as the dashed line as a function of PZT voltage. The PZT voltage is used to electronically tune the ECDL. The photodiode voltage is measured using an external photodiode and this voltage is proportional to the output power of the ECDL.

operating frequency of the ECDL while the dashed line represents the photodiode voltage, which is proportional to the ECDL output power. In this figure we see that
Figure 3.9: A plot of the output power as a function of frequency measured using an optical spectrum analyzer. This optical spectrum was measured when the ECDL was tuned to location A shown in figure 3.8 on the previous page.

as the PZT voltage increases, the laser operating frequency decreases as well as the output power of the ECDL until a mode hop occurs at which time both the operating frequency and the output power experience a discontinuity as the ECDL experiences a mode hop. As the PZT voltage increases further, both the operating frequency and optical power decrease again until a second mode hop occurs. Because an OSA is used to capture an optical spectrum for each individual setting of the PZT voltage, a study of the evolution of the optical structure can be looked at. A plot of the optical spectrum is shown in figure 3.9 when the laser is tuned to the left of a mode hop labeled as point A in figure 3.8 on the previous page. In this figure the side mode suppression ratio is measured to be 41 dB. A plot of the optical spectrum is shown in figure 3.10 on the following page to the right of the mode hop labeled B in figure 3.8 on the previous page. In this figure, the amplified spontaneous emission is seen near
Figure 3.10: Plot of the output power as a function of frequency measured using an OSA. This optical spectrum was measured when the ECDL was tuned to location B shown in figure 3.8. Note the increase in the spontaneous emission in this optical spectrum as compared with the optical spectrum shown in figure 3.9. The increase in the spontaneous emission results in the higher output power of the ECDL as seen in figure 3.8.

the main laser mode. The effects of the spontaneous emission are to decrease the side mode suppression ratio to 38 dB while increasing the optical output power of the ECDL, as seen in figure 3.8 on page 32, by 4 percent. These results were obtained by tuning the ECDL with an increasing voltage applied to the PZT. Similar results occurred when the ECDL was tuned using a decreasing voltage applied to the PZT.

Looking at the optical spectra for each PZT voltage, a plot of the side mode suppression ratio as a function of applied voltage to the PZT can be generated. A plot of the side mode suppression ratio as a function of the voltage applied to the PZT is shown in figure 3.11 on the next page. The solid line represents the side mode suppression ratio while the dashed line represents the voltage seen by a photodiode monitoring the output power of the ECDL. As the ECDL is tuned via the PZT,
Figure 3.11: A plot of the side mode suppression ratio shown as the solid line and the photodiode voltage shown as the dashed line as a function of the PZT voltage used to tune the ECDL. The photodiode voltage is proportional to the output power of the ECDL. As the spontaneous emission grows due to the external cavity moving away from its resonance condition, the side mode suppression ratio decreases and the output power of the ECDL increases.

The side mode suppression ratio is increasing as the external cavity length begins to match the resonance condition and correspondingly the optical power decreases as the spontaneous emission is suppressed.

One way to keep the external cavity at the proper length to maintain the resonance condition as the ECDL is tuned is to monitor the output power of the ECDL. The external cavity length can be maintained in the resonance condition by adjusting the optical path length of the external cavity so that the output power of the ECDL remains constant. This idea is used to extend the continuous tuning range of an ECDL.
The ECDL will experience a mode hop when the change in the optical path length of the external cavity does not match the changing wavelength feedback into the diode laser due to the first order reflections from the optical grating. One way to make small corrections to the optical path length of the external cavity is to make small changes to the laser drive current, causing a change in the index of refraction due to a change in the carrier density as well as a change in the physical length of the diode due to thermal expansion. This method of correcting the optical path length of the external cavity will be exploited to extend the continuous tuning range of the ECDL.

A schematic of the experimental setup used to extend the continuous tuning range is shown in figure 3.12. The output from the ECDL described above is incident on a first beam splitter. Light reflected from the first beam splitter is incident on a photo detector while light transmitted through the first beam splitter is directed to a...
second beam splitter. The second beam splitter is used to send part of the light to a Burleigh WA-1500 Wavemeter or an Optical Spectrum Analyzer (OSA) via a single mode optical fiber while the remaining light is sent through a scanning flat plate Fabry-Perot interferometer. The Fabry-Perot interferometer has a free spectral range of 4.2 GHz with a measured finesse of 70. The scanning Fabry-Perot interferometer, which has a frequency resolution of 60 MHz, was used to confirm mode hop free operation of the ECDL as the laser is tuned. The current controller described above is used to provide a forward current to the ECDL. The dc set point of the current driver was set at 60mA throughout all the experiments described in this section of the thesis. The drive current resulted in an output power of 2.3 mW. A function generator was used to provide a small sinusoidal modulation to the dc set point. The modulation was set at 150 kHz and provided a sinusoidal additional current at 150 kHz with a peak current excursion of 1 µA. Thus, the sinusoidal modulation will broaden the laser line width by 1 µA * 1.25 GHz/mA = 1.25 MHz. The broadening of the ECDL laser line width does not present a problem when trying to measure spectral features on the order of GHz. The 1 µA current is also 47 dB below the dc drive current set point, so intensity variations due to the modulation can be neglected when considering the output power of the ECDL. The signal from the function generator was also used as a reference signal for a lock-in amplifier. The lock-in amplifier compares the phase of the reference signal from the function generator with the phase of the signal generated at the detector at the frequency set by the function generator and outputs a voltage related to this phase difference. The output of the lock-in amplifier is sent to a differential amplifier and this signal is compared to a reference voltage. The output of the differential amplifier is proportional to the difference between the lock-in amplifier and reference signal and is used as the input to the small signal correction port of the current driver.
To understand how the electronic feedback loop can be used to extend the tuning range of the ECDL, consider the output power as a function of the tuning voltage applied to the PZT shown in figure 3.8 on page 32. A small modulation signal is applied to the current set point causing the ECDL to tune. This small tuning will cause a small modulation in the output power of the ECDL. The lock-in amplifier compares the phase of the RF signal used to modulate the drive current with the phase of the modulated signal produced by the modulated output power of the ECDL as seen by a photodiode. The lock-in amplifier produces an output voltage related to this phase difference. The modulated output power of the ECDL changes when the ECDL is tuned near a mode hop due to the jump in optical power as seen in figure 3.8 on page 32. This change in the modulated signal due to the output power will have a different phase relationship compared to the RF signal used to modulate the drive current thus causing the voltage output of the lock-in amplifier to change. In this way the voltage output of the lock-in amplifier is used to monitor when the ECDL approaches a mode hop due to a mismatch in the external cavity resonance condition. The output voltage of the lock-in amplifier can be thought of as an error signal that is next conditioned with a differential amplifier. This conditioning consists of subtracting a dc offset voltage and provides the appropriate gain. The output of the differential amplifier is used to supply a voltage to the small signal port of the current controller. The voltage is converted into a current and this correction current is added to the current set point. The correction current changes the optical path length of the external cavity to bring the external cavity back into a resonance condition and in this way, mode hops are suppressed and the tuning range of the ECDL is extended.

A plot of the operating frequency as a function of the voltage applied to the PZT is shown in figure 3.13 on the next page. Without feedback, external cavity and facet mode hops are clearly visible. When the electronic feedback is connected, the
mode hops are suppressed. The ECDL can now tune over 65 GHz as demonstrated in figure 3.13.

Figure 3.13: A plot of the operating frequency as a function of voltage applied to the PZT with and without the electronic feedback connected. Without the electronic feedback, the ECDL experiences a 1 GHz mode hop for every 2.5 V applied to the PZT and a 26 GHz facet mode hop for every 24 V applied to the PZT. When the electronic feedback is connected, the external cavity and facet mode hops are suppressed as the laser is continuously tuned over 65 GHz. The continuous tuning in this case was limited by the fact that only 100 V can be applied to the PZT before the PZT is damaged.

The broadening of the laser line width due to the 150 kHz sinusoidal modulation needed to create the error signal was estimated to produce a laser line width of 1.25 MHz. This estimation results from realizing that the current tuning response was 1.25 GHz/mA while the sinusoidal modulation to the current had a peak current excursion of 1 $\mu$A. The above experiments were repeatable down to a minimum current excursion of 0.3 $\mu$A corresponding to a line width of 375 kHz. This narrow line width, while broader than a typical ECDL line width, is very narrow compared
to spectroscopic features of many molecules and should not limit the usefulness of tunable ECDL’s for spectroscopic experiments.

Once the extended tuning ECDL was successfully demonstrated at 760 nm, the method was reproduced and applied to water vapor differential absorption measurements at 830 nm where fast on-line and off-line tuning are required to obtain accurate water vapor number density profiles. The control loop consisting of two nested feedback systems used to monitor and control the DIAL transmitters wavelength was achieved using hardware and software feedback mechanisms. The electronic (hardware) feedback loop explained above as the extended tuning ECDL was used to prevent mode hops between on-line and off-line wavelength operation. A secondary nested control loop consisting mainly of electronic monitoring and software feedback was also implemented to control and stabilize the DIAL transmitter to within a target wavelength range of the specified on-line and off-line wavelengths [31]. The feedback loop used to control the DIAL transmitter will be described in further detail in section 3 on page 42.

The requirements for DIAL measurements with an error due to individual laser properties of less than three percent are stated in Bosenberg [25]. These properties arise due to 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, errors will arise in the water vapor retrievals owing to uncertainties in the actual cross section of the water vapor associated with transmitted laser light. The requirements for the laser transmitter for an error of less than three percent from individual laser properties include a linewidth of less than 298 MHz, a spectral purity of greater than 0.995, and a frequency stability of better than ±160 MHz [25]. The measured laser transmitter properties include a linewidth of less than 0.300 MHz, a spectral purity of 0.995, and a frequency stability
of ±88 MHz [31, 32, 38, 39]. Thus, the laser transmitter meets the requirements needed for accurate water vapor retrievals.

**DIAL Receiver**

A schematic of the DIAL receiver is shown in figure 3.14 on the following page. Light scattered by the atmosphere is collected using a commercial f/10 Schmidt-Cassegrain telescope (Celestron CGE1100) with a 28 cm diameter primary mirror, which gives a nominal effective focal length of 2.8 m for the telescope. Light collected by the telescope passes through a focus and is then incident on a collimating lens with a focal length of 10 cm. The collimated beam diameter is approximately 1.5 cm. The collimated light passes through a narrow band filter (BARR Associates) with a center wavelength of 828.06 nm (air) and a full width at half maximum linewidth of 0.2 nm. After the narrow band filter, the light is focused using a focusing lens with a focal length of 2.5 cm. The focused light is launched into a multimode fiber with a core diameter of 105 µm and a numerical aperture of NA=0.22 that acts as the system field stop. A fiber-coupled-photon-counting avalanche photodiode (APD) (Perkin-Elmer SPCM-AQR-13-FC) module with a 170 µm active area is used to detect the collected optical signal, yielding a far-field full-angle field of view of 150 µrad. The receiver optics were chosen so that the f number of the telescope and collimating lens are matched. The collimated light is needed because the transmission of the narrow-band optical filter is strongly dependent on the angle of incidence of the light on this filter. The focusing lens was chosen so that the f number associated with this lens matched the f number associated with the multimode optical fiber used to deliver the received light to the APD.
Figure 3.14: The f number of the telescope and the f number of the fiber coupling lens are matched to that of the collimating lens and the multimode fiber, respectively, to yield a far field full field-of-view of 150 $\mu$rad.

Data Collection

Automated control and data acquisition for the DIAL instrument is achieved using the Labview programming environment on a portable laptop computer. The data acquisition software works in the follow manner. The laser transmitter is first tuned onto a user-defined wavelength that corresponds to the peak absorption of a water vapor line at 828.0069 nm (828.187 nm) in air (vacuum). The wavelength of the laser transmitter is monitored using the light rejected from the first PBS shown in figure 3.1 on page 22 using a Burleigh Wavemeter (WA-1500), which has a frequency resolution of 88 MHz. The wavelength is polled every two seconds 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 of the selected wavelength. Next, an arbitrary waveform generator (AWG) is used to begin data collection from the APD and the multi channel scalar card (MCS) for 5 µs with the output from the laser transmitter turned off to obtain background measurements used for background subtraction during post-measurement data processing. After the 5 µs delay used for background measurements, the AWG triggers the AOM, creating a 1 µs pulse corresponding to a 150 m range bin at a 20 kHz pulse repetition rate, resulting in a 2 percent duty cycle for the first order diffracted beam from the AOM. During the 6 µs delay between the initial trigger and the end of the laser pulse, the MCS samples the APD data across 120 bins, each of width 50 ns. The subsequent return signal resulting from the laser interaction with the atmosphere accounts for the remaining 380 bins sampled by the MCS. These 380 bins correspond to 19 µs of return data. This process is repeated 25µs later and averaged 20,000 times over one second, yielding 400 range resolved range bins of 7.5 m each, corresponding to an altitude of 3.0 km. The data collection process is repeated for the on-line wavelength of 828.0069 nm (828.187) in air (vacuum) for a user-defined period of time, normally 60 seconds. The software then tunes the laser to the off-line wavelength of 828.1069 nm (828.287) in air (vacuum) and data is collected for a user-defined time, normally 60 seconds. This entire process is repeated for approximately one hour so that sufficient returns are obtained to begin calculating the range-resolved water vapor number density profile using the DIAL equation.

Once the data are obtained, MATLAB programs are used to analyze the raw returns. First, spectral filtering is achieved by analyzing the polled wavelength from the wavemeter so that only the data that meets the ±160 MHz of the selected wavelength requirements are considered for the water vapor profile measurement. Once the desired DIAL raw returns are obtained, the data are spatially averaged
Figure 3.15: Plot of the background subtracted atmospheric returns as a function of range. Sufficient overlap between the DIAL transmitter and receiver yields measurable atmospheric returns up to 2.5 km. The attenuated returns at the on-line wavelength are attributed to water vapor absorption through the lower troposphere. These measurements were taken starting at 21:09 (local time) on 9 March 2008 and calculated using 150-m vertical range bins which were averaged over 67 minutes.}

into sets of 20 bins according to the highest resolution defined by the transmitter pulse width of 300 meters for the 1 µs pulse which corresponds to a 150 m range bin size. Next, the raw returns are normalized by the reference power measurements and averaged on a second to second basis to account for the shot to shot laser intensity fluctuations. Finally, the spatially averaged background measurements obtained from the first 5 µs of data collected before each laser pulse are used to subtract background light counts from each range bin, yielding a plot of the range-resolved on-line and off-line return signals. A plot of the background-subtracted counts as a function of range from night time data taken on March 09, 2008 is shown in figure 3.15. The open and closed circles represent the on-line and off-line counts measured by the DIAL
instrument respectively. The processed atmospheric returns shown in figure 3.15 on the previous page are used with co-located radiosonde derived temperature and pressure measurements to calculate water vapor number density profiles using the DIAL equation presented in equation 2.11 on page 14. With the correction factor, $T_{corr(r)}$ set to zero, the only unknowns in the DIAL equation needed to calculate the water vapor number densities are the on-line and off-line absorption cross sections $\sigma$ at a given range $r$. The temperature profile obtained from the radiosonde measurements are then used in equation 2.15 on page 16 and equation 2.22 on page 18 along with the ground state energy transition $E''$ for the water vapor absorption line obtained from the Hitran database [41] to calculate the water vapor line absorption cross section as a function of range. Using the range dependent on-line and off-line cross sections together with the data shown in figure 3.15 on the previous page, equation 2.11 on page 14 can be used to calculate the water vapor number density as a function of range as shown in figure 3.16 on the next page. The water vapor number densities measured using the DIAL instrument show good agreement with the co-located radiosonde measurements above approximately 700 m. The deviations of the measured results using the DIAL instrument and the radiosonde below 700 m are best described by an angle-dependent wavelength detuning of the narrow band filter that is discussed in the next section. The error bars associated with the dial measurement were calculated based on a statistical variance in the shot to shot APD background noise and intrinsic noise. The noise characteristics of the DIAL instruments detector are described in greater detail in section 4 on page 58.
Figure 3.16: Vertical water vapor number density profile recorded starting at 21:09 (local time) on 9 March 2008 using the atmospheric returns obtained from figure 3.15 on page 44.
EXPERIMENTAL RESULTS AND INSTRUMENT CORRECTION FACTORS

DIAL Correction Factor

The correction factor, $T_{\text{corr}}(r)$, introduced in equation 2.11 and equation 2.12 on page 14 can be calculated in the following manner. The center wavelength, $\lambda$, for a narrow-band filter shifts to shorter wavelengths as the angle of incidence, $\theta$, of the incoming light increases. The center wavelength of the narrow band filter, $\lambda'$, can be written as [41]

$$\lambda' = \lambda_0 \cos \frac{\theta}{n} \quad (4.1)$$

where $\lambda_0$ is the center wavelength of the filter at $\theta = 0$ and $n$ is the index of refraction of the narrow band filter. The maximum angle of incidence on the filter can be calculated by considering the geometry of the receiver as shown schematically in figure 4.1.

Figure 4.1: Geometrical schematic of the DIAL receiver. Misplacement of the collimation optic behind the focal plane of the telescope denoted as $\varsigma$, results in wavelength detuning of the narrow band filter and results in false DIAL measurements.
Using the thin lens equation, a scattering center at a distance $r$ will produce an image formed by the telescope lens at a distance $d_1$ from the effective lens

$$d_1 = \frac{rf_t}{r - f_t} \quad (4.2)$$

While the telescope has a nominal focal length of 2.8 m, characteristic measurements of the telescope indicate that the effective focal length is $f_t = 2.807$ m. Using the image at $d_1$ as the object for the second collimating lens with a focal length $f_c$, the object distance from the collimating lens is found as

$$d_2 = f_t + f_c + \varsigma - d_1 \quad (4.3)$$

where the effective lens of the telescope and the collimating lens are separated by $f_t + f_c + \varsigma$. For the DIAL instrument described in this paper, $\varsigma = 2 \text{ cm}$. With $\varsigma = 2 \text{ cm}$, light from a point object at $r = 300 \text{ m}$ will pass through the filter with $\theta = 0$. Objects closer or farther than $r = 300 \text{ m}$ will pass through the filter with $\theta \neq 0$ and will experience a change in transmission due to a change in the angle of incidence on the filter. The image at $d_2$ will create an image associated with the collimating lens at

$$d_3 = \frac{d_2 f_c}{d_2 - f_c} \quad (4.4)$$

Finally, using the small angle approximation, the maximum angle of incidence for a ray incident on the narrow band filter, $\theta_{max}$, is

$$\theta_{max} = \frac{R}{d_3} \quad (4.5)$$

where $R$ is the radius of the nominally collimated beam seen after the collimating lens. A value of $R = 0.75 \text{ cm}$ was measured for the DIAL instrument.
The narrow-band filter has a center wavelength of $828.01 \pm 0.05 \ nm$ and a half width at half maximum (HWHM) value of $\Delta \lambda = 0.125 + / - 0.025 \ nm$. The transmission as a function of wavelength, $T(\lambda)$, has a Lorentzian profile that can be written as

$$T(\lambda) = T_0 \frac{\Delta \lambda^2}{\Delta \lambda^2 + (\lambda - \lambda')^2}$$

(4.6)

where $T_0 = 0.65$ is the maximum transmission of the narrow band filter. A plot of the narrow-band optical filter transmission as a function of wavelength is shown in figure 4.2 on the next page. The on-line, $\lambda_{on}$, and off-line, $\lambda_{off}$, wavelengths for the water vapor DIAL are also plotted in this figure. Taking into account the angle tuning of the filter as a function of $\theta$, equation 4.1 on page 47 can be substituted into equation 4.6 using a small angle approximation to yield the following filter transmission as a function of wavelength and angle of incidence

$$T(\lambda, \theta) = T_0 \frac{\Delta \lambda^2}{\Delta \lambda^2 + \left(\lambda - \lambda_0 - \frac{\lambda_0 \theta^2}{2n^2}\right)^2}$$

(4.7)

The effective transmission, $T_{eff}$, can then be found from

$$T_{eff}(\lambda) = \frac{1}{\theta_{max}} \int_0^{\theta_{max}} T(\lambda, \theta) \, d\theta$$

(4.8)

The effective transmission found in equation 4.8 is a function of range, $r$, since the maximum angle of incidence, $\theta_{max}$, is a function of range, $r$.

The effective transmission as a function of range for the water vapor DIAL instrument described in this thesis can be found using the above analysis. For these calculations, $\lambda_0 = 828.069 \ nm$, $\Delta \lambda = 0.1 \ nm$, $f_t = 2.807 \ m$, $f_c = 10.0 \ cm$, $\varsigma = 2.0 \ cm$, and $n = 1.4$. A plot of the maximum angle and the effective transmission for the on-line and off-line wavelengths are shown in figure 4.3 on page 51. Using these
Figure 4.2: Plot of the narrow band optical filter transmission as a function of wavelength. The on-line and off-line wavelengths in air for the water vapor DIAL instrument are also indicated.

results, the correction factor, $T_{corr}(r)$, is plotted as a function of range in figure 4.4 on the following page. Note that for $r = 300$ m in figure 4.4 on the next page, the correction factor is approximately zero, hence a zero incidence angle at the narrow band filter at this altitude can be seen in figure 4.3 on the following page as expected from the lens separation mentioned earlier. The correction factor affects the DIAL equation mostly for lower elevations where the light collected by the DIAL receiver experiences a larger maximum angle of incidence at the narrow-band filter that affects the overall filter transmission.

A plot of the water vapor profile using the DIAL equation presented in equation 2.11 on page 14 with the correction factor, $T_{corr}$, calculated above is shown in figure 4.5 on page 52. The solid line represents the water vapor profile measured using a co-located radiosonde while the circles connected by the dotted line represent
Figure 4.3: Plot of the maximum incident angle projected onto the narrow band filter along with the effective transmission for the on-line and off-line wavelengths as a function of range.

Figure 4.4: Plot of the correction factor $T_{corr}(r)$ as a function of range derived using equations 4.2 on page 48- 4.8 on page 49.
the measurements made using the DIAL instrument. For this data, the radiosonde temperature and pressure profiles were used to calculate the absorption cross section of the water vapor. Good agreement between the expected and measured profiles is now seen between 225 m and 2500 m.

![Graph](image)

Figure 4.5: Plot of the water vapor number density profile using the DIAL equation presented in equation 2.11 on page 14 with the correction factor, $T_{corr}$ included to correct for wavelength detuning in the narrow band filter as a function of altitude. The temperature and pressure profiles measured using the radiosonde were used to calculate the absorption cross section of the water vapor as a function of range. This profile was recorded starting at 21:09 (local time) on 9 March 2008 using the atmospheric returns obtained from figure 3.15 on page 44.
Adiabatic Lapse Rate Derived Profiles

The goal of the water vapor DIAL instrument is to collect water vapor profiles using a ground-based instrument. In the absence of radiosonde measurements, temperature and pressure profiles in the troposphere can be estimated using surface temperature, $T_s$, and surface pressure, $P_s$. The temperature in the lower troposphere, $T(r)$, is modeled using

$$T(r) = T_s + \gamma_a r$$

(4.9)

where $\gamma_a = -10$ K/km is the adiabatic lapse rate. Using this temperature profile, the pressure as a function of altitude is found using

$$P(r) = P_s \left[ \frac{T(r)}{T_s} \right]^{\frac{-g}{R_L \gamma_a}}$$

(4.10)

where $g$ is the gravitational constant and $R_L \left[ \frac{J}{Kg \cdot K} \right]$ is the dry-air gas constant.

Using the temperature and pressure profiles generated from equation 4.9 and 4.10, a water vapor profile was calculated based on the same data used for the water vapor profile shown in figure 4.5 on the previous page. Figure 4.6 on the following page shows a plot of the percent error as a function of range between the number density profile shown in figure 4.5 on the previous page using the radiosonde temperature and pressure profiles and the number density profile calculated using temperature and pressure profiles calculated from the surface temperature and pressure values and equation 4.9 and 4.10. The difference between these two measurements is less than 2 percent, indicating that water vapor profiles can be measured using the ground-based DIAL instrument, and a lapse rate profile using the surface temperature and surface pressure measurements when a clear and quiet atmosphere is present. Although the
Figure 4.6: Plot of the percent error as a function of range between the radiosonde derived temperature and pressure profiles and the calculated temperature and pressure profiles using equation 4.9 on the previous page and 4.10 on the preceding page used to calculate the water vapor number density profile.

A plot of the water vapor number density as a function of altitude for a second night is shown in figure 4.7 on the following page. This number density profile was calculated using the DIAL equation with the same correction factor calculated above. Because a lapse-rate atmosphere was present, the surface temperature and surface pressure measurements were used along with equation 4.9 and 4.10 on page 53 to
Figure 4.7: Plot of the water vapor number density as a function of altitude for a second night of data using the same correction factor used in figure 4.5 on page 52. Surface temperature and surface pressure measurements were used along with equation 4.9 and 4.10 on page 53 to calculate the temperature and pressure profiles used to then calculate the range dependent absorption cross section for the water vapor. These measurements were taken starting at 21:00 (local time) on 19 February 2008 and calculated using 150-m vertical range bins which were averaged over 78 minutes.

calculate the temperature and pressure profiles used to then calculate the range-dependent absorption cross section for the water vapor. The circles connected by the dotted line represent the measurements made using the DIAL instrument, while the solid line represents measurements made using a co-located radiosonde. Good agreement between the measured water vapor profile using the DIAL instrument and measurements using the radiosonde are demonstrated over the altitude range of 225 m to 2500 m.
The current DIAL instrument uses a lower pulse power of 0.125 $\mu J$ with a high pulse repetition frequency of 20 kHz to obtain enough return counts to measure water vapor profiles in the lower troposphere. One important question to be addressed for this instrument is how long of an averaging time is needed to obtain a sufficiently accurate water vapor profile. A plot of the water vapor profile as a function of altitude is shown in figure 4.8 on the following page for averaging times ranging from 2 minutes (one minute on-line, one minute off-line) to 78 minutes (33 minutes on-line, 45 minutes off-line). The solid circles with the error bars represent the measurements made using the DIAL instrument, while the solid line represents the water vapor profile measured using the co-located radiosonde. This figure indicates that a reasonable water vapor profile to within a 10 percent error relative to the in situ measurement can be obtained with about a 20 minute averaging time (10 minutes on-line, 10 minutes off-line).
Figure 4.8: Plot of the water vapor number density profile as a function of altitude for averaging times ranging from 2 minutes (one minute on-line, one minute off-line) to 78 minutes (33 minutes on-line, 45 minutes off-line). These measurements were taken starting at 21:00 (local time) on 19 February 2008 and calculated using 150-m vertical range bins.
Instrument Signal to Noise Ratio

Because the DIAL transmitter exhibits such low pulse energies, longer integration periods are required to retrieve adequate returns to calculate water vapor profiles. As integration periods increase, the signal to noise ratio (SNR) of the instrument also increases due to an increase in atmospheric returns, yielding more accurate range resolved water vapor profiles. Conversely, as integration periods increase for the DIAL instrument, the capability of retrieving water vapor profiles at high temporal resolutions become significantly less. In order to retrieve water vapor profiles on time scales approaching those of lower tropospheric cycles, a compromise between integration time and the SNR must be met. The signal to noise ratio for the DIAL instrument can be expressed as [49]

\[
SNR(r) = \frac{I(r)G}{\sqrt{eBG^2F(I(r) + I_{dark}) + 4eBI_{dark,nogain} + 4kTB}} \tag{4.11}
\]

where \( e \) is the charge of an electron, \( B \) is the bandwidth of the APD, \( G \) is the overall gain of the APD, \( I_{dark} \) is the dark current of the APD, \( k \) is Boltzmann’s constant, \( T \) is the temperature \([\text{K}]\), \( R_L \) is the load resistance, \( F \) is the excess noise factor, \( I_{dark,nogain} \) is the dark current that is not multiplied by the gain the gain \( G \) of the APD, and \( I(r) \) is the photocurrent generated by the APD from a scattered photon at a range \( r \) [49]. The photocurrent \( I(r) \) induced by incoming photon absorption forming an electron hole pair can be expressed as [49]

\[
I(r) = \frac{P(r)\lambda\nu Ge}{hc} \tag{4.12}
\]

where \( P(r) \) is the optical power of light scattered by the atmosphere at range \( r \), \( \nu \) is the quantum efficiency of the APD and \( h \) is Planck’s constant. From equations 4.11 and 4.12, it can be seen that by increasing the effective transmitted power, which is
Figure 4.9: Plot of the signal to noise ratio for the off-line wavelength for 1 second, 1 minute, and 1 hour averaged returns.

proportional to the number of transmitted laser shots (averaging time), the received photocurrent increases yielding a higher SNR for the instrument.

A plot of the SNR for 1 second, 1 minute, and 1 hour averaging times can be seen in figure 4.9.

The lidar returns corresponding to the 1 second, 1 minute, and 1 hour averaged returns used to calculate the SNR of the instrument shown in figure 4.9 can be seen in figures 4.10-4.12 respectively. As the number of averaged laser shots is increased, the presence of noise is averaged out and appears to decrease relative to the accumulated backscattered atmospheric returns, therefore allowing for accurate measurements of atmospheric water vapor to be obtained. At higher altitudes above approximately 2.5 km where the signal is drastically attenuated due to atmospheric absorption and scattering, temporal averaging of the backscattered returns gains an order of magnitude from approximately 1 to 10 in the SNR for a 1 second to a 1 hour averaging time respectively. An averaging time of approximately 20 minutes as discussed in sec-
Figure 4.10: Plot of lidar returns averaged over one second ($2 \times 10^4$ laser shots).

Figure 4.11: Plot of lidar returns averaged over one minute ($1.2 \times 10^6$ laser shots).
tion 4 yields a SNR of approximately 8.5, allowing for accurate water vapor profiles to be obtained up to 2.5 km to within 10 percent of an in situ co-located radiosonde measurement.

Water Vapor DIAL Side-Line Tuning

Obtaining accurate water vapor profiles up through the lower troposphere requires care in water vapor line selection as described in section 2 on page 14. Water vapor profiles shown in figures 3.16 and 4.7 were taken during the dry winter of months of 2008 where dry atmospheric conditions did not pose water vapor line saturation effects. In order to obtain accurate range resolved water vapor profiles, sufficient attenuated backscatter returns are needed to evaluate the DIAL equation. In order for the DIAL instrument to be operational year round, appropriate water vapor
Figure 4.13: Plot of the background subtracted atmospheric returns as a function of range. Sufficient overlap between the DIAL transmitter and receiver yields measurable atmospheric returns up to 2.5 km for the off-line wavelength. The attenuated returns at the on-line wavelength are attributed to high water vapor concentrations through the lower troposphere to the extent that little or no backscattered returns are collected at higher altitudes. These measurements were taken starting at 22:00 (local time) on 01 August 2008 and calculated using 150-m vertical range bins which were averaged over 60 minutes.

Absorption line strengths must be selected to accommodate to different atmospheric conditions. A plot of the background subtracted backscattered counts as a function of altitude for a third night during August of 2008 is shown in figure 4.13. Although the laser transmitter and receiver have a unity overlap function for the data shown in figure 4.13, the backscattered returns at the on-line wavelength have been attenuated due to water vapor absorption to the extent that no or little detectable backscattered returns are seen above an altitude of 1.6 km. The limited returns from figure 4.13 are a direct result from selecting too strong of a water vapor absorption line for the atmospheric conditions at that time, hence leading to a saturation effect at the same
Figure 4.14: Vertical water vapor number density profile recorded starting at 22:00 (local time) on 01 August 2008 using the atmospheric returns obtained from figure 4.13 on the preceding page. Water vapor line saturation can be seen around 1.5 km where the measured values begin to vary from the co-located radiosonde measurements.

range in the water vapor number density profile shown in figure 4.14. This number density profile was calculated using the DIAL equation with the same correction factor calculated above.

Because the narrow band filter used in the receiver exhibits a 0.2 nm FWHM pass band, a simple solution of choosing a weaker line strength water vapor absorption feature in the nearby vicinity to accommodate to the water vapor saturation affects could not be used. An alternative method was employed where the SOA output was controlled by locking the injection seeded ECDL to a water vapor absorption line by a wave-meter as described previously. The DIAL instrument was then operated by alternating between strong (line center) and weak (side of a strong line) water vapor absorption cross sections for the on-line DIAL wavelength in order to measure
Figure 4.15: Plot of the Lorentzian absorption cross section for the MSU DIAL water vapor line as a function of frequency denoted by the black solid line. The corresponding optical transmission for a given cross section and a round trip path length of 4 km can also be seen as the red dotted line. Both standard atmospheric pressure and temperature were used to calculate the absorption cross section.

Water vapor throughout the lower troposphere. By assuming that the majority of the measurement was made where pressure broadening was the dominant effect, the line center absorption cross section was scaled by a Lorentzian line shape as described in equation 2.17 such that the cross section could be obtained at any spectral position along the absorption feature. The absorption cross section can then be related to the round trip transmission of the transmitted light by equations 13-19. A plot of the absorption cross section denoted by the black solid line and the corresponding effective round trip transmission for a 4 km round trip path length shown as the dotted red line can be seen in figure 4.15. By side-line tuning on the cross section
Figure 4.16: Plot of the background subtracted atmospheric returns as a function of range. Side-line tuning on the absorption feature yields higher backscattered returns at higher altitudes. These measurements were taken starting at 23:00 (local time) on 01 August 2008 and calculated using 150-m vertical range bins which were averaged over 60 minutes.

From figure 4.15, a side-line tuning of 0.097 cm$^{-1}$ wavenumbers relative to line center yields a 50 percent decrease in the absorption cross section. Because the cross section and the round trip transmission of the transmitted light are related by an exponential as discussed in equations 13-14, a 50 percent decrease in the absorption cross section yields an 18 percent increase in the overall round trip transmission from approximately 5 percent to 23 percent. A plot of the background subtracted backscattered counts as a function of altitude using side-line tuning for the same night as the data shown in figure 4.13 is shown in figure 4.16.
Combining the on-line returns which provides range resolved water vapor profiles for lower altitudes before saturation effects dominate and the side-line tuning returns which provides more accurate water vapor profiles at higher altitudes yields a water vapor number density profile extending from the near surface to the lower troposphere. A plot of the combined water vapor profiles for the night of 01 August 2008 is shown in figure 4.17 on the next page. Good agreement between the DIAL results and the in situ co-located radiosonde measurements can be seen. The line center measurements shown in the blue provide accurate water vapor number densities up to approximately 1.5 km in which then saturation affects dominated. Superimposed on the same figure is the profile deduced from the side-line tuning returns where sufficient counts at higher altitudes provided accurate water vapor number densities relative to the in situ measurement.

The water vapor DIAL instrument at Montana State University is fully operational and is taking routine data. Although not yet a turn-key instrument, the water vapor DIAL is fully automated and accounts for several non-linear effects introduced by the receiving optics, and saturation effects presented by the atmosphere. Several nights worth of water vapor data both with and without an independent in situ measurement can be seen in figure 4.18 on page 68. The plots display the capability of the DIAL instruments repeatability in taking routine accurate night time range resolved water vapor number density measurements up through the lower troposphere.
Figure 4.17: A plot of the combined water vapor profiles from both the line center and detuned backscattered returns. These measurements were taken starting at 22:00 (local time) on 01 August 2008 and calculated using 150-m vertical range bins which were averaged over 120 minutes (60 minutes line center (blue line) and 60 minutes side-line tuning (red line)).
Figure 4.18: Plots of water vapor profiles taken with and without co-located radiosonde measurements during the winter and summer months of 2008.
CONCLUSION

A diode-laser-based DIAL instrument for measuring water vapor profiles in the lower troposphere has been built, tested, and has measured water vapor profiles across several nights that compare favorably with co-located radiosonde measurements. The laser transmitter is based on a widely tunable ECDL capable of accessing any water vapor absorption line in the 824 nm to 841 nm spectral region, an important capability that has been called for in other studies. Despite the low power limitations of the instrument, water vapor profiles with relatively low error values have been measured using the DIAL instrument and have compared favorably with data gathered from a co-located radiosonde, indicating that accurate water vapor profiles can be measured with an averaging time of approximately 20 minutes.

Accurate measurements of water vapor profiles, particularly at lower altitudes require care in using the DIAL equation. In particular, a correction factor has been introduced into the DIAL equation to take into account the effects of the angle of incidence of the collected light on the narrow band filter used in the DIAL receiver. The correction factor plays an important role in light scattered from lower altitudes because this scattered light will have a larger maximum angle of incidence on the narrow band filter, allowing water vapor profiles to be extended down to approximately 250 meters above the instrument.

Accurate measurements of water vapor profiles have also been retrieved up to higher altitudes during unfavorable conditions where the water vapor concentrations approached levels that saturated the water vapor absorption feature. Electronic sideline tuning was used to address the saturation effects by alternating between strong (line center) and weak (side of a strong line) water vapor absorption cross sections.
for the on-line DIAL wavelength such that adequate backscattered returns could be realized and accurate water vapor profiles could be calculated.

Future Work

Because the DIAL transmitter exhibits such low pulse energies, longer integration periods are required to retrieve adequate returns to calculate water vapor profiles. Work is currently underway at Montana State University to build a second generation water vapor DIAL instrument based on widely tunable ECDL’s and SOA’s to increase the output pulse energy of the instrument by a factor of 10 to 20, yielding maximum output pulse energies of $2 \mu J$ with a pulse repetition frequency of 20 kHz. The increase in power will allow for shorter integration periods that will provide range-resolved water vapor flux data on time periods approaching that of the lifetime of atmospheric cycles in the lower troposphere.

An alternative to the tapered amplifier approach for amplifying the output of the ECDL is also under investigation. The second approach will utilize an injection seeded diode laser pumped solid state laser based on a Cr:LiSAF gain medium. The improved performance of the laser transmitter has the potential to lead to the next generation of widely tunable DIAL instruments that in the future may be acceptable candidates for use in multi-point lidar networks or satellite arrays to study water vapor flux profiles.
REFERENCES CITED


