

A MICROPULSE DIFFERENTIAL ABSORPTION LIDAR FOR TEMPERATURE
PROFILING

by

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NOMENCLATURE

APD	Avalanche PhotoDiode
BSR	Backscatter Ratio
DBR	Distributed Bragg Reflector (laser)
DIAL	Differential Absorption Lidar
FOV	Field Of View
FWHM	Full Width Half Max
HITRAN	High-resolution TRANsmission molecular absorption database
HSRL	Hight Spectral Resolution Lidar
LIDAR	Light Detection And Ranging
MEMS	Micro-ElectroMechanical Systems
MPD	MicroPulse DIAL
MSU	Montana State University
NCAR	National Center for Atmospheric Research (NSF NCAR)
ORSL	Optical Remote Sensor Lab (at MSU)
TSOA	Tapered Semiconductor Optical Amplifier
WV	Water Vapor

ABSTRACT

This dissertation describes the development and testing of a Differential Absorption Lidar (DIAL) technique to retrieve temperature. This work showcases the accuracy of temperature retrievals using a perturbative technique, combining a DIAL measurement of a temperature-sensitive oxygen (O_2) absorption profile with a high spectral resolution lidar (HSRL) measurement of the backscatter ratio profile near 770 nm. This dissertation also introduces advancements to the DIAL temperature instrument and retrieval. First, the spectroscopic model used to represent absorption of light by O_2 has been enhanced, via a more complete physical representation, improving measurement accuracy. Second, the error estimation and masking have been developed using the bootstrapping technique. Third, a comparison of temperature profiles from the instrument with collocated radiosondes, evaluating the accuracy of updated measurements is performed. Finally, modeling of the lidar overlap function and atmospheric propagation and temperature retrieval allows for the modeling of sources of bias.

A test of the DIAL temperature instrument was performed by NSF NCAR (National Center for Atmospheric Research) in Fort Collins CO in 2021. The data were collected between June 17 and August 20, 2021. Radiosonde comparisons were available for comparison. Results show temperature comparisons with radiosonde that have a bias of about 1 °C and a standard deviation of about 3 °C.

Another test of the DIAL temperature instrument was performed at Montana State University. The laboratory-based lidar instrument was operated over a six-month period between April 21, 2022 and September 22, 2022. During this time, we launched 40 radiosondes, providing reference data to validate the accuracy of the DIAL-based temperature profiles. The results indicate that DIAL-based temperature retrievals are within ± 2.5 °C between 0.4 km and 3 km (3.5 km) range during daytime (nighttime) operation, using a 300 m range resolution and a 60 min averaging time.

INTRODUCTION

The introduction chapter will describe the atmosphere and its layers. It will then discuss the importance of thermodynamic profiling and existing thermodynamic profiling instruments. Afterwards, this chapter will present previous work on the MPD instruments and MPD architecture advantages. The temperature profiling component of DIAL will be introduced and my contributions to the temperature DIAL work will be presented.

Atmospheric Composition

The earth's atmosphere is separated into four layers that are named in order from the surface as the troposphere (0-12 km), stratosphere (12-50 km), mesosphere (50-86 km), and thermosphere (>86 km) as shown in Fig. 1.1. In the troposphere temperature decreases with height and in the stratosphere the temperature increases, they are connected at the tropopause. In the mesosphere the temperature again decreases with height from about 50 km to 85 km. The thermosphere is the thin outer part of the earth's atmosphere that extends into space.

The troposphere is mostly where weather occurs and is located from the ground up to about 12 km. Pressure in the troposphere decreases as a function of altitude and can be modeled from surface measurements. Temperature usually decreases linearly as a function of altitude and can be described by what is called a temperature lapse rate. A typical temperature lapse rate is $-6.5^{\circ}\text{C}/\text{km}$ where for every increasing kilometer in altitude the temperature decreases 6.5°C [44], but the lapse rate can vary from a moist adiabatic $-4^{\circ}\text{C}/\text{km}$ to a dry adiabatic $-9.8^{\circ}\text{C}/\text{km}$. Temperature inversions are layers where temperature increases with height. Normally the troposphere is well mixed, but

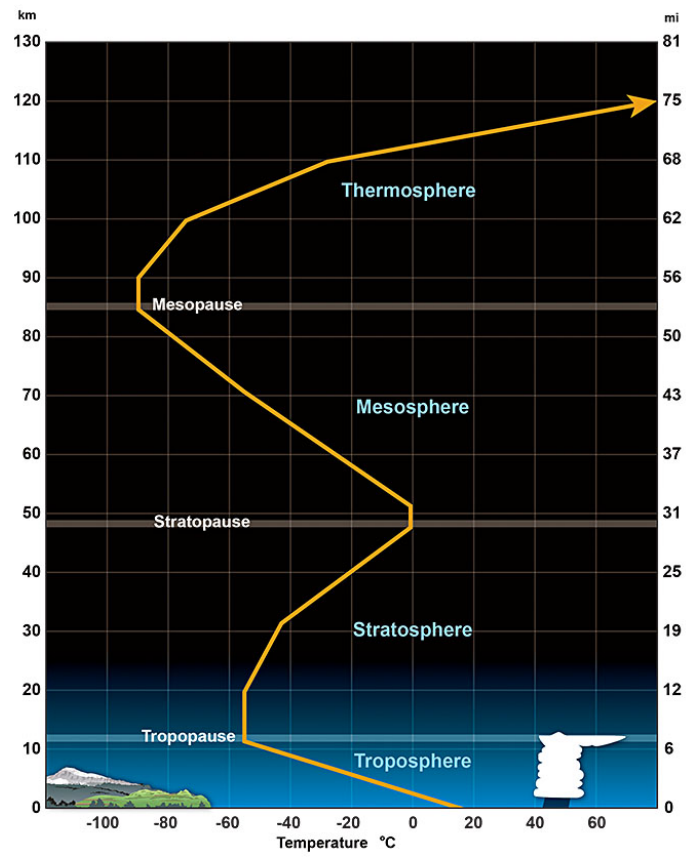


Figure 1.1: Average temperature profile for the lower layers of the atmosphere [52]

temperature inversions inhibit vertical mixing while strong temperature gradients result in convective mixing [75].

The lowest layer within the troposphere is the atmospheric boundary layer, which is the part of the atmosphere that is in direct contact with the Earth’s surface. During the day, surface heating causes buoyantly-driven convective mixing, lifting surface constituents, like moisture and aerosols, into the atmosphere. The average convective boundary layer heights over land range from 1 to 2 km. At night, the boundary layer is driven by turbulent drag at the Earth’s surface, resulting in less significant mixing and a lower boundary layer height, generally ranging from 100 to 200 m. Often, moist and aerosol-dense air from the previous day’s convective boundary layer remains lofted over a stable layer, forming a residual layer. This residual layer is moist and aerosol-dense while remaining decoupled from surface conditions. The transition between the convective boundary layer or the residual layer and the free troposphere is known as the capping inversion, characterized by a steep decrease in absolute humidity and aerosol density.

Thermodynamic Profiling

Thermodynamic profiling, including absolute humidity and temperature, of the lower troposphere is important for understanding the state of the atmosphere and its importance for many atmospheric science applications as well as weather forecasting. The need for thermodynamic profiling has been expressed by the National Research Council [42, 43] and by a report to the National Science Foundation and National Weather Service [26] and a National Academies of Sciences, Engineering, and Medicine report [6]. Huge observational gaps exist with respect to thermodynamic profiling in the lower troposphere. Many instruments and techniques are available to fill the needs for lower tropospheric measurements, including passive and active sensing systems. Low-cost lidar systems have been identified for their potential to address the observational thermodynamic profiling need

[81]. As noted by Wulfmeyer et al., “Networks of ground-based passive and active remote sensing systems operating in the optical, IR, and MW spectral regions have the potential to close major gaps with respect to lower tropospheric TD [thermodynamic] profiling.” The World Meteorological Organization (WMO) requirements for a threshold (breakthrough) technology are 3 K (1 K) accuracy for a time period of 6 h (60 min) and a vertical resolution of 1 km (0.25 km) for global high-resolution numerical weather prediction for the lower troposphere [53].

Current Profiling Instruments

Passive thermodynamic profilers include infrared radiometers like the Atmospheric Emitted Radiance Interferometer (AERI) [28, 29, 73] and microwave radiometers [59, 74] and are a mature technology used for good effect in science campaigns and weather forecasting. Passive remote sensing profilers typically have lower spatial and temporal resolution than active profilers. At 1 km above ground level AERI has a resolution of almost 2 km which increases with range [5]. Microwave radiometers require an internal cooled blackbody for calibration and passive radiometers require a priori information for profile retrieval. Passive profilers also have large errors under clouds and have difficulty when temperature inversions are present. However, in the atmospheric boundary layer, passive sensors can have very accurate measurements. Low-level temperature inversions can be measured by vertically scanning [15, 62, 77]

Raman lidar systems are an active remote sensing technology that can deliver a full thermodynamic profile of the lower troposphere [33, 50, 51, 78, 79]. The water vapor mixing ratio can be measured using vibrational inelastic Raman scattering and temperature can be measured using rotational inelastic Raman scattering. Temperature measurements with Raman lidar use a ratio of two wavelengths of inelastic rotational transitions of N_2 and O_2 . The ratio of rotational transitions is a relative measurement and calibration must be

done with ancillary radiosonde measurements. Raman lidar can be used to measure the water vapor mixing by determining the ratio of vibrational inelastic scattering between water vapor and N_2 . Since the measurement is a ratio and dependent on lidar overlap the measurements must also be regularly calibrated with radiosonde measurements [34, 50]. Implementation of Raman systems can come with challenges. The small Raman scattering cross section in the atmosphere requires high power lasers that can be complex and do not favor unattended operation or eye safety. Rotational Raman lidars are unable to utilize etalons as spectral filters or ultra-narrow interference filters and thus struggle to profile temperature during the day. Raman systems usually have high initial and maintenance costs and must be regularly calibrated using radiosondes, making them unsuited for unattended long-term network deployment.

Differential absorption lidar (DIAL) is a technique that utilizes elastic scattering which is three orders of magnitude more efficient than Raman scattering. This means that lower-power semiconductor lasers can be used that provide the benefits of high stability and low cost. Semiconductor-based lasers and amplifiers are also commercially available and can be wavelength tuned and cover the near infrared spectral region containing many gas absorption features of interest. DIAL uses the differential absorption between two closely spaced wavelengths to calculate the electromagnetic absorption of a specific molecule in the atmosphere. The laser wavelengths are chosen based on the absorption spectrum of the molecule to be measured. The online wavelength is placed on a narrow absorption line of the molecule of interest and the offline wavelength is placed just off of the absorption line so that the only difference between the light received by the DIAL due to the atmospheric scattering at the two wavelengths results from the absorption due to the molecule of interest. The laser spectrum must have a narrow bandwidth and high frequency stability for accurate DIAL measurements. The narrow bandwidth also allows for the ability to use ultra-narrowband etalons and/or interference filters for blocking of sunlight. Semiconductor micropulse DIAL

(MPD) systems can be eye-safe and can provide the needed frequency stability for long-term unattended operation. Large telescope area and low power transmit pulses ensure eye safety. DIAL systems do not need calibration with radiosondes because the DIAL technique is a direct measurement of absorption, allowing recovery of the gas concentration. Water vapor number density profiling with diode-laser-based micropulse DIAL systems has been proven to be reliable [46–49, 56, 64, 65, 76].

Temperature Profiling With DIAL

The temperature profile can be retrieved from DIAL by measuring the O_2 absorption. Figure 1.2 shows the O_2 absorption coefficient as a function of temperature. The main contribution to the absorption temperature dependence is the absorption linestrength. The linestrength temperature dependence is based on the ground state energy of the absorption line. There are many other factors that affect the absorption temperature dependence but can all be calculated from known molecular absorption models and measured values from the high-resolution transmission molecular absorption database (HITRAN) [20]. Many factors are also dependent on pressure but pressure can be calculated from measured surface pressure and a temperature profile. The absorption spectrum is broadened by temperature dependent Doppler broadening and pressure and temperature dependent Lorentz broadening. The absorption line is shifted in wavelength by a pressure dependence. The absorption is affected by the molecular density in air which is dependent on temperature and pressure by the ideal gas law. The absorption calculation is presented in Ch. 2 Sec. 2.

Theopold and Bösenberg have demonstrated that atmospheric temperature measurements are theoretically possible using a temperature-sensitive oxygen (O_2) absorption line [72] using work performed in the decade before [1, 2, 31, 38]. However, in practice, the measurement of temperature is difficult. The temperature must be found by using an iterative process from an initial seed temperature profile and the measured O_2 absorption.

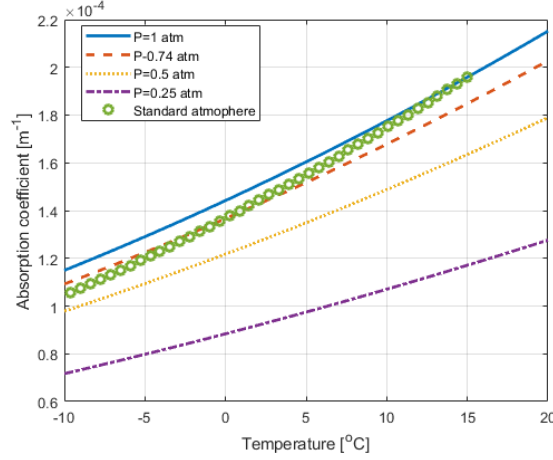


Figure 1.2: Absorption coefficient of O_2 as a function of temperature. Multiple pressure levels are shown from 1 atmosphere to 0.25 atmospheres. The circles represent the U.S. Standard Atmosphere[44].

Small errors in the measured absorption can lead to large errors in temperature. Furthermore, in the absorption measurement the broadening in wavelength of the backscattered lidar signal from molecular scattering must be accounted for. The backscattered light from molecules is spectrally broadened to a width comparable to the width of the absorption line itself, about 1 GHz. The spectrum of the backscattered light from aerosols is nearly identical to the spectrum of the laser transmitter. Therefore, temperature measurements using DIAL are sensitive to the ratio of aerosol to molecular backscatter. Bösenberg showed if this effect is not taken into account errors of greater than 10 °C can result [9]. The O_2 absorption spectrum and a model of molecular backscatter and a scan of the lidar receiver is shown in Fig. 1.3. This figure shows the O_2 absorption spectrum and the online and offline wavelength to demonstrate the DIAL retrieval. The figure also shows the Doppler backscatter linewidth for each wavelength in black to show the similar linewidth between the absorption linewidth and backscatter linewidth that can result in errors. The optical receiver spectrum for the molecular channel is shown in blue showing the etalon transmission at each wavelength to reduce background light. In this paper, the ratio of total backscatter to molecular backscatter

will be referred to as the backscatter ratio (BSR). Modeling studies have been used to prove that measurements with accuracies of $\pm 2^\circ\text{C}$ are possible with knowledge of the BSR [57]. The BSR is measured with a high spectral resolution lidar (HSRL) and this ability has allowed temperature profiling with DIAL to be possible. The DIAL instrument uses an integrated HSRL channel to obtain the backscatter lineshape and a perturbative solution to the DIAL equation is used to apply a correction factor, dependent on the BSR, to what the DIAL instrument measures [12, 57, 67, 68].

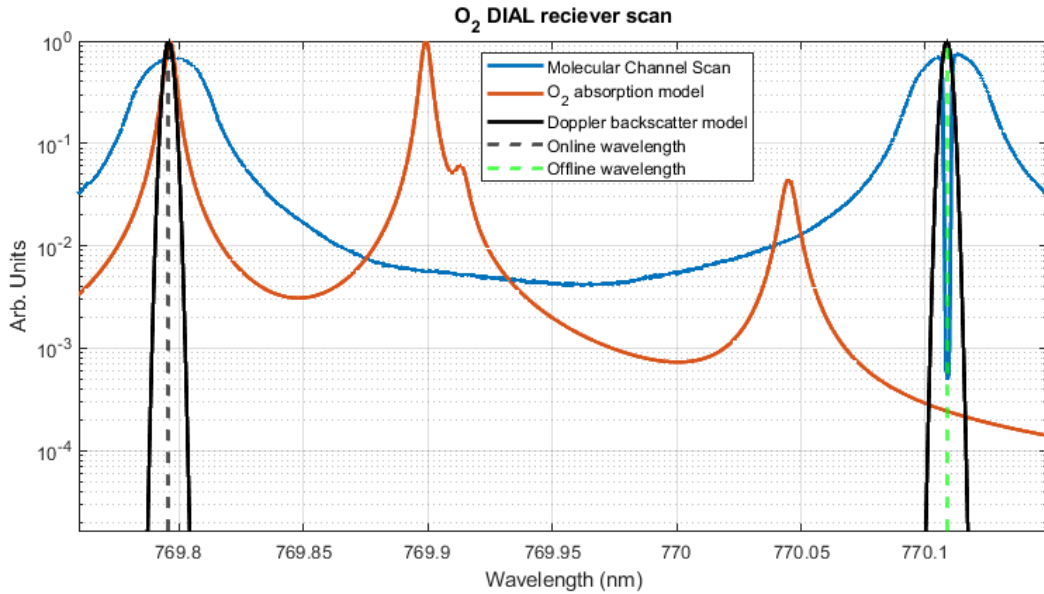


Figure 1.3: Section of the calculated O_2 absorption spectrum in red with the calculated Doppler backscatter spectrum in black and measured receiver transmission spectrum of the molecular channel in blue. The online and offline laser wavelengths are represented by the dashed vertical lines. The O_2 absorption cross section is taken at 300 K. The combined channel absorption spectrum is identical to the molecular channel without the KD_1 absorption line shown as the large dip at the offline wavelength. The online wavelength is chosen at the line center of the 769.7958 nm O_2 absorption line and the offline wavelength is chosen at the line center of the KD_1 line at 770.1085 nm.

A high spectral resolution lidar uses a single laser wavelength and two receiver channels to separate aerosol and molecular scattering [23, 63]. One channel uses an atomic vapor absorption cell to filter narrow scattering from aerosols leaving the Doppler

broadened molecular backscatter signal intact. The other channel detects both the molecular backscatter and aerosol backscatter combined. A spectral scan of both receivers is necessary to measure frequency dependent transmission to provide calibration constants. A spectral scan of the molecular channel is shown in Fig. 1.3 where the atomic absorption line can be seen as a narrow dip in the blue at the offline wavelength. Using the measured signals and calibration constants, the aerosol backscatter profile can be retrieved. The planetary boundary layer height can be found by locating steep gradients within these profiles [16]. Some of the specifications of the DIAL and HSRL system are listed in Table 4.1.

Past Work on Micropulse DIAL

In my M.S. thesis I described the development of the MPD instrument. In this dissertation, I discuss the work on the retrieval algorithm and results from a validation experiment. Improvements I have made to the retrieval algorithm beyond Repasky et al. [57] include adding multiple O_2 absorption lines to the iterative temperature retrieval process, improving the model of pressure used in the retrieval based on the retrieved temperature, improving the speed and generalization and accuracy of the MATLAB code, and an error estimate of temperature.

An MPD temperature profiling instrument has been built at MSU and three more have been built at the NSF National Center for Atmospheric Research (NCAR) in Boulder, Colorado. A combination of DIAL to measure the temperature-sensitive O_2 absorption line and a high spectral resolution lidar (HSRL) to measure the BSR are used together with the same instrument and is based on the water vapor MPD architecture. Another DIAL to measure water vapor absolute humidity is integrated into the MPD. The MPD is designed using mostly off the shelf components and designed for unattended operation by using components such as fiber coupled diode lasers. Currently the MPD at MSU does not have an integrated water vapor DIAL, but a final version of the MPD and some of the current

NCAR MPDs have water vapor profiling capabilities. The instrument located at MSU is in a rooftop equipped laboratory and is shown in Fig. 4.2.

My Contributions to the Micropulse DIAL

At the chosen O_2 absorption line, another small line underlying the main line is present. Using the HITRAN line parameters the total absorption needed for the absorption retrieval can be calculated by adding the absorption of the lines together. The iterative temperature retrieval uses line parameters to convert absorption to temperature. I have added a method of using multiple absorption lines in the iterative temperature retrieval process to increase the accuracy of the temperature retrieval.

The HSRL retrieval, perturbative absorption correction, and iterative temperature retrieval require a model of temperature and pressure as a function of range. An inaccurate model can lead to small errors in temperature that may increase with altitude. A temperature model can be made from the recorded surface temperature with a linear $-6.5^\circ\text{C}/\text{km}$ lapse rate. A pressure model can be made from the surface pressure and the temperature model. These models can be inaccurate due to large differences in temperature at the surface and in the bulk troposphere or changes in lapse rate or temperature inversions. I have developed a method to attempt to minimize the errors in the temperature retrieval from the model by using the final retrieval temperature. Once the new models of temperature and pressure are created the retrieval can use them in a second iteration of the HSRL, absorption, and temperature retrieval.

My contributions to the MPD project include, building a functional temperature profiling system with an O_2 DIAL and HSRL, operating and testing the operation of the system, collecting data and launching radiosondes for comparison, writing a full retrieval program in MATLAB with an error estimate, developing a technique for adding multiple O_2 absorption lines to the temperature retrieval, incorporating a model of pressure

to increase the accuracy of the temperature retrieval, investigating the results of the DIAL measurements, building a model of the lidar overlap function and the atmospheric propagation to investigate sources of error or bias in the temperature retrieval.

Dissertation Organization

This dissertation is organized as follows: the theory of lidar, atmospheric absorption, and the DIAL temperature retrieval is presented in chapter 2. Chapter 3 presents the method of temperature retrieval and error estimate. Chapter 4 provides an overview of the micropulse DIAL hardware. The modeling of the MPD hardware and the atmospheric propagation and temperature retrieval is presented in chapter 5. A discussion of the results of testing campaigns is presented in chapter 6. Finally, some brief concluding remarks are presented in chapter 7.

THEORY

This chapter presents the theory of the lidar equation, molecular absorption cross section, DIAL retrieval, perturbative DIAL correction, the iterative temperature retrieval, and the HSRL retrieval.

The Lidar Equation

The single scattering lidar equation [32, 39] describes the received optical power, $P(\nu, r)$, as

$$P(\nu, r) = P_t(\nu) \frac{A}{r^2} \Delta r \beta(\nu, r) T^2(\nu, r) \eta_O(r) \eta_R(\nu, r) \eta_D(\nu, r) + B. \quad (2.1)$$

The equation is a function of the variables ν and r which are the wavenumber in inverse meters and range from the receiver in meters. The transmitted power is expressed as $P_t(\nu)$ and is in units of watts. It is assumed the transmitted pulse does not vary over time. The instrument parameters are A as the telescope receiver area in m^2 , Δr is the range resolution in meters, $\eta_O(r)$ is the lidar system overlap function and is unitless, $\eta_R(\nu, r)$ is the unitless receiver efficiency, and $\eta_D(\nu, r)$ is the unitless detector efficiency. The atmospheric parameters are the backscatter coefficient $\beta(\nu, r)$ in inverse meters per steradian, and the two-way transmission $T^2(\nu, r)$ which is unitless. The background is represented as B and is assumed to be constant in range and wavelength/wavenumber. The power can be converted to a photon signal rate by $N(\nu) = hc\nu$, where h is Plank's constant, c is the speed of light, and ν is the wavenumber. Hereafter, the lidar signal will be represented by N .

The backscatter and transmission can be broken up into aerosol and molecular components as

$$\beta(\nu, r) = \beta_a(\nu, r) + \beta_m(\nu, r) \quad (2.2)$$

and

$$T^2(\nu, r) = \exp \left(-2 \int_0^r (\alpha_a(\nu, r) + \alpha_m(\nu, r)) dr \right), \quad (2.3)$$

where the subscripts a and m represent the aerosol and molecular components and α is the optical absorption coefficient with units of inverse meters.

The DIAL equation can be derived from the lidar equation, Eq. 2.1. DIAL is used to measure the optical absorption as a function of range of a specific molecule with two laser wavelengths. All factors between the two wavelengths are assumed to be equal except for the absorption specific molecule of interest. This assumption is based on the small separation in wavelength for the online and offline wavelengths, typically about 0.1 nm. With closely spaced wavelengths it can be assumed that aerosol and molecular backscatter at both wavelengths are equal and aerosol absorption and absorption due to other molecules at both wavelengths are equal. With these assumptions a new lidar equation can be written as

$$\begin{aligned} N_{(1,2)}(\nu, r) = & N_{t,(1,2)}(\nu) \frac{A}{r^2} \Delta r (\beta_a(\nu, r) + \beta_m(\nu, r)) \\ & \exp \left(-2 \int_0^r (\alpha_a(\nu, r) + \alpha_m(\nu, r)) dr \right) \\ & \exp \left(-2 \int_0^r \alpha_{O_2,(1,2)}(\nu, r) dr \right) \eta_O(r) \eta_R(\nu, r) \eta_D(\nu, r) + B. \end{aligned} \quad (2.4)$$

Since the molecule of interest is oxygen, the subscript O_2 represents this atmosphere constituent. The subscripts 1 and 2 represent the DIAL online and offline wavelength.

Absorption Cross Section

The absorption coefficient is represented as

$$\alpha(\nu) = n\sigma(\nu), \quad (2.5)$$

where n is the atmospheric molecular number density in units of inverse meters cubed and σ is the molecular absorption cross section in units of meters squared. The molecular absorption cross section can be calculated with parameters in the HITRAN database [20] with specific parameters for the O₂ A-band in Drouin et al. [18].

The absorption line strength is calculated as

$$S(T) = S(T_0) \frac{Q(T_0)}{Q(T)} \frac{\exp(-hcE''/k_B T)}{\exp(-hcE''/k_B T_0)} \frac{[1 - \exp(-hc\nu_0/k_B T)]}{[1 - \exp(-hc\nu_0/k_B T_0)]}, \quad (2.6)$$

where $T_0=296$ K is the reference temperature, $Q(T_0)/Q(T)$ is the total internal partition sum ratio and for O₂ can be approximated as T_0/T at temperatures near the reference temperature, h is Plank's constant, c is the speed of light, k_B is Boltzmann's constant, E'' is the ground state energy of the line in inverse centimeters, and ν_0 is the line transition wavenumber (for water vapor the total internal partition sum ratio can be approximated as $(T_0/T)^{1.5}$). The transition wavenumber is shifted by pressure as,

$$\nu = \nu_0 + \delta_{air}(P_0)P \quad (2.7)$$

where P is the atmospheric pressure and δ is a shift parameter at the reference pressure of one atmosphere. With a self broadening parameter the equation is

$$\nu = \nu_0 + \delta_{air}(P_0)(P - P_{self}) + \delta_{self}(P_0)P_{self}. \quad (2.8)$$

With a temperature dependence of the lineshift the equation is

$$\delta = \delta_{air} + (T - T_0)\delta'_{air}. \quad (2.9)$$

The temperature dependence term, δ' , is assumed to be zero for this work.

The absorption cross section is broadened spectrally by atmospheric pressure and can be represented by a Lorentzian line shape with a half width of

$$\gamma_L = \gamma_0 \left(\frac{P}{P_0} \right) \left(\frac{T_0}{T} \right)^{n_{air}}, \quad (2.10)$$

where γ_0 is the reference Lorentzian half width and n_{air} is the linewidth temperature dependence parameter. The Lorentzian half width can also be used with a self broadening parameter or other gas as,

$$\gamma_L = \gamma_0 \left(\frac{P - P_{self}}{P_0} \right) \left(\frac{T_0}{T} \right)^{n_{air}} + \gamma_{self} \left(\frac{P_{self}}{P_0} \right) \left(\frac{T_0}{T} \right)^{n_{self}}, \quad (2.11)$$

where pressure broadening is negligible the temperature broadening dominates. The temperature broadening can be represented by a Doppler Gaussian distribution with a half width of

$$\gamma_D = \left(\frac{\nu_0}{c} \right) \left(\frac{2kT \ln(2)}{m} \right)^{1/2}, \quad (2.12)$$

where $\ln$ is the natural log and m is the mass of an O_2 molecule. For the work here, only the air broadening parameters are used because it is assumed O_2 broadening is included in the air broadening term.

The combination of the pressure broadening and temperature broadening can be approximated as a Voigt profile. The Voigt profile can be calculated using the equation

$$V(x, y) = \frac{\sigma(x, y)}{K} = \frac{y}{\pi} \int_{-\infty}^{\infty} \frac{\exp(-t^2)}{y^2 + (x - t)^2} dt, \quad (2.13)$$

where $\sigma(x, y)$ is the absorption cross section, $x = \left(\frac{\nu - \nu_0}{\gamma_D} \right) (\ln(2))^{1/2}$, $y = \left(\frac{\gamma_L}{\gamma_D} \right) (\ln(2))^{1/2}$, and $K = \left(\frac{S(T)}{\gamma_D} \right) \left(\frac{\ln(2)}{\pi} \right)^{1/2}$. The Voigt profile can then be solved for the absorption cross section. The parameters taken from HITRAN for each absorption line are S_0 , ν_0 , E'' , γ_0 , n_{air} ,

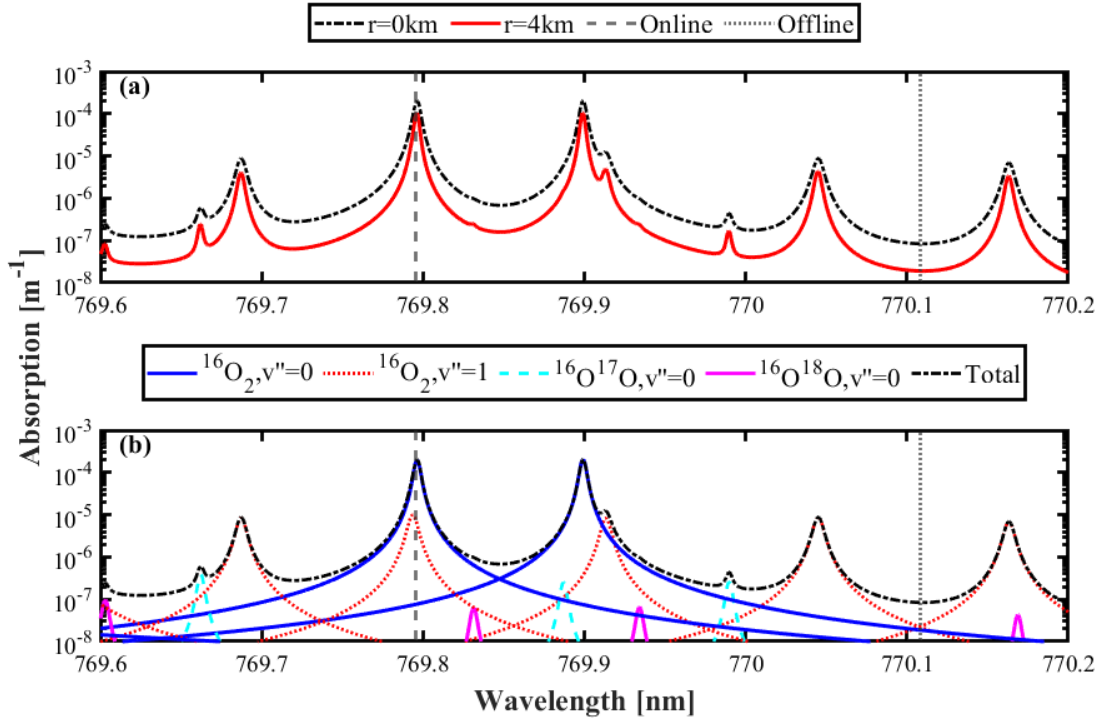


Figure 2.1: (a) O₂ absorption spectrum in the wavelength region of interest. The model is shown at the ground and at a range of 4 km (assuming the 1976 US Standard atmosphere[44]). (b) The total O₂ absorption spectrum as dot-dashed black line and each individual absorption line in the region of interest at the surface. Dashed vertical lines represent the online and offline DIAL wavelengths. All lines used are listed in Table C.1 in Appendix C.

and δ_{air} shown in Table C.1 in Appendix C. The calculated O₂ absorption is shown in Fig. 2.1. Figure 2.1a shows how the absorption strength and shape changes with temperature and pressure according to altitude. Figure 2.1b shows all of the individual absorption lines in the region of interest.

Some more accurate methods of calculating the molecular absorption cross section exist such as speed-dependent Voigt profiles [21, 35–37, 55, 61, 70], however, the extra parameters are zero for the O₂ absorption lines that are used by the MPD. This work uses parameters found in the HITRAN 2016 database.

The DIAL equation [60] can be described in the diagram in Fig. 2.2. The return signal

as a function of range (I) is shown as the red (offline) and blue (online). The signal is the same for the online and offline channels other than the specific gas of interest. In the diagram there is a gas layer of interest with a specific height and a consistent number density. As both the online and offline signals pass through the layer, the online is absorbed and the offline is not. The ratio of the two signals is constant outside the layer because of the assumption that absorption and scattering for the two wavelengths is the same other than the gas of interest. The online and offline wavelengths may also have different transmitter power but this has no effect on the DIAL retrieval since the DIAL equation relies on the ratio of return signals. In the gas layer, the ratio of the two wavelengths is an exponential due to absorption so a natural logarithm of the ratio is taken to make it linear. The derivative in range of the natural log ratio is then taken to find the difference in absorption between the online and offline channels.

The ratio of the online and offline signal from the lidar equation, Eq. 2.1, assuming only P_t and $T^2(r)$ are different between the online and offline wavelengths is

$$\frac{N_1(r)}{N_2(r)} = \frac{N_{1,t}}{N_{2,t}} \frac{T_1^2(r)}{T_2^2(r)} = \frac{N_{1,t}}{N_{2,t}} \frac{\exp(-2 \int_0^r \alpha_1(r') dr')}{\exp(-2 \int_0^r \alpha_2(r') dr')}, \quad (2.14)$$

taking the natural log of both sides

$$\ln(N_1(r)) - \ln(N_2(r)) = \ln(N_{1,t}) - \ln(N_{2,t}) - 2 \int_0^r \alpha_1(r') dr' + 2 \int_0^r \alpha_2(r') dr', \quad (2.15)$$

taking the derivative in range of both sides cancels the transmitted powers,

$$\begin{aligned}
\frac{d}{dr} [\ln(N_1(r)) - \ln(N_2(r))] &= \ln(N_1(r + \Delta r)) - \ln(N_2(r + \Delta r)) - [\ln(N_1(r)) - \ln(N_2(r))] \\
&= -2 \int_0^{r+\Delta r} \alpha_1(r') dr' + 2 \int_0^{r+\Delta r} \alpha_2(r') dr' \\
&\quad - \left[-2 \int_0^r \alpha_1(r') dr' + 2 \int_0^r \alpha_2(r') dr' \right],
\end{aligned} \tag{2.16}$$

and evaluating the integral cancels the value at $r=0$ and assuming the pulse is relatively short and α varies only slightly over Δr results in

$$\begin{aligned}
&\ln(N_1(r + \Delta r)N_2(r)) - \ln(N_1(r)N_2(r + \Delta r)) \\
&= -\frac{2\Delta r\alpha_1(r + \Delta r)}{2} + \frac{2\Delta r\alpha_2(r + \Delta r)}{2} - \left[-\frac{2\Delta r\alpha_1(r)}{2} + \frac{2\Delta r\alpha_2(r)}{2} \right] \\
&= -2\Delta r(\alpha_1(r) - \alpha_2(r)).
\end{aligned} \tag{2.17}$$

This simplifies to the DIAL equation

$$\alpha_{online}(r) = \alpha_{offline}(r) - \frac{1}{2\Delta r} \ln \left(\frac{N_1(r + \Delta r)N_2(r)}{N_1(r)N_2(r + \Delta r)} \right). \tag{2.18}$$

The number density of the gas (i.e. for water vapor profiling) can be found using the relation $\alpha(r) = \sigma(r)n(r)$ where σ is the absorption cross section and n is the number density.

The number density is calculated using the equation

$$n(r) = -\frac{1}{(\sigma_{online} - \sigma_{offline})} \frac{1}{2\Delta r} \ln \left(\frac{N_1(r + \Delta r)N_2(r)}{N_1(r)N_2(r + \Delta r)} \right). \tag{2.19}$$

The central difference numerical derivative may improve the error [41] and does not

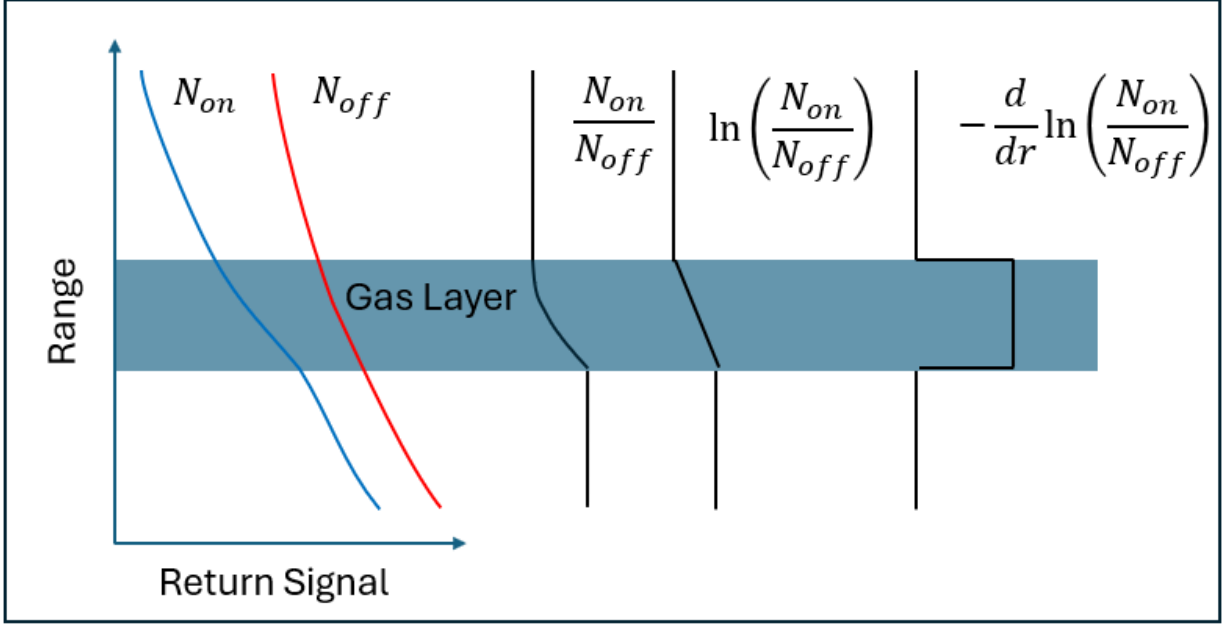


Figure 2.2: Diagram of the DIAL process.

require a shift and can be written

$$\alpha_{online}(r) = \alpha_{offline}(r) - \frac{1}{4\Delta r} \ln \left(\frac{N_1(r + \Delta r)N_2(r - \Delta r)}{N_1(r - \Delta r)N_2(r + \Delta r)} \right). \quad (2.20)$$

Perturbative DIAL correction

The first step in the temperature retrieval is to use the perturbative solution to the DIAL equation to retrieve the O_2 absorption coefficient. Once the O_2 absorption profile is retrieved, the temperature profile is then estimated. The perturbative solution requires an initial guess at the temperature profile. For calculations presented in this dissertation, the initial guess at the temperature profile will consist of the surface temperature and a simple lapse rate. Furthermore, completion of the retrieval of the O_2 absorption coefficient requires a model of the molecular backscatter profile and the retrieval of the aerosol backscatter

coefficient based on the HSRL data. The following is a summary of theory presented in Repasky et al. [57] and Bunn et al. [12] with changes to improve the pressure model and add a second O₂ absorption line to the iterative temperature retrieval.

The standard DIAL equation calculates the molecular absorption coefficient at the online wavelength as a function of range. Using the lidar returns at the online wavelength (N_1) and the offline wavelength (N_2) the absorption coefficient is calculated as

$$\alpha_{0th}(r) = \alpha_{m,2}(r) - \frac{1}{2\Delta r} \ln \left(\frac{N_1(r + \Delta r)N_2(r)}{N_1(r)N_2(r + \Delta r)} \right). \quad (2.21)$$

The offline absorption coefficient is represented by $\alpha_{m,2}$ which is small and is approximated using the assumed temperature profile. The range difference, Δr , is the pulse length of the lidar or the averaging length if the lidar returns are averaged.

The perturbative DIAL absorption contains two correction terms to the standard DIAL equation. Using the absorption coefficient from the standard DIAL equation as the zeroth order absorption

$$\alpha_{m,1}(r) = \alpha_{0th}(r) + \Delta\alpha_{1st}(r) + \Delta\alpha_{2nd}(r), \quad (2.22)$$

represents the final result of the second order perturbative DIAL process.

The first- and second-order correction terms account for the spectral broadening of the molecularly scattered light and rely on the normalized backscatter lineshape, $g_x(\nu, r)$, with the combination of the molecular backscatter lineshape and the aerosol backscatter lineshape. The equation is written as

$$g_x(\nu, r) = \left(1 - \frac{1}{BSR}\right) h_x(\nu) + \frac{1}{BSR} [h_x(\nu) \otimes l(\nu, r)], \quad (2.23)$$

where $h_x(\nu)$ is the laser lineshape, $l(\nu, r)$ is the molecular backscatter broadened lineshape, $\otimes$ is the convolution, and the subscript x is either 1 for the on-line wavelength or 2 for the

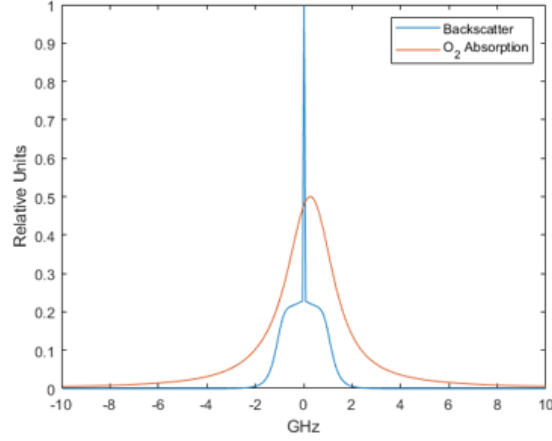


Figure 2.3: Combined aerosols and molecular backscatter spectrum and O₂ absorption spectrum. The narrow point in the center is the aerosol backscatter and the wider shape is the molecular backscatter spectrum. The backscatter ratio is 1.1 for this figure. Units are arbitrary.

off-line wavelength. For the work described in this paper, the laser lineshape is assumed to be a delta function. The molecular backscatter can be represented by a Doppler-broadened lineshape [63] based on the average molecular mass of the atmospheric molecules with a Brillouin approximation correction [80]. For the most accurate calculation of the Rayleigh-Brillouin molecular scattering a Tenti S6 model is used [8, 71] with a precalculated principal component analysis for fast computation [3]. The normalized backscatter lineshape is known from the HSRL retrieval of the backscatter ratio and is defined as $BSR = \frac{\beta_a + \beta_m}{\beta_m}$. Here, β_a is the aerosol backscatter coefficient and β_m is the molecular backscatter coefficient model which uses the broadened lineshape model. The backscatter spectrum for a BSR of 1.1 is shown in Fig. 2.3.

The first-order correction to the absorption coefficient may be written

$$\Delta\alpha_{1st}(r) = \frac{1}{2} [\alpha_{0th}(r)\Delta W_{1st}(r) + \Delta G_{1st,1}(r) - \Delta G_{1st,2}(r)], \quad (2.24)$$

where

$$\Delta W_{1st}(r) = \frac{\int \zeta_1(\nu, r)[1 - f(\nu, r)]d\nu}{\int \zeta_1(\nu, r)d\nu} \quad (2.25)$$

and

$$\Delta G_{1st,x}(r) = \frac{\int \eta_x(\nu, r)d\nu}{\int \zeta_x(\nu, r)d\nu}, \quad (2.26)$$

where $f(\nu, r)$ is the molecular absorption lineshape with a maximum value of 1 at line center.

The terms $\eta_x(\nu, r)$ and $\zeta_x(\nu, r)$ are given by

$$\eta_x(\nu, r) = \frac{dg_x(\nu, r)}{dr} E(\nu) T_{m0th,x}(\nu, r) \quad (2.27)$$

and

$$\zeta_x(\nu, r) = g_x(\nu, r) E(\nu) T_{m0th,x}(\nu, r). \quad (2.28)$$

where $E(\nu)$ is the normalized lineshape of the optical filter transmission in the receiver of the DIAL instrument, $T_{m0th,1}(\nu, r) = \exp\left(-\int_0^r \alpha_{0th}(r')f(\nu, r')dr'\right)$ and $T_{m0th,2}(\nu, r) = \exp\left(-\int_0^r \alpha_{m,2}(\nu, r')dr'\right)$. It should be noted that in regions where the aerosol backscatter coefficient is small and changing rapidly, care must be taken in estimating $\frac{dg_x(\nu, r)}{dr}$ since the instantaneous derivative may be different than an estimate of this derivative based on a difference between points separated by a finite Δr .

The second-order correction to the absorption coefficient is found from

$$\Delta\alpha_{2nd}(r) = \frac{1}{2} [\Delta\alpha_{1st}(r)\Delta W_{1st}(r) + \alpha_{0th}(r)\Delta W_{2nd}(r) + \Delta G_{2nd,1}(r) - \Delta G_{2nd,2}(r)], \quad (2.29)$$

where

$$\Delta W_{2nd}(r) = \left[\frac{\int \zeta_1(\nu, r)[1 - f(\nu, r)]d\nu \int \zeta_1(\nu, r)[1 - f(\nu, r)][1 - T_{m1st,1}(\nu, r)]d\nu}{\int \zeta_1(\nu, r)[1 - f(\nu, r)][1 - T_{m1st,1}(\nu, r)]d\nu} - \frac{\int \zeta_1(\nu, r)[1 - f(\nu, r)][1 - T_{m1st,1}(\nu, r)]d\nu}{\int \zeta_1(\nu, r)d\nu} \right] \quad (2.30)$$

and

$$\Delta G_{2nd,x}(r) = \left[\frac{\int \eta_x(\nu, r) d\nu}{\int \zeta_x(\nu, r) d\nu} \frac{\int \zeta_x(\nu, r) [1 - T_{m1st,x}(\nu, r)] d\nu}{\int \zeta_x(\nu, r) d\nu} - \frac{\int \eta_x(\nu, r) [1 - T_{m1st,x}(\nu, r)] d\nu}{\int \zeta_x(\nu, r) d\nu} \right], \quad (2.31)$$

with $T_{m1st,1}(\nu, r) = \exp\left(-\int_0^r \Delta\alpha_{1st}(r') f(\nu, r') dr'\right)$ and $T_{m1st,2}(\nu, r) = 1$. The first-order correction to the offline atmospheric transmission resulting from molecular absorption, $T_{m1st,2}(\nu, r) = 1$, is assumed with the realization that the zeroth-order transmission is minimally affected by the offline molecular absorption and thus the first-order offline molecular absorption will have no impact on the offline atmospheric transmission resulting from molecular absorption. With the assumption that $T_{m1st,2}(\nu, r) = 1$, $\Delta G_{2nd,2}(r) = 0$ implying that only $\Delta G_{2nd,1}(r)$ need be considered.

Iterative Temperature Retrieval

The iterative temperature retrieval starts with the initial guess at a temperature profile with a simple lapse rate. The same temperature guess is used for the perturbative absorption retrieval. The temperature guess and the retrieved perturbative absorption are used to estimate a new temperature profile. The process iterates using the new temperature profile as the guess until the guess profile matches the updated temperature profile. The following is a summary of the theory presented in Repasky et al. [57] with changes to the calculation of the pressure model. The pressure model can increase accuracy of the temperature [30].

To calculate the updated temperature profile, the O_2 absorption coefficient profile must be calculated from the initial guess as [72] (from Eq. 2.13)

$$\alpha_{O_2}(r) = S(T_0) \frac{T_0}{T(r)} \exp\left(\frac{\epsilon}{k_B T_0} - \frac{\epsilon}{k_B T(r)}\right) g(\nu - \nu_0, r) n_{O_2}(r), \quad (2.32)$$

where $S(T_0)$ is the line strength at the temperature T_0 , ϵ is the ground state energy, k_B is the Boltzmann constant, $g(\nu - \nu_0, r)$ is the absorption lineshape function, $n_{O_2}(r)$ is the O_2 number density, and $T(r)$ is the temperature profile. The line parameters are taken from the HITRAN database [18–20]. The O_2 number density is dependent on Loschmidt's number, $n_L(r)$, and is a function of both temperature and pressure, where

$$n_{O_2}(r) = q_{O_2} [n_L(r) - n_{wv}(r)] = q_{O_2} [1 - q_{wv}(r)] n_L(r) = q(r) n_L(r). \quad (2.33)$$

The atmospheric mixing ratios are q_{O_2} and $q_{wv}(r)$, which represent O_2 and H_2O , respectively. The water vapor mixing ratio, $q_{wv}(r)$, is provided by the retrieval from the water vapor MPD. Loschmidt's number can be written $n_L(r) = \frac{P(r)}{k_B T(r)}$, where the pressure is found using the barometric formula [7]

$$P(r) = P_s \exp \left(- \int_0^r \frac{g_0 m_{air}}{k_B T(r')} dr' \right). \quad (2.34)$$

In the barometric formula, g_0 is the acceleration due to gravity, m_{air} is the molecular mass of air, and k_B is Boltzmann's constant. If necessary, the pressure model can be simplified by substituting the temperature lapse rate model, $T(r) = T_s + rL$. Using the above relationships, the absorption coefficient may be written as [10]

$$\alpha_{O_2}(r) = \frac{S(T_0) T_0 P(r) \exp \left(\frac{\epsilon}{k_B T_0} \right)}{k_B} g(\nu - \nu_0, r) q(r) T(r)^{-2} \exp \left(\frac{-\epsilon}{k_B T(r)} \right). \quad (2.35)$$

The updated temperature and pressure profiles may be written as

$$T_{i+1}(r) = T_i(r) + \Delta T(r) = T_i(r) \left[1 + \frac{\Delta T(r)}{T_i(r)} \right], \quad (2.36)$$

$$P_{i+1}(r) \approx P_s \exp \left(- \frac{g_0 m_{air}}{k_B} \int_0^r \frac{1}{T_i(r')} dr' \right) \left[1 + \Delta T \frac{g_0 m_{air}}{k_B} \int_0^r \frac{1}{T_i^2(r')} dr' \right] \quad (2.37)$$

where $T_i(r)$ is the initial guess at the temperature profile and $\frac{\Delta T(r)}{T_i(r)}$ is assumed to be small. The two temperature-dependent terms on the right-hand side of Eq. 2.35 can be expanded to first order (using the approximation $f(x + \Delta x) \approx f(x) + f'(x)\Delta x$) such that $T_{i+1}(r)^{-2} \approx T_i(r)^{-2} \left[1 - 2\frac{\Delta T(r)}{T_i(r)}\right]$ and $\exp\left(\frac{-\epsilon}{k_B T_{i+1}(r)}\right) \approx \exp\left(\frac{-\epsilon}{k_B T_i(r)}\right) \left[1 + \frac{\epsilon}{k_B T_i^2(r)} \Delta T(r)\right]$. Substituting these approximations into Eq. 2.35 and keeping terms to first order in $\frac{\Delta T(r)}{T_i(r)}$, one can show that

$$\Delta T(r) = \frac{\alpha_{O_2}(r) - C_1(r)C_2(r)g(\nu - \nu_0, r)q(r)}{C_1(r)C_2(r)C_3(r)g(\nu - \nu_0, r)q(r)}, \quad (2.38)$$

where

$$C_1 = \frac{S(T_0)T_0P_s \exp\left(\frac{\epsilon}{k_B T_0}\right)}{k_B}, \quad (2.39)$$

$$C_2(r) = T_i(r)^{-2} \exp\left(\frac{-\epsilon}{k_B T_i(r)}\right) \exp\left(\frac{-g_0 m_{air}}{k_B} \int_0^r \frac{1}{T_i(r')} dr'\right), \quad (2.40)$$

and

$$C_3(r) = \frac{-2}{T_i(r)} + \frac{\epsilon}{k_B T_i^2(r)} + \frac{g_0 m_{air}}{k_B} \int_0^r \frac{1}{T_i^2(r')} dr'. \quad (2.41)$$

Calculating $\Delta T(r)$ allows the initial temperature profile guess to be updated. Using a linear least-squares fit on the updated temperature profile allows for an estimate of the lapse rate associated with the updated temperature profile.

Modeling results for realistic atmospheric models has been done in Respasky et al. [57]. In general, the temperature retrieval maintains a temperature deviation of less than ± 1 K in areas with higher aerosol backscatter coefficients. However, when the atmospheric scattering is dominated by molecular scatter, the temperature retrieval results in a larger temperature deviation.

Adding a second (or more) O_2 absorption line is relatively simple. Figure 2.1b shows multiple absorption lines that affect the main absorption line. Absorption due to each line

can be added together to find total absorption as shown in

$$\alpha(r) = \alpha_a(r) + \alpha_b(r) + \dots, \quad (2.42)$$

where the subscripts a and b represent two different absorption lines. The equation for one absorption line is

$$\alpha_x(r) = \frac{S_{0,x}(T_0)T_0P_i(r)\exp\left(\frac{\epsilon_x}{k_B T_0}\right)}{k_B} g_x(\nu - \nu_0, r) q(r) T(r)^{-2} \exp\left(\frac{-\epsilon_x}{k_B T(r)}\right), \quad (2.43)$$

where S_0 is the reference linestrength, T_0 is the reference temperature, P_s and T_s are the surface pressure and temperature, γ is the acceleration due to gravity times molar mass of air divided by the universal gas constant, L is the temperature lapse rate and is negative in the lower troposphere, ϵ is the line ground state energy, g is the Voigt lineshape, q is the mixing ratio, and k_B is Boltzmann's constant. The only terms that are specific to the line are S_0 , ϵ , and g so they will be designated with subscripts a and b .

Combining the a and b lines together and substituting approximations defined earlier results in

$$\begin{aligned} \alpha_x(r) = & \frac{S_{0,a}(T_0)T_0P_i(r)\exp\left(\frac{\epsilon_a}{k_B T_0}\right)}{k_B} g_a(\nu - \nu_0, r) q(r) T(r)^{-2} \\ & * \left[1 - 2 \frac{\Delta T(r)}{T_i(r)} \right] \exp\left(\frac{-\epsilon_a}{k_B T_i(r)}\right) \left[1 + \frac{\epsilon_a}{k_B T_i^2(r)} \Delta T_i(r)^{-2} \right] \\ & + \frac{S_{0,b}(T_0)T_0P_i(r)\exp\left(\frac{\epsilon_b}{k_B T_0}\right)}{k_B} g_b(\nu - \nu_0, r) q(r) T(r)^{-2} \\ & * \left[1 - 2 \frac{\Delta T(r)}{T_i(r)} \right] \exp\left(\frac{-\epsilon_b}{k_B T_i(r)}\right) \left[1 + \frac{\epsilon_b}{k_B T_i^2(r)} \Delta T_i(r)^{-2} \right]. \end{aligned} \quad (2.44)$$

A term S for each line is defined for simplification as

$$S_x = \frac{S_{0,x}(T_0)T_0P_i(r)\exp\left(\frac{\epsilon_x}{k_BT_0}\right)}{k_B}g_x(\nu - \nu_0)q(r)T_i^{-2}(r)\exp\left(\frac{-\epsilon_x}{k_BT_0}\right). \quad (2.45)$$

The equation for absorption can then be simplified to

$$\begin{aligned} \alpha(r) &= S_a(r) + S_a(r) \left[1 - 2\frac{\Delta T(r)}{T_i(r)} + \frac{\epsilon_a}{k_BT_i^2(r)} \right] \\ &\quad + S_b(r) + S_b(r) \left[1 - 2\frac{\Delta T(r)}{T_i(r)} + \frac{\epsilon_b}{k_BT_i^2(r)} \right] \\ &= S_a(r) + S_b(r) \\ &\quad + \Delta T(r) \left\{ S_a(r) \left[\frac{-2}{T_i(r)} + \frac{\epsilon_a}{k_BT_i^2(r)} \right] + S_b(r) \left[\frac{-2}{T_i(r)} + \frac{\epsilon_b}{k_BT_i^2(r)} \right] \right\}. \end{aligned} \quad (2.46)$$

The absorption equation can then be rearranged and the C terms defined earlier can be substituted to find

$$\begin{aligned} \Delta T(r) &= \frac{\alpha(r) - S_a(r) - S_b(r)}{S_a(r)C_{3,a}(r) + S_b(r)C_{3,b}(r)} \\ &= \frac{\alpha(r) - C_{1,a}(r)C_{2,a}(r)g_a(\nu - \nu_0, r)q(r) - C_{1,b}(r)C_{2,b}(r)g_b(\nu - \nu_0, r)q(r)}{C_{1,a}(r)C_{2,a}(r)C_{3,a}(r)g_a(\nu - \nu_0, r)q(r) + C_{1,b}(r)C_{2,b}(r)C_{3,b}(r)g_b(\nu - \nu_0, r)q(r)}. \end{aligned} \quad (2.47)$$

A summation of lines can be used for more than two lines as

$$\Delta T(r) = \frac{\alpha_{O_2}(r) - \sum_{k=1}^{\#oflines} C_{1,k}C_{2,k}(r)g_k(\nu - \nu_0, r)q(r)}{\sum_{k=1}^{\#oflines} C_{1,k}C_{2,k}(r)C_{3,k}(r)g_k(\nu - \nu_0, r)q(r)}. \quad (2.48)$$

HSRL

This HSRL uses the online and offline O₂ DIAL wavelengths (specified in Table 4.1). The offline DIAL wavelength is on an absorption line of potassium (KD_1). Using the DIAL

wavelengths eliminates the need for a third laser for a separate rubidium HSRL at 780 nm. Another benefit of this configuration is that the online wavelength can be used for efficiency and overlap correction between the molecular and combined channels.

The HSRL data can be processed using a process developed for rubidium HSRL [23]. The signal in the combined channel is described by

$$N_c(r) = N_t K \frac{\eta_c(r)}{r^2} [\beta_m(r) + \beta_a(r)] \exp \left(-2 \int_0^r \alpha(r') dr' \right) + B_c, \quad (2.49)$$

where $N_c(r)$ is the measured combined channel signal as a function of range, K is an arbitrary constant for power and efficiency terms, $\eta_c(r)$ is the combined channel geometric overlap function, $\beta_m(r)$ is the molecular backscatter coefficient, $\beta_a(r)$ is the aerosol or cloud backscatter coefficient, $\alpha(r)$ is the total absorption coefficient and B_c is the combined channel background counts.

The molecular channel is described by

$$N_m(r) = K \frac{1}{G_m} \frac{\eta_m(r)}{r^2} [C_{mm}(r)\beta_m(r) + C_{am}\beta_a(r)] \exp \left(-2 \int_0^r \alpha(r') dr' \right) + B_m, \quad (2.50)$$

where $N_m(r)$ is the measured molecular channel signal, $1/G_m$ is the difference in efficiency between the combined and molecular channels, $\eta_m(r)$ is the molecular channel geometric overlap function, C_{am} is the aerosol-to-molecular crosstalk representing the amount of narrowband light leakage through the potassium vapor optical notch filter and B_m is the molecular channel background counts. The term $C_{mm}(r)$ is the efficiency of the molecular return through the molecular channel filter. Since the spectral shape of the molecular backscatter varies with temperature and pressure, $C_{mm}(r)$ is calculated as a function of range based on the models used in the temperature retrieval.

Using the online signal, the geometric overlap between the molecular and combined

channels can be measured as

$$\frac{\eta_m}{\eta_c} = \tilde{G}_m^{on} \frac{\tilde{S}_m^{on}(r) - \tilde{B}_m^{on}}{\tilde{S}_c^{on}(r) - \tilde{B}_c^{on}} = O(r), \quad (2.51)$$

where the superscript (*on*) represents the factors at the online DIAL wavelength. The right side of the equation is defined as an overlap correction factor $O(r)$.

To compare the two signals we can integrate the measured constants and efficiencies into new signal terms.

$$\hat{N}_c(r) = \tilde{N}_c(r) - \tilde{B}_c, \quad (2.52)$$

and

$$\hat{N}_m(r) = \frac{\tilde{G}_m [\tilde{S}_m(r) - \tilde{B}_m] - \tilde{C}_{am} O(r) [\tilde{S}_c(r) - \tilde{B}_c]}{\tilde{C}_{mm}(r) - \tilde{C}_{am}} \quad (2.53)$$

represent the combined and molecular signals that can be used to calculate the aerosol and molecular backscatter.

The backscatter coefficient of atmospheric aerosols is calculated as

$$\tilde{\beta}_a(r) = \left[\frac{\hat{N}_c(r)}{\hat{N}_m(r)} - 1 \right] \tilde{\beta}_m(r), \quad (2.54)$$

where $\tilde{\beta}_a(r)$ is the estimated aerosol backscatter coefficient and $\tilde{\beta}_m(r)$ is the estimated molecular backscatter coefficient. The molecular backscatter coefficient is estimated from pressure and temperature profiles using [39]

$$\tilde{\beta}_m(r) = 5.45 \times 10^{-32} \frac{P(r)}{k_B T(r)} \left[\frac{550 \text{ nm}}{\lambda} \right]^4 m^{-1} sr^{-1}, \quad (2.55)$$

where $P(r)$ is the pressure in Pa, $T(r)$ is the temperature in K, λ is the wavelength of the laser in nm and k_B is the Boltzmann constant. This estimate is less accurate away from 532 nm, however the final BSR (Eq. 2.60) does not rely on this estimation.

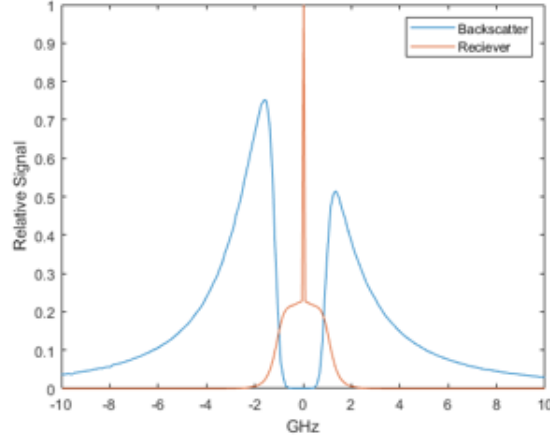


Figure 2.4: Combined molecular and aerosol backscatter spectrum with a scan of the HSRL molecular channel transmission spectrum. The units are arbitrary. The backscatter ratio for the backscatter spectrum is 1.1.

The backscatter ratio (BSR) is defined as the ratio of total backscatter (molecular and aerosol), β_t , to molecular backscatter, β_m , and is obtained from HSRL observations using Eq. 2.55 and Eq. 2.54

$$BSR(r) = \frac{\beta_t}{\beta_m} = \frac{\beta_a(r) + \beta_m(r)}{\beta_m(r)}. \quad (2.56)$$

The HSRL for the O₂ DIAL system uses a potassium vapor cell that offers certain advantages for hardware simplicity [68]. The O₂ offline laser acts as the laser for the HSRL retrieval and is absorbed by the potassium filter. The O₂ online laser passes through the potassium filter without being affected. The online signal can therefore be used to calibrate the lidar overlap and differential sensitivity of the molecular and combined HSRL channels. Conversions for aerosol and molecular backscatter are usually required for other lidar systems due to HSRL systems being at a different wavelength (e.g. Raman lidar retrievals). However, with the HSRL and O₂ DIAL being the same wavelength, no conversion is required. A plot of the combined aerosol and molecular backscatter and the HSRL molecular channel scan used to find the HSRL coefficients is shown in Fig. 2.4.

Using the frequency dependent lidar equation, Eq. 2.4, and assuming a different lidar overlap and receiver efficiency but the same backscatter and transmission, the following equation can be found:

$$\frac{N_{Comb}^{O_2On}}{N_{Mol}^{O_2On}} = \frac{\eta_{Comb}^{O_2On}(\nu) O_{Comb}^{O_2On}(r)}{\eta_{Mol}^{O_2On}(\nu) O_{Mol}^{O_2On}(r)}. \quad (2.57)$$

The HSRL terms can be described by the equation

$$\begin{bmatrix} N_{Comb}^{O_2Off} \\ N_{Mol}^{O_2Off} \end{bmatrix} = \begin{bmatrix} \eta_C & 0 \\ 0 & \eta_M \end{bmatrix} \begin{bmatrix} C_{MC} & C_{AC} \\ C_{MM} & C_{AM} \end{bmatrix} \begin{bmatrix} \beta_{Mol}^{O_2Off}(\nu, r) \\ \beta_{Aer}^{O_2Off}(\nu, r) \end{bmatrix} \quad (2.58)$$

The ratio of the combined and molecular signal is

$$\frac{N_{Comb}^{O_2Off}}{N_{Mol}^{O_2Off}} = \left[\frac{\eta_{Comb}^{O_2Off}(\nu) O_{Comb}^{O_2Off}(r)}{\eta_{Mol}^{O_2Off}(\nu) O_{Mol}^{O_2Off}(r)} \right] \left[\frac{C_{MC} \beta_{Mol}^{O_2Off}(\nu, r) + \beta_{Aer}^{O_2Off}(\nu, r)}{C_{MM} \beta_{Mol}^{O_2Off}(\nu, r) + C_{AM} \beta_{Aer}^{O_2Off}(\nu, r)} \right] \quad (2.59)$$

The term C_{MM} captures the efficiencies of the offline laser through the potassium cell and by design $\eta_{Comb}^{O_2On}(\nu) = \eta_{Comb}^{O_2Off}(\nu)$. The term C_{MC} captures the efficiencies of the offline laser through the combined channel. Also by design the overlap is equal between the two wavelengths so that $O_{MOL}^{O_2On}(r) = O_{Mol}^{O_2Off}(r)$ and $O_{Comb}^{O_2On}(r) = O_{Comb}^{O_2Off}(r)$. These equivalencies can be inserted into Eq. 2.57 and then into Eq. 2.59 for an expression of the aerosol backscatter. The backscatter ratio can then be expressing in terms of only the four lidar signal channels and the HSRL calibration constants by

$$BSR = \frac{\beta_{Aer}^{O_2Off} + \beta_{Mol}^{O_2Off}}{\beta_{Mol}^{O_2Off}} = 1 - \left\{ \frac{C_{MM} [N_{Comb}^{O_2Off} N_{Mol}^{O_2On}] - C_{MC} [N_{Mol}^{O_2Off} N_{Comb}^{O_2On}]}{C_{AM} [N_{Comb}^{O_2Off} N_{Mol}^{O_2On}] - [N_{Mol}^{O_2Off} N_{Comb}^{O_2On}]} \right\}. \quad (2.60)$$

Masking

Data are unusable when there are clouds in the data set. Clouds cause a large spike in the photon counting returns and could saturate the photon counting modules. One way clouds can be detected is using a rolling standard deviation window [4]. First the return photon counts are range corrected (data are range corrected by multiplying by the square of the range to compensate for inverse-range-squared measurement dependence), $N_{corrected}(r) = N(r) \times r^2$. Each bin is assigned a value of the standard deviation of all the bins around it in range and time. If the standard deviation is above a certain value, the bin is classified as a cloud and is masked out of the data. All data above the clouds are also masked. The thresholds for standard deviation mask is set manually by using a range-corrected profile without clouds.

RETRIEVAL METHODS

This chapter describes the practical methods of the retrieval from Ch. 2, including the specific steps of the temperature retrieval and error estimate.

Temperature Retrieval

The temperature retrieval program processes raw photon data and ground weather station data and retrieves temperature profiles with an estimate of error. A diagram of the retrieval is shown in Fig. 3.1. I have written the temperature retrieval in MATLAB. The code is vectorized for speed in MATLAB and split into functions for separate steps of the temperature retrieval. The code is available at <https://github.com/owen-cruikshank/MicroPuseDIALMSU>.

The return photon signals for both the online and offline wavelengths for both the molecular and total receiver channels are first loaded and pre-processed including integration in time and range and preparation for error analysis discussed in the next section. All photon data are demuxed into separate DIAL wavelengths. The photon data are then summed into the data bins according to the selected integration time. For this work the data is saved in bins of 37.5 m in range and 2 s in time and integrated to 75 m in range and 10 min in time. The weather station data of surface temperature and pressure are imported from the MSU ORSL lab or the integrated MPD weather station and interpolated to the selected time grid. The LabVIEW program that operates the MPD gathers other diagnostic data such as laser wavelength and set temperature and power, etalon temperature, TSOA power, room temperature, internal and external HSRL vapor absorption cell temperature. These data are used as diagnostics and not in the MPD retrieval.

The HSRL retrieval is discussed in detail in Hayman and Spuler [23] and Stillwell et al. [68] and used here without modification with measured calibration data files specific to this

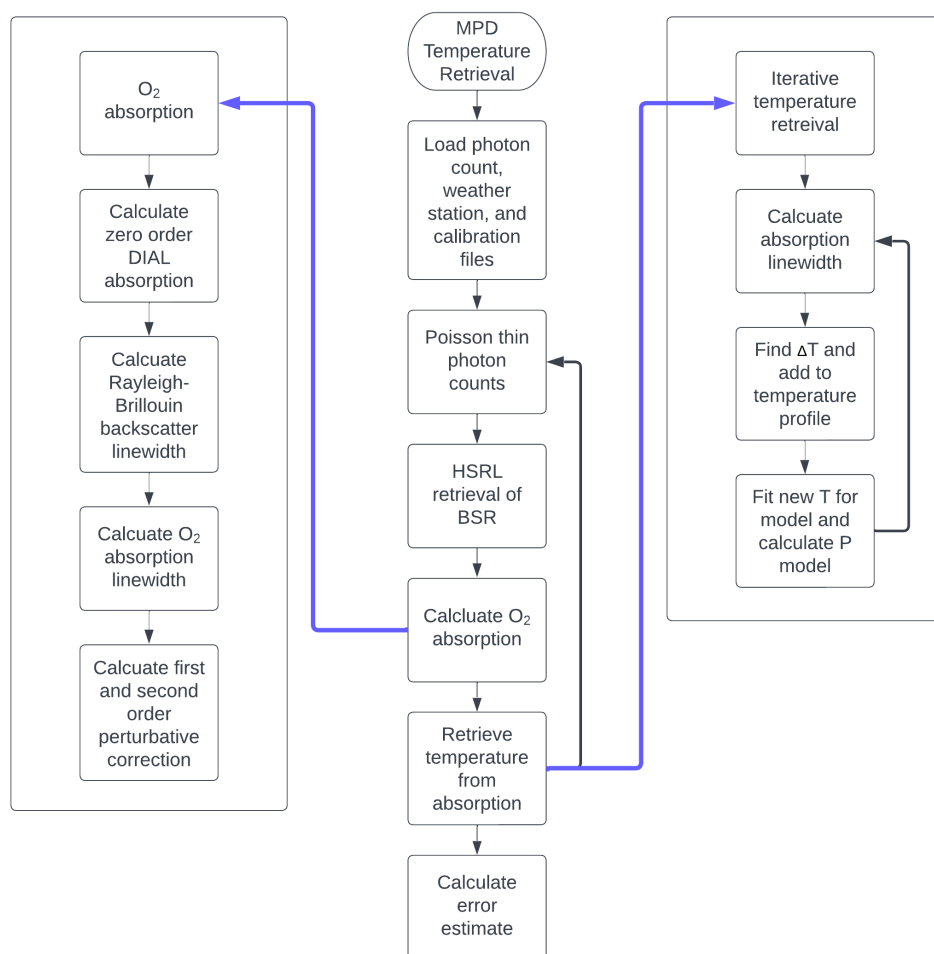


Figure 3.1: Chart of temperature retrieval algorithm.

instrument. The calibration data is collected by turning off power to the TSOA and allowing some of the seed laser light leak past it. A block is placed after the 60 mm telescope coupling lens. A small amount of the laser light incident on the block is diffusely reflected and coupled into the lidar receiver and detected by the avalanche photodiodes. Careful consideration must be made to get enough signal to the APDs without over saturation. A program in LabVIEW is run to scan the laser wavelength over the etalon and HSRL vapor cell transmission by changing the laser temperature and record the transmission. This process takes minutes or hours depending on the desired resolution. The data are then used as transmission of the receiver as a function of wavelength. The transmission of the combined and molecular channels are then multiplied by the calculated theoretical aerosol and molecular backscatter spectrum to find the C values used in the HSRL retrieval described in the HSRL section in Ch. 2.

The zero-order DIAL O_2 absorption is calculated using Eq. 2.20.

In the next step of the temperature retrieval algorithm, the perturbative retrieval is applied to find the O_2 absorption coefficient as discussed in Ch. 2. First, the spectrum of the backscattered light is estimated using the BSR retrieved from the HSRL with a Rayleigh-Brillouin lineshape applied to the molecularly scattered light. The Rayleigh-Brillouin lineshape is weakly temperature dependent, so an approximation is made here. We assume a simple starting temperature profile that is based on the surface temperature and lapse rate of -6.5 K/km. However, since the lapse rate and model temperature profile are updated each iteration, the choice of the starting lapse rate does not affect the final temperature profile (provided the initial lapse falls within a reasonable guess of between -5 and -10 K/km). It should be noted that the Rayleigh-Brillouin lineshape changes from a $\text{FWHM} = 2.18$ GHz at 300 K to a $\text{FWHM} = 2.16$ GHz at 290 K, i.e., HSRL measurements are not exceptionally sensitive to temperature. Furthermore, the Rayleigh-Brillouin lineshape comes into the perturbative retrieval through the first and second-order correction terms,

which affect the overall absorption coefficient by approximately 10% and 1% respectively. Thus, errors in the assumed temperature profile used to determine the lineshape for the molecularly scattered light will affect the retrieved absorption coefficient minimally. Next, the absorption linewidth is calculated using the HITRAN parameters and a Voigt profile (Eq. 2.13). The Rayleigh-Brillouin lineshape and the absorption lineshape are calculated using principal component analysis [24] and from the spontaneous Tenti s6 model [71] adapted from the code written by Xinggou Pan [54]. The backscatter derivative is calculated as a central order derivative to avoid shifting. The zero-order, first-order, and second-order corrections are then calculated and used to retrieve the total O_2 absorption profile.

The next step in the retrieval algorithm is to use the retrieved O_2 absorption profile to complete the iterative temperature retrieval. First, an initial temperature profile is modeled using the surface temperature and lapse rate. Next, a pressure profile is calculated as described in Eq. 2.34. The temperature deviation ΔT is then calculated using the retrieved absorption coefficient and Eq. 2.48. A new temperature profile is then calculated by adding the initial temperature guess and ΔT . This new temperature profile is then used as the temperature guess and pressure on the next iteration of the temperature retrieval. This process is repeated using the updated temperature and pressure profiles until the temperature profile converges (i.e., when ΔT goes to within some tolerance of zero).

The final retrieved temperature is then smoothed by convolving with a two dimensional rectangle with dimensions of the desired resolution. For this work the smoothing is done to 150 m and 60 min. That means the smoothing kernel has dimensions of 2 bins in range and 6 bins in time with each element having a value of $1/(2 * 6)$. Using an even number of bins in the convolution kernel the result must be shifted by half of a smoothing kernel bin.

Error Analysis

Standard lidar analysis has heavily leveraged linear propagation of error, i.e., taking a Taylor expansion of the equation of interest and assuming Poisson statistics, to bound measurement uncertainty. This common method fails in this case for a number of reasons. An estimate of the error is difficult for the two-step temperature retrieval described above due to the nonlinear nature of the retrieval. Furthermore, the errors observed are not all Poisson distributed, including uncertainties in BSR and WV profiles. In lieu of standard error propagation techniques, a bootstrapping method for estimating the error is used. This method has been developed for the water vapor MPD [65] and adapted for temperature profiling.

The bootstrapping error estimate starts by using a Poisson thinning technique to separate the return signals for the photon counts for the online and offline wavelengths [25]. The online (offline) photon number profiles are summed over two seconds and then written to the data file. These profiles are randomly split into two statistically independent but identically distributed number profiles for both the online and offline wavelengths. This splitting is accomplished by sampling a binomial distribution with a probability of 0.5 for each photon measurement. The two online and offline profiles are then processed using the temperature retrieval, yielding two unique temperature profiles: $T^f(r)$ and $T^g(r)$. For the analysis chain shown in Fig. 3.1, this process tends to converge in approximately 20 iterations, and the standard deviation of the multiple temperature profiles can then be used as an error estimate [65]

$$\sigma_T^2(r) \approx \frac{1}{2[B-1]} \sum_{b=1}^B [T^{b,f}(r) - T^{b,g}(r)]^2, \quad (3.1)$$

where b is the iteration number, B is the total number of bootstrap iterations, and $\sigma_T(r)$ is

the estimated error in °C.

The error estimate for the smoothed data is the square root of the sum of the squares of the same data that comprises the kernel used to smooth the data, following standard error propagation.

Photon Count Rate Correction

The detectors for the MPD are avalanche photodiode single photon counting modules (Excelitas SPCM-AQRH-13). The avalanche photodiodes have a dead time, a time where the diode is recovering and cannot count a new photon, of 22 ns. The actual count rate can be approximated by the equation [69]

$$N_{actual} = \frac{(N_{measured}C) - N_{dark}}{\eta}, \quad (3.2)$$

where N is the count rate, C is the correction factor, N_{dark} is the dark count rate, and η is the photon counting efficiency. The correction factor is

$$C = \frac{1}{1 - (t_d N_{measured})}, \quad (3.3)$$

where t_d is the dead time. In the temperature retrieval, the dark count rate is factored into the background measurement and the detector efficiency is factored into the lidar equation. The count rate of the MPD detectors is usually low enough that a correction factor is not needed.

MPD HARDWARE

The new MPD instrument is based on an existing architecture, that was developed for water vapor profiling, and has been optimized for performance and autonomous operation. The latest modifications to the DIAL instrument include fiber coupled distributed Bragg reflector (DBR) lasers for ease of setup and autonomous operation, spectrally narrow optical filters and an etalon for increased signal to background ratio, and a near-field receiver for higher signal at ranges below 1.5 km.

A schematic of the instrument is shown in Fig. 4.1 and specifications are listed in Table 4.1. Figure 4.1 shows the instrument at MSU, which is a technology demonstrator and does not include the WV DIAL. This removes the whole transmitter up to the beam combiner and the WV channel of the receiver past and including the dichroic beam splitter. The instrument operated by NCAR includes the WV DIAL. The transmitter starts with two distributed bragg reflector (DBR) lasers. The lasers are at a wavelength of 770 nm (and 828 nm for the WV DIAL) and are sourced from Photodigm. The laser light then passes through a single mode fiber splitter with a 10% tap. The tap is directed into a wavemeter (Bristol 671) and a 2x1 (4x1 with the WV DIAL and O₂ DIAL combined) MEMS fiber optic switch (Agiltron nanospeed) controlled by a computer used to wavelength lock the lasers using their operating temperature. The main laser light passes through 1x1 and 2x1 (Agiltron nanospeed) switches to switch the wavelength of the transmitted light and isolate the other wavelength. Between the MEMS switches are fiber optic polarization paddles for polarization control. The MEMS switches are polarization dependent and the polarization is adjusted for maximum transmission. A traveling wave amplifier (Thorlabs BOA780) is used to amplify the seed laser to maintain good seeding and spectral purity (percent of transmitted power in the main narrow linewidth mode) of the tapered semiconductor optical amplifier. The light is collimated from the fibers (Thorlabs fiberport) through an optical isolator and a half

waveplate and into the tapered semiconductor optical amplifier (TSOA). The TSOA (Toptica Eagleyard EYP-TPA-0780-03000-4006-CMT04-0000) is the pulsed amplifier generating the transmitted signal that is seeded by the DBR lasers. Brief characterization of the TSOA, amplifier, and lasers is presented in Appendix A. The TSOA is in a temperature controlled housing with an aspheric lens on either side for coupling light into and out of the TSOA. A cylindrical lens is needed in addition to the aspheric lens to collimate the astigmatic TSOA output. The beam then passes through a matched axicon pair to create an annular beam profile with a hole in the center. The annular shape of the beam allows the transmitted power to pass around the secondary mirror of the Newtonian telescope with minimal losses. A mirror with a 10mm hole allows the transmitter beam to pass. The light is then incident on a 60 mm coupling lens which is matched to the $f/3$ telescope so that the transmitter beam covers the inner portion of the telescope's primary mirror. An optical window mounted a small angle, in either the environmental housing for field deployments or the MSU lidar room) is used to protect the telescope from the elements. The interior of the optical window has an anti-reflective coating to prevent back reflections and an etalon interference effect.

The backscattered photons are collected using the outside ring of the telescope. The telescope is a Newtonian $f/3$ with a diameter of 406 mm and a gold coated primary and secondary mirror. The mirror with a 10 mm diameter hole drilled in the middle reflects the received light collected by the outer portion of the telescope's primary mirror. The first stage receiver consisted of a beam reduces with an achromatic 80mm lens and an achromatic negative 20mm lens and a fiberport with an 11mm focal length. All collected light is coupled into a $105\mu\text{m}$ core mulitmode fiber in the first stage and directed into a second stage containing filtering elements. Between the first and second stage receiver is a $105\mu\text{m}$ core mulitmode fiber that acts as a field stop and a mode scrambler to remove range dependence of collected light through the etalons and narrow band filters. Due to the extended overlap function of the primary telescope, it collects few photons under 400 m. For

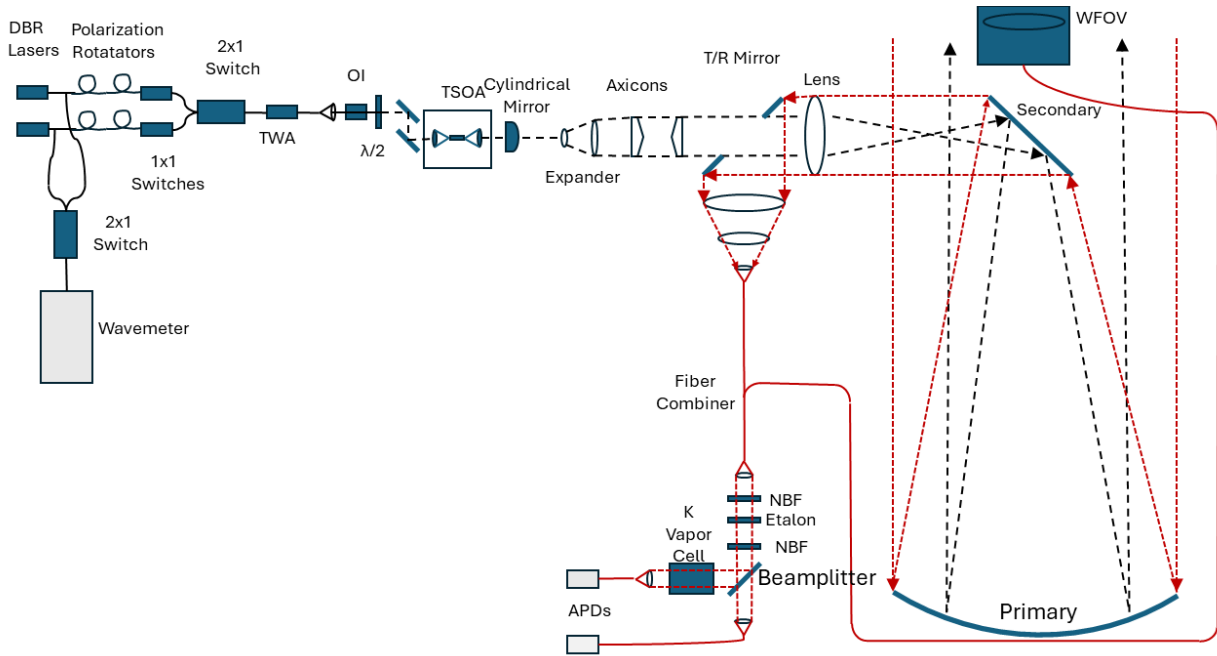


Figure 4.1: Schematic of O₂ DIAL and HSRL instrument. Solid lines indicate fiber optics. Dashed lines indicate free space beam lines. Dotted lines indicate collected backscatter light. Black indicates transmitted light and red indicates received light. DBR = Distributed Bragg Reflector laser, TWA = Traveling Wave Amplifier, TSOA = Tapered Semiconductor Optical Amplifier, T/R = Transmit/Reflect, OI = Optical Isolator, APD = Avalanche Photo Diode

this reason, a secondary telescope with a wide field of view is used to collect more signal at low ranges. The secondary telescope is fiber-coupled, and light collected by it is combined with the signal from the primary telescope in a 90:10 fiber coupler. The secondary telescope is a refractor with a wider field of view than the primary telescope (Thorlabs C80FC-B). The light from the primary and secondary telescope is combined in a 90/10 fiber combiner. Either ends of the second stage have an 11mm focal length fiber port for coupling into and out of the fibers and a beam expander/reducer with a -20mm achromatic lens and a 45mm achromatic lens. This is to increase the area and decrease the angular dependence of the light through the optical filters and etalons. There are two sections for water vapor and oxygen wavelengths separated by a dichroic beam splitter.

Each section has two narrow band filters and an etalon to filter background light. The etalons are tilt tuned and temperature controlled so that the online and offline wavelengths are one free spectral range apart. In the oxygen receiver a 70/30 beamsplitter directs 70% of the light into a heated potassium vapor cell in order to filter out the aerosol backscatter returns and transmit the spectrally broad molecular backscatter returns into a $105\mu\text{m}$ multimode fiber and an avalanche photodiode for photon counting. The other side of the beamsplitter is coupled into a multimode fiber and into a separate single photon counting avalanche photodiodes (Excelitas SPCM-AQRH-13). The transmitted spectrum measurement is shown in Fig. 1.3.

The instrument is located in a roofport-equipped laboratory facility of MSU shown in Figure 4.2. Ancillary measurements of surface temperature and pressure are provided by a collocated weather station (Vaisala CS105, HMP45C) operated by the MSU Optical Remote Sensor Lab. The radiosonde station is located next to the roofport and allows the launching of Vaisala RS92 radiosondes that are monitored using the Vaisala SPS220 with GC25 ground check station. The DIAL-based temperature retrievals were compared to temperature profiles retrieved using the radiosondes as a reference.

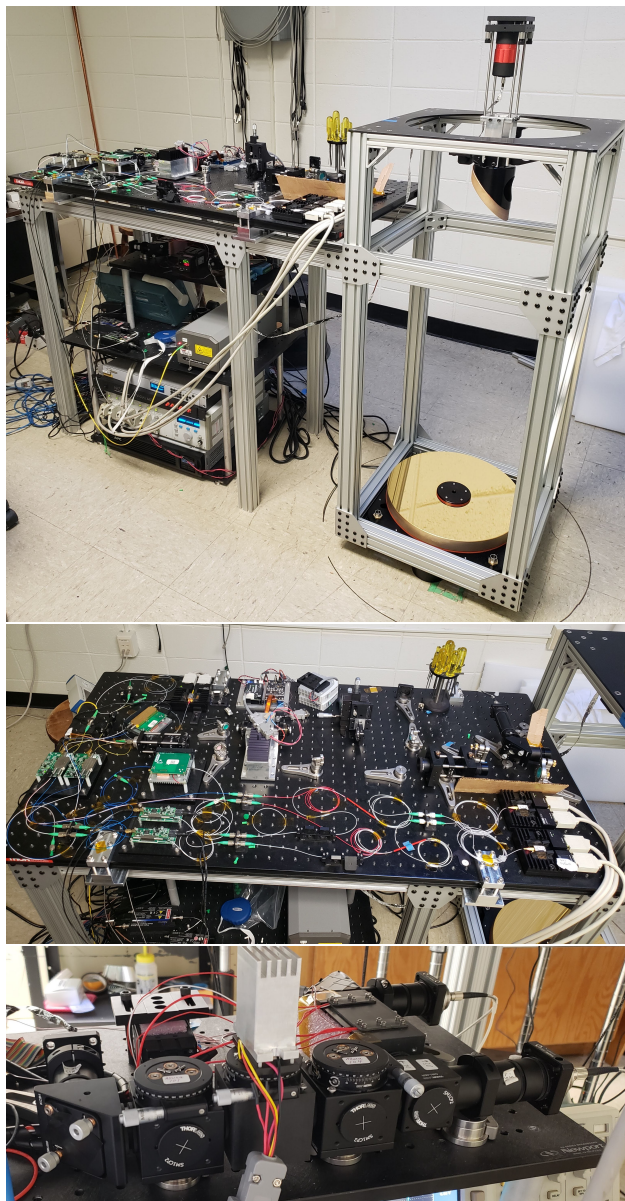


Figure 4.2: Picture of the MPD instrument in the lidar research room at Montana State University. An anti-reflective coated optical window is installed in the roof to allow for unattended operation.

Table 4.1: Specifications for the combined O₂ DIAL and HSRL system. Abbreviations used are: FSR = free spectral range and NBF = narrow band filter.

Transmitter	Specification	Receiver	Specification
Wavelength	769.7958 nm (online)	Etalon Finesse	15.43
	770.1085 nm (offline)	Etalon FSR	157.90 GHz
Output Power	~30 mW(combined)	NBF Bandwidth	0.75 nm
Linewidth	<1 MHz	NBF transmission	90%
Locking Tolerance	5×10^{-5} nm	Potassium cell length	72 nm
Spectral Purity	99.9%	Potassium cell temperature	378 K
Repetition Rate	7 or 8 kHz(combined)		

Radiosondes are used as an in-situ measurement of temperature and water vapor for comparison to the lidar. Manufacturer specifications for the radiosonde are shown in Table 4.2. Radiosondes are used commonly as comparisons for validation of remote sensing measurements [5, 33, 34, 59, 76]. Comparisons and studies of radiosonde measurements show confidence in radiosonde measurements [17, 27, 40].

Table 4.2: Manufacturer specifications of the Vaisala RS92 radiosonde.

	Temperature	Humidity	Pressure
Range	+60 to -90 °C	0-100%	1080-3hPa
Resolution	0.01°C	0.1%	0.01hPa
Response time	<0.4s	<0.5s	
Combined uncertainty	0.5°C<16km	5% RH	1.0 <100hPa
Reproducibility	0.2°C<100hPa	2%RH	0.5 <100hPa

A recent version of the MPD is described in Spuler et. al. [65]. In the latest version, the

MEMS switches are replaced by fiber coupled traveling wave amplifiers [66]. The traveling wave amplifiers increase the switching isolation between the two wavelengths and increase the seeding power into the TSOA.

MODELING

A model of temperature retrieval has been created to understand the efficacy of the MPD temperature retrieval. The atmospheric model is based on previous data measured and theoretical models. The lidar equation can be used to model the atmospheric transmission and backscatter signal. A fully ray traced model of the lidar transmitter and receiver has been built to better understand transmitter-atmosphere-receiver interaction. The geometric overlap function can be theoretically determined and compared with results from the measured overlap from the HSRL. The overlap is calculated numerically using a method adapted from Chen et al. [14]. The full model can give an estimate of bias due to lidar pulse length, avalanche photodiode afterpulsing, and transmitter spectral purity.

MPD overlap function

A consistent bias in the DIAL retrieval has been noticed in ranges below 1km. Changing the overlap function using the front lens before the Newtonian telescope changes the location and magnitude of the bias. This may be due to a small difference in the lidar overlap function between the online and offline DIAL wavelengths. Due to the extended overlap of the MPD system and the sensitivity of the narrow band DIAL technique, a small difference in overlap between the online and offline wavelengths can result in a large bias. The difference in overlap may be caused by a small difference in beam divergence coming from the tapered semiconductor optical amplifier (TSOA). To gain a better understanding of the lidar overlap function a simple raytracing model using ABCD matrices was created using MATLAB. This method for calculating the overlap function was adapted from Ruigiang Chen et. al [14]. This method propagates the transmitted beam using a specified beam power distribution and divergence. The beam at each range is split into discrete sections. Each section is then treated as a single point with multiple rays propagated through the air and the receiving

optics using ABCD matrices. The area of the rays in the detector plane is compared to the detector area to find the overlap function for the specific section of the beam. In the case of the MPD system the detector plane is a $105\text{ }\mu\text{m}$ diameter multimode fiber with a numerical aperture of .22. All rays must be within the fiber diameter and within the numerical aperture to be coupled into the fiber. The overlap for each beam section are added together to find the total overlap at the specific range. Using this model, the variables such as telescope focus, lens focal length and position, fiber focus, and transmit beam size and divergence can all be changed.

Figures 5.1 and 5.2 are an example of how the receiver lens and fiber position can be changed to affect the lidar overlap function. These figures also show that the overlap function is highly sensitive to small changes in receiver alignment.

The beam divergence from the TSOA was measured by using a beam profiler camera through a focus. Due to the inaccuracies in this method and the poor beam quality, no significant difference was found between the online and offline beams.

Using different parameters, the overlap function can be calculated and then used in a separate model for calculating lidar returns and the DIAL retrieval. Using these multiple models, the effect of changing the transmit beam or the receiving optics on the DIAL retrieval can be explored.

An example of a calculated overlap function, including the main Newtonian telescope (Narrow FOV) and the secondary refractor telescope (Wide FOV), is shown in Fig. 5.3. The overlap function for the real instrument is difficult to calculate due to small differences in receiver alignment having a large impact in the shape of the overlap function. There is also a large uncertainty in the power distribution and divergence of the transmitted beam. The overlap function can be measured using the HSRL channels of the MPD. Using the lidar equation, an estimate of molecular scattering and absorption, an estimate of the aerosol absorption, and the measured aerosol backscatter; an overlap function can be estimated

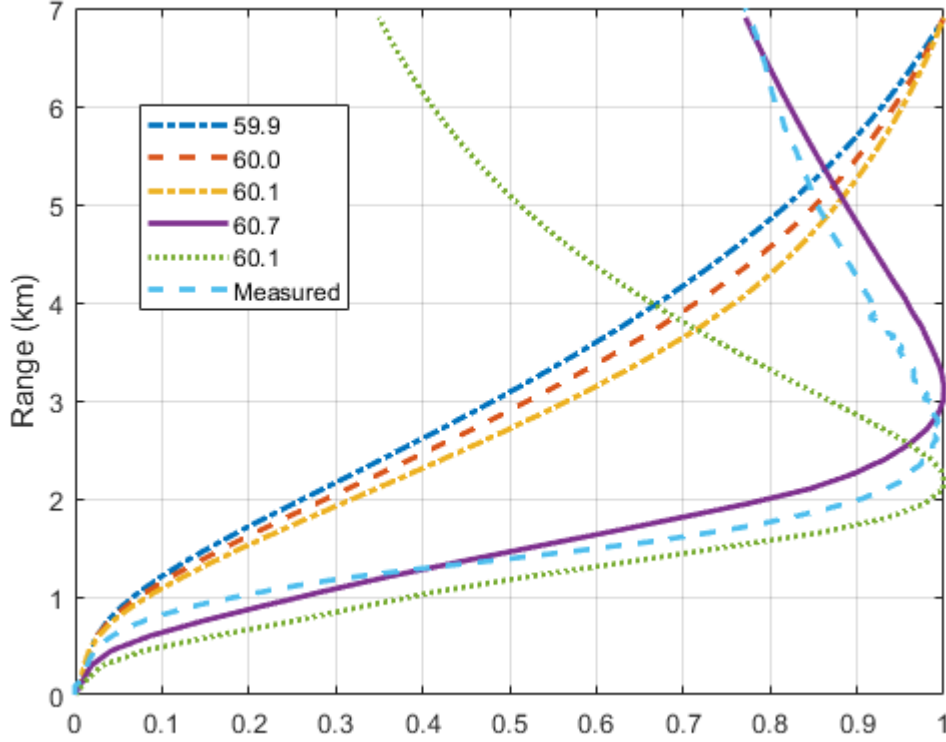


Figure 5.1: Numerical calculation of the lidar overlap function. The position of the 60 mm front collimating lens (in millimeters) is varied to produce different overlap functions. The dashed line is the measured overlap function.

from the offline molecular channel of the MPD. Measured aerosol backscatter was taken on a clear night with temperature profiles from radiosondes. These examples are only an example of what this model can achieve. It is difficult to match the exact conditions in the MPD instrument.

The parameters used in the telescope model are as follows. The beam is an annular beam with an inner diameter of 101.6 mm (4 in) and an outer diameter of 203 mm (10 mm expanded by the telescope). The total beam divergence is modeled at $53 \mu\text{rad}$. The outer edges are modeled as expanding at $26.5 \mu\text{rad}$ and the inner edges are modeled as reducing by $26.5 \mu\text{rad}$. The telescope aperture is modeled with a diameter of 406 mm with a shadow of

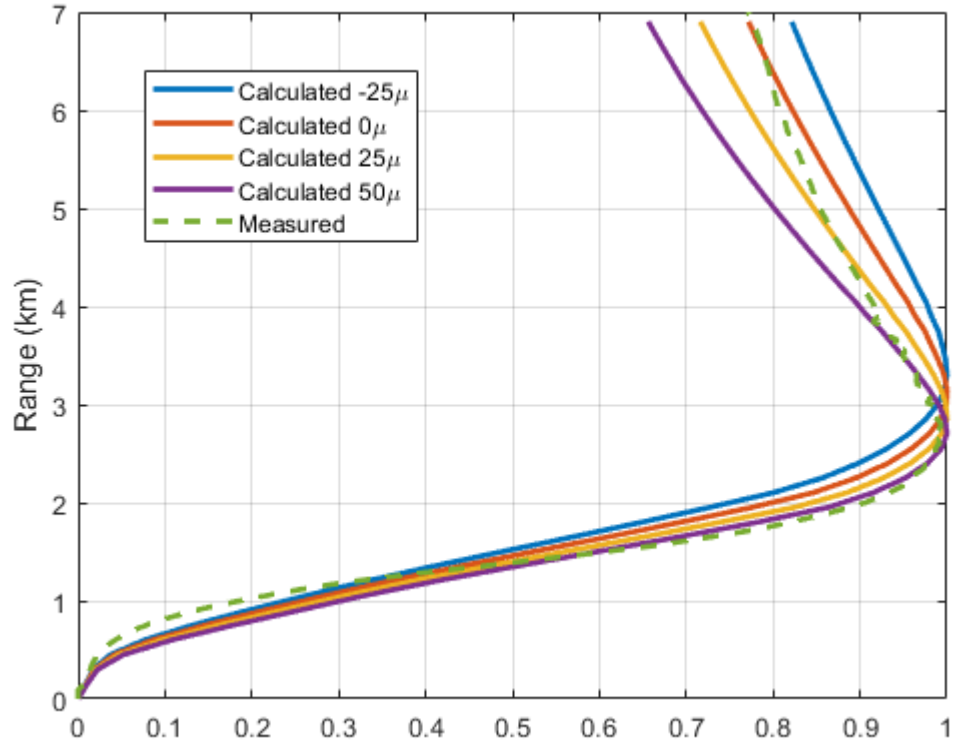


Figure 5.2: Numerical calculation of the lidar overlap function. The position of the 11mm fiberport focusing lens is varied to produce different overlap functions. The dashed line is the measured overlap function.

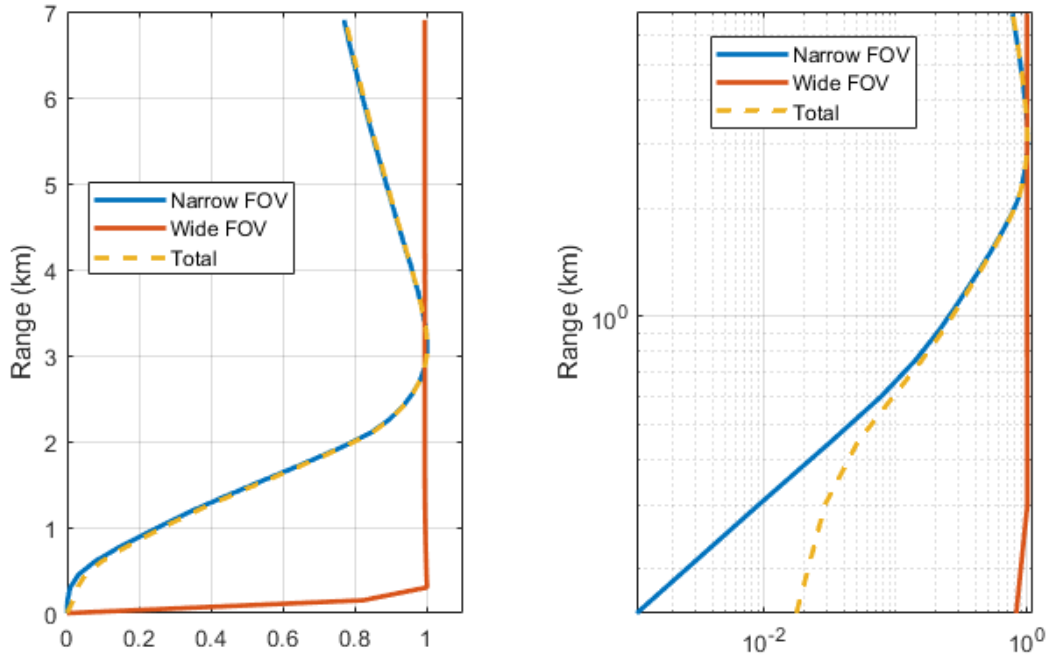


Figure 5.3: The calculated overlap function of the narrow and wide FOV telescopes. The combined overlap function using 98% narrow FOV and 2% wide FOV is also shown as the dashed line.

Surface	Focal length	Distance to next surface
origin	N/A	R
Telescope primary	1216.2	$1216.2 + 60.7$
Telescope coupler	60	10
First lens of beam reducer	80	$80 - 20$
Second lens of beam reducer	-20	20
Fiber coupler	11	$11 + dd$

Table 5.1: List of thin lens surfaces for modeling the primary telescope overlap function. R is the range. The variable dd is the fiber focus parameter. Units are in millimeters.

101.6 mm of the secondary mirror. A second shadow from the receiving area of the collecting mirror after the coupling lens (from the 10 mm hole drilled in the mirror for the transmitted beam) is projected outwards to the telescope aperture. To account for focus alignment of the telescope coupling lens (seen in Fig. 5.1), a small defocus has been added to the primary telescope. To account for the deflection alignment of the mirror after the coupling lens a deflection is added to the beam at this point. The angle of the rays is adjusted by 41.5 mrad. This is about 1/18 of a turn of the adjustment knobs on the mirror. This value matched the measured overlap function the most closely. Finally the image plane is modeled as the fiber diameter of $105\ \mu\text{m}$. The numerical aperture of the fiber is 0.22. The fiber acts as the field stop. The surfaces used in the model are shown in Table 5.1.

The secondary wide field of view telescope is modeled as a single 80 mm focal length lens. The fiber has a diameter of $105\ \mu\text{m}$, .22 numerical aperture, and is placed 80 mm from the front lens. For the instrument at MSU, the secondary telescope is placed in the center of the primary mirror. For the NSF NCAR MPDs the secondary telescope is placed inside the primary mirror area close to the outer radius. The NSF NCAR MPDs therefore need an additional shadow for the primary telescope with a diameter of 2 in at the location of

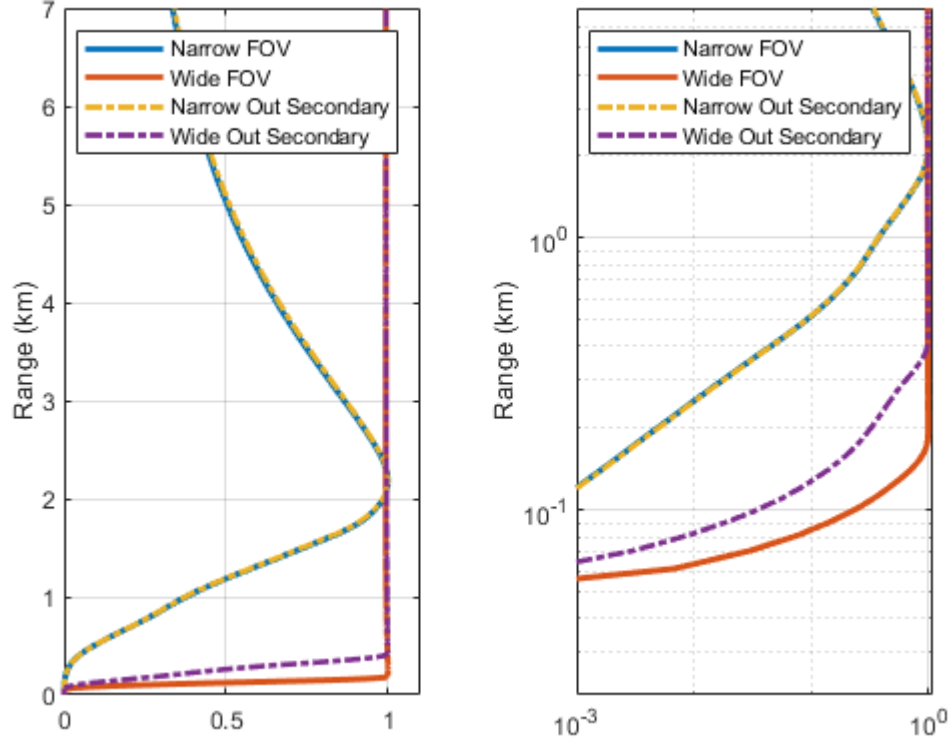


Figure 5.4: Overlap functions for narrow and wide field of view receivers. Solid lines are with the secondary wide field of view receiver in the center of the secondary mirror. Dot-dashed lines are with the secondary wide field of view on the outside of the primary mirror.

the secondary telescope. The overlap function of the secondary telescope at the edge of the primary telescope comes into full overlap about 200 m farther than at the center of the secondary mirror. The two comparisons are shown in Fig. 5.4.

Retrieval Modeling

Wavemeter Sensitivity

The MPD team at NCAR discovered that the wavemeter used for locking the wavelength of the lasers to the specified wavelengths has a bias. The O_2 absorption line is quite narrow and therefore the online absorption is highly sensitive to the laser transmitter wavelength.

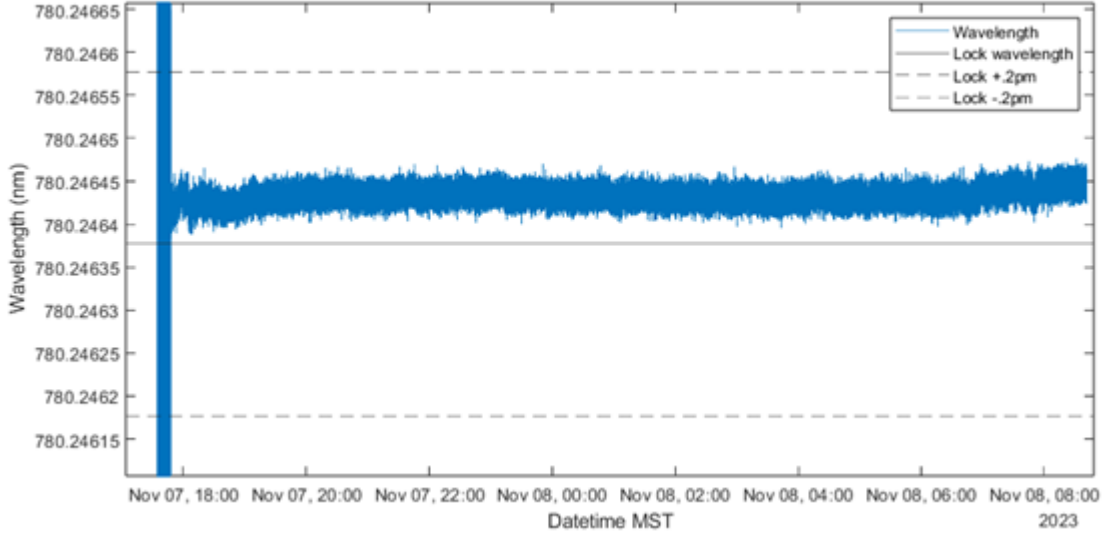


Figure 5.5: The wavemeter used for locking the lasers in the MSU MPD compared to a laser locked to a Rubidium vapor transmission.

A bias to the wavemeter used to measure wavelength can cause the lasers to be locked to the wrong wavelength. The team at NCAR reported the wavemeter was reading 0.24 pm high with doppler free absorption spectroscopy. The wavemeter used by MSU is newer and has less problems than the wavemeters at NCAR. The Bristol Instruments 671A laser wavelength meter has an absolute accuracy of 0.2 parts per million (0.2 pm at 1000 nm) continuously calibrated with an internal HeNe laser. The wavemeter at MSU was measured against a laser locked to a Rubidium vapor cell transmission at 780.246 377 nm with an uncertainty of 0.018 pm. The plot of the measured wavemeter data is shown in Fig. 5.5 with the wavemeter data in blue, the locked line is shown as the solid horizontal line and 0.2 pm is shown in the dashed lines above and below the locked wavelength. The bias for the MSU wavemeter is about 0.05 pm and did not significantly change over the 11 hour observation period.

The bias in temperature retrieval that can be caused by a bias or inaccuracy in the locking wavemeter can be calculated by inputting different wavelengths into the temperature retrieval. The absorption strength is dependent on the laser wavelength. Figure 5.6 shows a

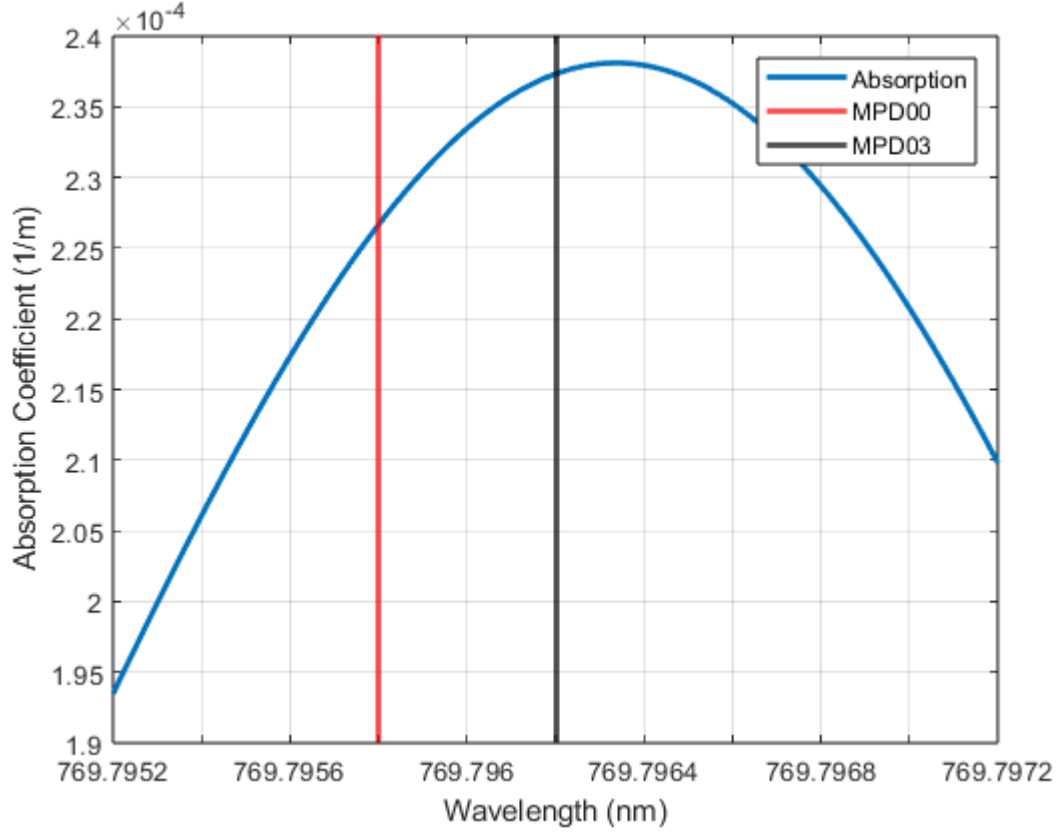


Figure 5.6: Model O₂ absorption by the online laser wavelength for two of the MPD instruments. MSU operates MPD00 and NCAR operates MPD03. The model is at surface level T=296 K and P=1 atm.

model absorption by the online laser of the O₂ DIAL transmitter. The MPD00 operated by MSU in the summer of 2022 was locked to 769.7958 nm and the MPD03 operated by NCAR in 2023 was locked to 769.7962 nm. The MPD00 is unfortunately locked to the vacuum wavelength of the absorption line and the MPD03 is locked to a more central portion of the absorption spectrum because the center wavelength is shifted at atmospheric pressure. Figure 5.7 shows the same laser wavelengths with the absorption modeled at a range of 4 km where the wavelength shift of the absorption is less due to the lower pressure.

Testing the temperature retrieval sensitivity to the wavemeter accuracy is shown in Figs. 5.8 and 5.9. At the wavelength of MPD00 and at ground level a wavemeter inaccuracy

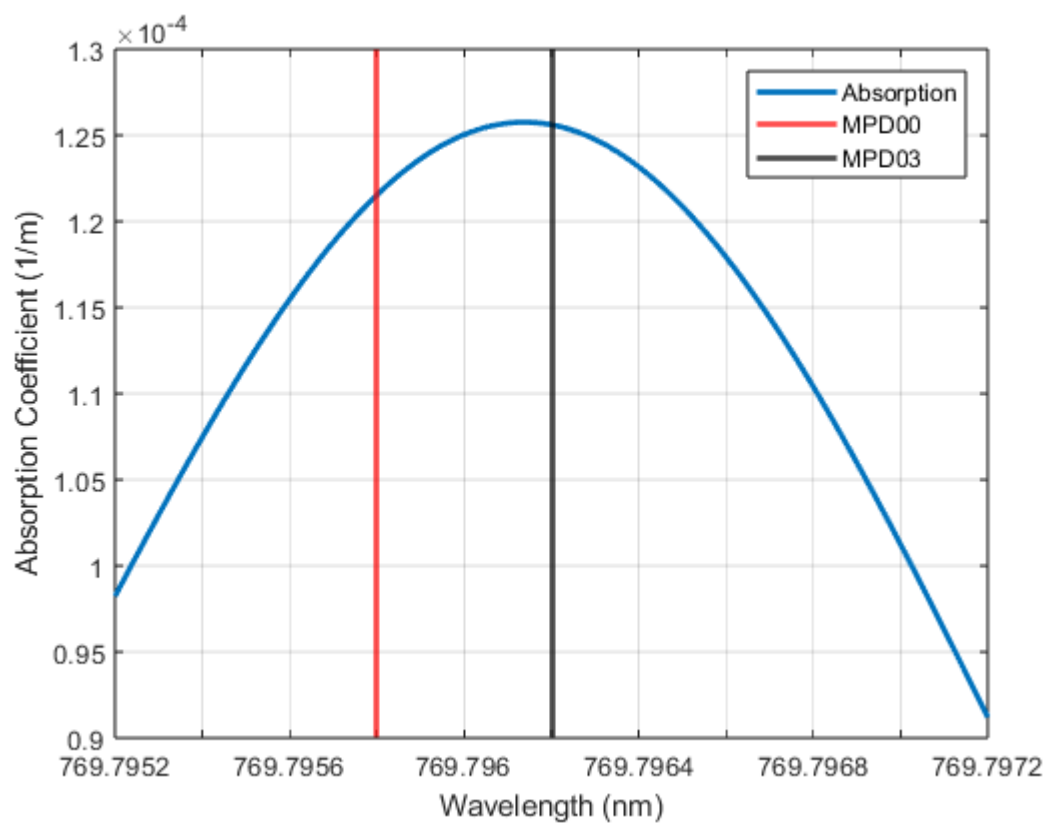


Figure 5.7: Model O_2 absorption by the online laser wavelength for two of the MPD instruments. MSU operates MPD00 and NCAR operates MPD 03. The model is at 4km from the surface $T=270$ K and $P=0.62$ atm.

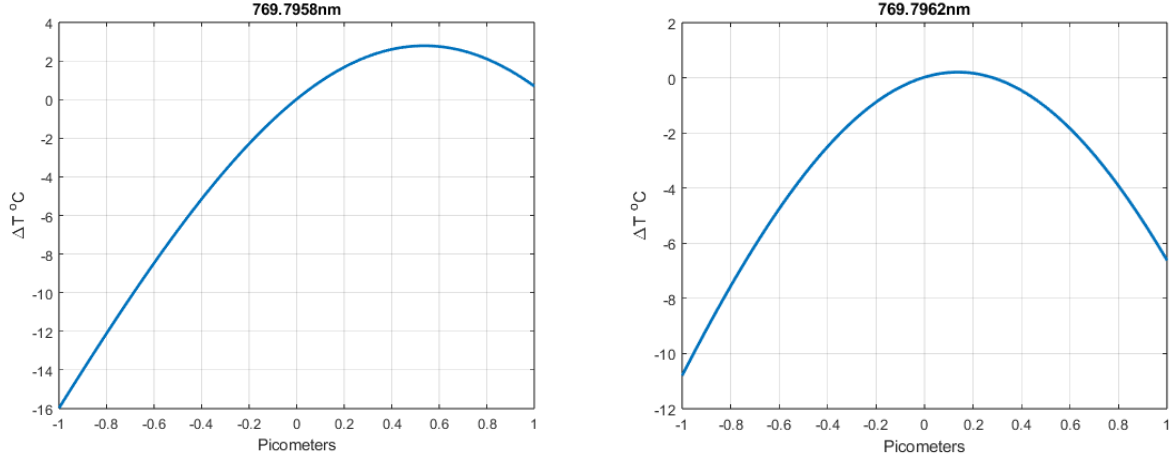


Figure 5.8: Error in temperature retrieval due to bias in wavemeter at two different wavelengths. Calculated at surface temperature and pressure.

of 0.2 pm results in a Temperature error of 1.68 °C, an inaccuracy of −0.2 pm results in an inaccuracy of −2.29 °C. At 4 km 0.2 pm results in 1.25 °C and −0.2 pm is −2.5 °C. At the wavelength of MPD03 and at ground level a wavemeter inaccuracy of 0.2 pm results in a Temperature error of 0.164 °C, an inaccuracy of −0.2 pm results in an inaccuracy of −0.88 °C. At 4 km 0.2 pm results in 1.0 °C and −0.2 pm is −0.2 °C. The results of this sensitivity test show that the temperature errors due to wavemeter inaccuracy can be quite high, up to 2.5 °C. The wavelength of MPD03 is a much better choice because of the location of the O₂ absorption peak at atmospheric pressure causes much lower errors due to inaccuracy in the laser lock because of the wavemeter.

Atmospheric-Retrieval Modeling

Using the lidar equation (Eq. 2.4) and the model of the overlap function and a model atmosphere to model the lidar signal. The modeled signal can then be used in the absorption and temperature retrieval to find the effects of different instrument parameters and retrieval methods. An atmospheric model is created using the U.S. Standard Atmosphere

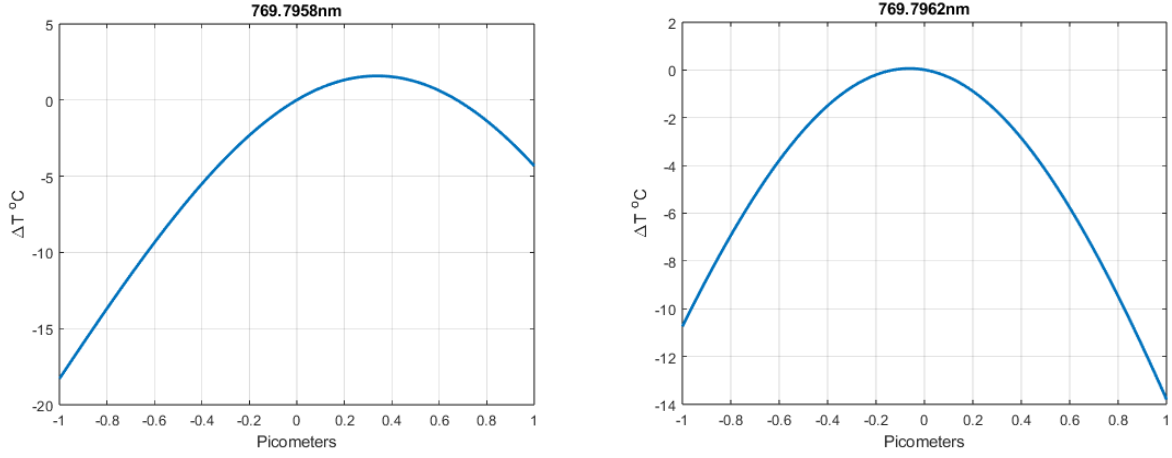


Figure 5.9: Error in temperature retrieval due to bias in wavemeter at two different wavelengths. Calculated at 4 km from surface temperature and pressure.

for temperature and pressure and a measured aerosol profile (shown in Fig. 5.10) from the MPD. The modeled signal counts are shown in Fig. 5.11 and the transmitted photons and receiver efficiency are adjusted to match measured MPD profiles (for a 10 min time bin and 75 m range bin). The final temperature shown in the Figs. is interpolated up to 400 m.

Pulse Length

The MPD uses a long pulse length of $0.75 \mu\text{s}$ to $1 \mu\text{s}$. The longer pulse lengths causes scattering from a region in space that is covered by the pulse. The lidar equation (Eq. 2.4) can be modified to account for the pulse length by [32]

$$P_c(t) = \int_0^\infty T_L(t')P(t-t')dt \quad (5.1)$$

where

$$1 = \int_0^\infty T_L(t')dt' \quad (5.2)$$

and P_c is the convolved pulse and P is the lidar signal for a short laser pulse and T_L is the intensity of the laser pulse in time. The effects of a long pulse lidar may be deconvolved

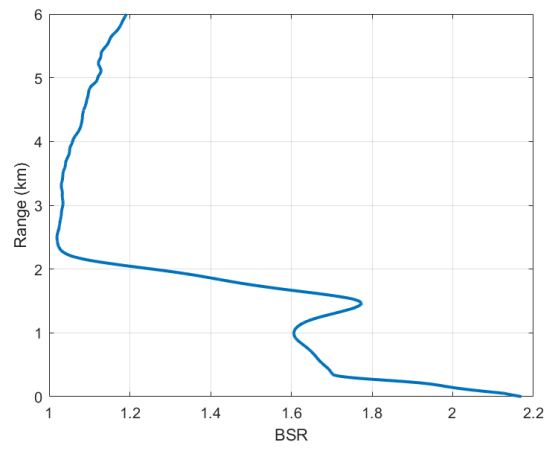


Figure 5.10: Backscatter ratio used as model for atmosphere.

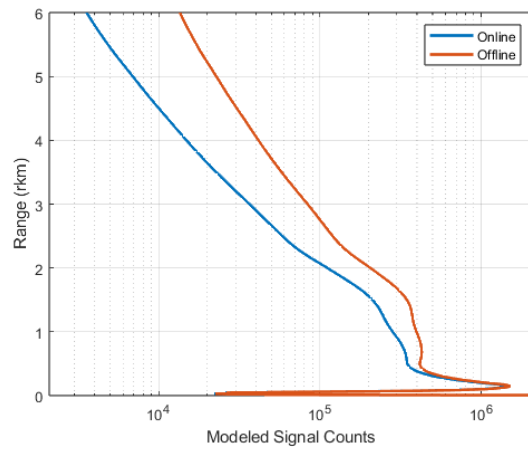


Figure 5.11: Modeled online and offline counts.

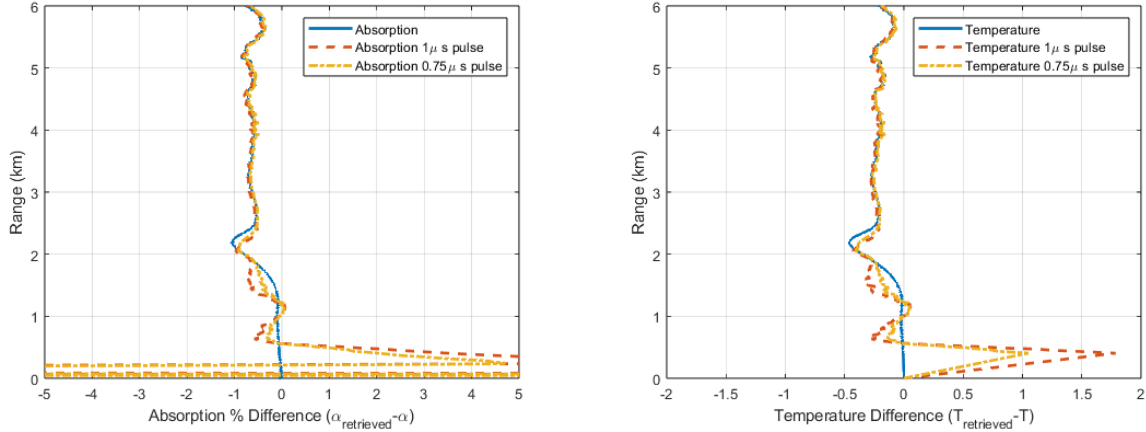


Figure 5.12: O_2 absorption and temperature from modeled receiver counts. Solid lines are without transmitter pulse convolution, dashed lines are with a $1\ \mu s$ pulse convolution, and dot-dashed lines are with a $0.75\ \mu s$ pulse convolution.

if the pulse shape is known [22], however the high noise in the the MPD signal makes this impractical for the DIAL retrieval.

Using the modeled atmosphere and the counts in Fig. 5.11, the absorption and temperature were calculated using the perturbative absorption and temperature retrieval. Temperature is interpolated between the ground and 400 m. The counts convolved with a square $1\ \mu s$ pulse and a $0.75\ \mu s$ pulse were also used to calculate absorption and temperature. The result is shown in Fig. 5.12. The pulse convolution introduces a small but noticeable influence on the DIAL retrieval.

Afterpulsing

The avalanche photodiode detectors experience afterpulsing. The initial lidar transmitter pulse is scattered into the receiver from optical elements such as the primary mirror and the optical window. The detectors become saturated from the lidar pulse and need recovery time. Electrons may not be completely recovered and may still generate signal pulses (afterpulsing) for a period of time. The lidar afterpulsing was measured by placing a

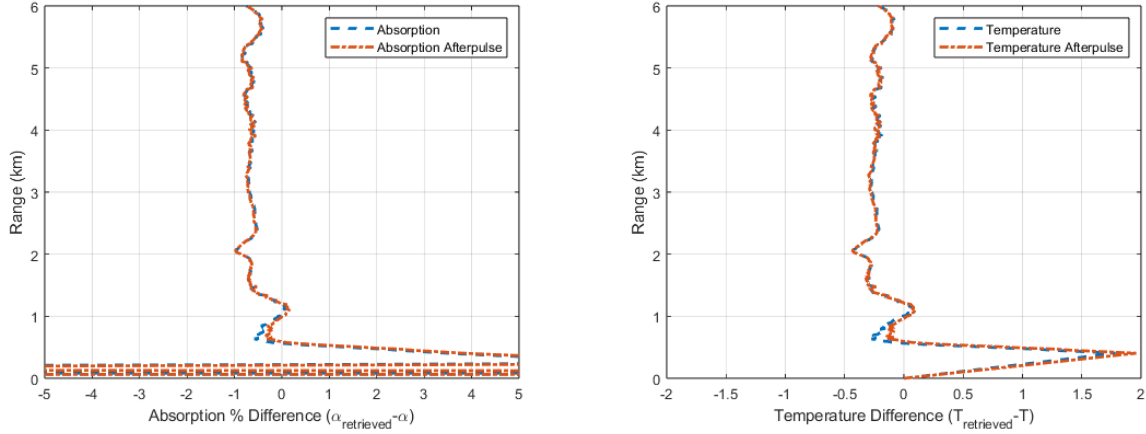


Figure 5.13: O₂ absorption and temperature from modeled receiver counts with a 1 μ s pulse convolution. Dashed lines are without afterpulsing added and dot-dashed lines are with modeled afterpulsing added.

black piece of foam over the primary telescope aperture and measuring the time depended lidar signal after a transmitter pulse. The afterpulsing was measured for over 30 min at the normal lidar operating transmitter frequency of 7 kHz. The afterpulsing can be fitted to an exponential to avoid measurement noise. The measurement was fitted to [83]

$$A(r) = a * \exp(b * r) + c * \exp(d * r), \quad (5.3)$$

where $A(r)$ is the afterpulsing as a function of lidar range, a , b , c , and d are the fitted values, and r is the range.

The modeled O₂ absorption and temperature with the fitted afterpulsing added is shown in Fig. 5.13. The afterpulsing value is reduced by a factor of 1000 because the afterpulsing is greater than normal operation without the blocker. An accurate measurement of the afterpulsing could be subtracted to improve the DIAL temperature retrieval. Low ranges especially could benefit from the afterpulsing correction.

Background Subtraction

The signal background subtraction is essential for the DIAL and HSRL retrievals. The background is considered to be photon counts added to the signal from continuous sources such as the sun, sky, or other random sources. The background is considered to be independent of range and time and can be subtracted from the signal as a singular value per each range profile. The background is measured by taking the mean of the last 20 range bins of each lidar profile for each lidar channel (online, offline, etc.). At a transmitter pulse repetition rate of 7 kHz and a range bin of 250 ns, each lidar profile contains 560 range bins from a range of 0 m to 21.000 m. For a pulse rate of 8 kHz only 490 range bins can be measured before the next pulse. This gives a maximum range of 18.375 m. By using this method of background subtraction, the signal at the last 20 range bins is assumed to be much smaller than the background. However, at night the background is so low that a small amount of signal may still be present in the last 20 range bins so that the signal may be incorrectly subtracted as background. Figure 5.14 shows modeled absorption and temperature with 1% of typical nighttime background added to the online channel and offline channel, and with 1% of typical nighttime background subtracted to the online channel and offline channel. Figure 5.15 shows modeled absorption and temperature with 1% of typical nighttime background added to the online channel and subtracted from the offline channel.

The background subtraction is important to measure correctly especially for the DIAL retrieval at high altitudes. Since the pulse frequency determines the maximum measurement altitude, if the pulse frequency is increased the background subtraction must be taken into consideration. The background subtraction must also take into account any remaining signal that may exist at the maximum altitude ranges. The background must be much higher than the signal at maximum altitude or errors may occur in the retrieval. Perhaps a method similar to Cao et al. can be used [13].

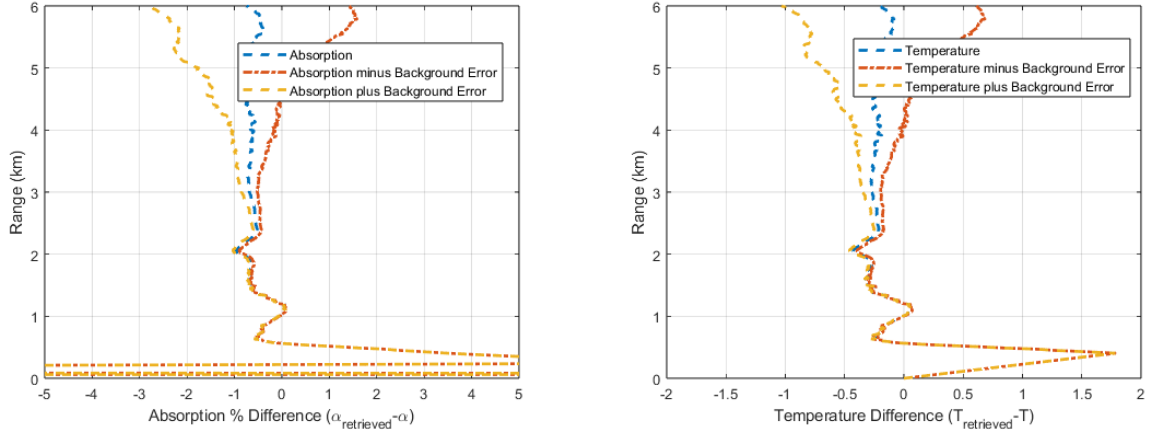


Figure 5.14: Absorption and temperature retrieval with a $1\mu s$ pulse convolution and background error. Background error is 1% of typical nighttime background subtracted and added to both the online and offline DIAL channels.

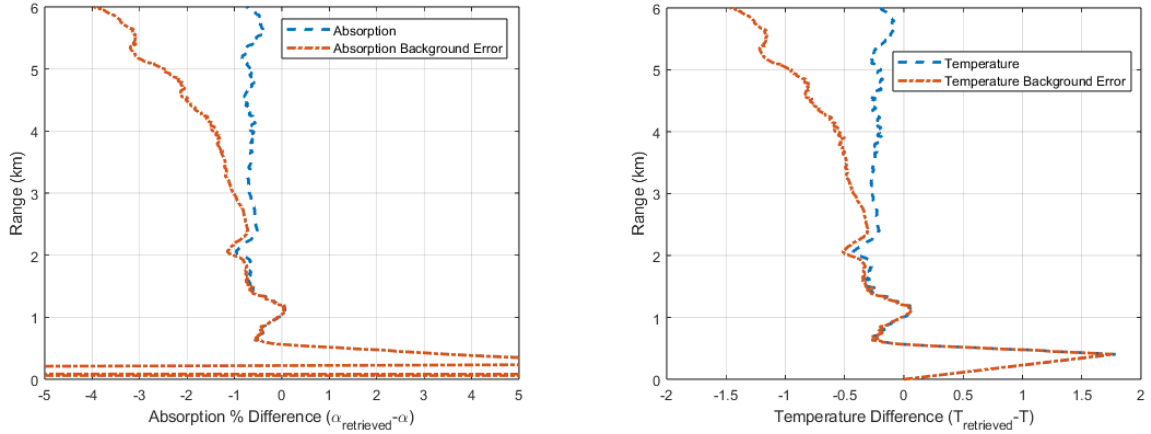


Figure 5.15: Absorption and temperature retrieval with a $1\mu s$ pulse convolution and background error. Background error is 1% of typical nighttime background added to the online channel and subtracted from the offline DIAL channel.

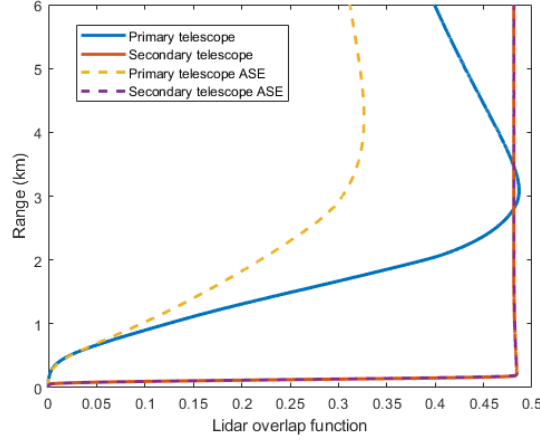


Figure 5.16: Lidar overlap function with the narrow and wide field of view models and with normal lidar transmitter and ASE models. The ASE overlap is modeled as double the transmitter divergence.

Spectral Purity

The TSOA transmitter has a spectral width outside of the narrow laser transmitter linewidth. The spectral purity is defined as the amount of optical power outside the central mode's spectral width. The spectral purity of the MPD O₂ transmitter has been measured to be 99.95% or as low as 90% with improper seeding of the TSOA[65]. This larger spectral width can be due to amplified spontaneous emission (ASE). Due to the shape of the O₂ absorption linewidth, a wider spectral width has an effect on the DIAL retrieval. The ASE also can have a larger divergence than the narrow stimulated emission. The ASE divergence is modeled as double the divergence as the narrow laser transmission. Figure 5.16 shows the normal overlap function and the ASE overlap function with double the divergence. The O₂ absorption and temperature are shown in Fig. 5.17 with a spectral purity of 90%. The retrieval also includes the 1 μ s pulse length. The small difference in retrieved temperature with a lower spectral purity than typically measured suggests that ASE has a low impact on the DIAL retrieval.

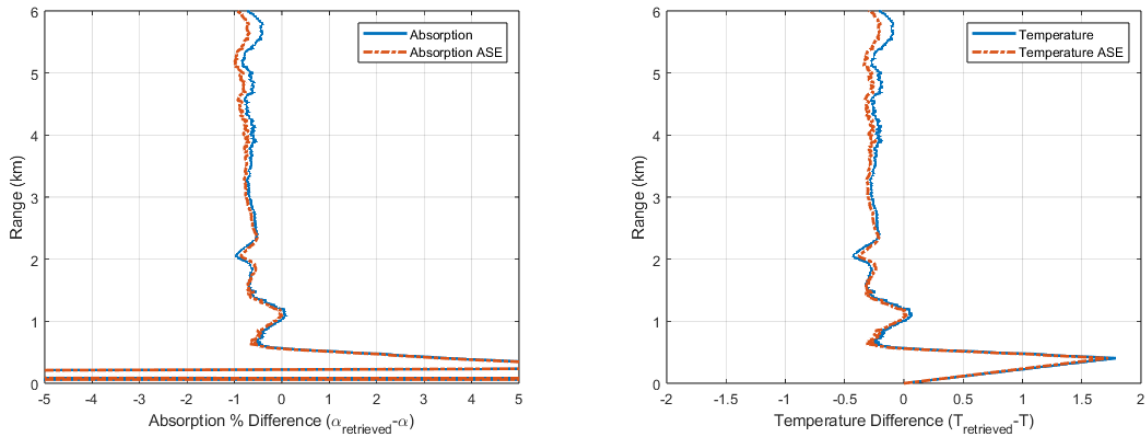


Figure 5.17: O_2 absorption and temperature from modeled receiver counts. Solid lines are without ASE and dashed lines are with ASE.

RESULTS AND DISCUSSION

This chapter will present results from data taken at MSU and during the Pre-CIP campaigns. A discussion of results from each period follows.

Results of Temperature Profiling at MSU

The instrument is located in a roofport-equipped laboratory facility of MSU. Ancillary measurements of surface temperature and pressure are provided by a collocated weather station (Vaisala CS105, HMP45C) operated by the MSU Optical Remote Sensor Lab. The radiosonde station is located next to the roofport and allows the launching of Vaisala RS92 radiosondes that are monitored using the Vaisala SPS220 with GC25 ground check station. The DIAL-based temperature retrievals were compared to temperature profiles retrieved using the radiosondes as a reference.

The instrument was operated between April 21, 2022 and September 22, 2022. Between April 21 and July 16, a pulse duration of $1\ \mu\text{s}$ and a pulse repetition rate of 7 kHz were used. Between July 26 and September 22, a pulse duration of 750 ns and a pulse repetition rate of 8 kHz were used. A collocated radiosonde station was used to launch a total of 40 radiosondes over the course of the lidar operation, with 30 launched between April 21 and July 16 and the remaining 10 launched between July 26 and September 22. The retrieved temperature profile as a function of time and range is shown in Fig. 6.1 with a selected section in Fig. 6.2 for detail. Figure 6.1a shows the retrieved temperature as a function of range and time for the April 21 – July 22 period. Figure 6.1b shows the corresponding surface temperature. Figure 6.1c shows the retrieved temperature as a function of range and time for the July 26 – September 22 period. Figure 6.1d shows the corresponding surface temperature. The dashed black vertical lines indicate when radiosondes were launched. The water vapor mixing ratio for Figs. 6.1 and 6.2 was interpolated from radiosonde data. For the data presented in

Figs. 6.1 and 6.2, a cloud mask and a signal-to-noise-ratio mask have been applied. The cloud mask is a moving standard deviation window of 150 m and 20 min of the BSR with a threshold of 5, set to remove clouds. The background counts are shown in Fig. 6.7 and shown the day and night cycle as well as high background from clouds and precipitation. The temperature is smoothed with a moving average of 300 m in range and 60 min in time. The signal-to-noise mask is created from the Poisson thinning process described in Ch. 3 Sec. 3 with a threshold of 5°C . This combination of smoothing and masking was chosen so the temperature mask covered up to 3.5 and 4 km in range and the temperature uncertainty from detector noise was within 5°C . Furthermore, data below 400 m is masked.

The early part of the data collection period had many days with low clouds and rain where data is limited. The later part of the data collection period had days with high aerosol concentration due to wildfire smoke, an increase in aerosols can help increase the range of the MPD due to higher scattering at high altitudes, however if the concentration is too high or gradients in range too steep the temperature retrieval has difficulty. In typical clear conditions the MPD temperature retrieval has a range of about 2.5 km at midday and about 3.5 km during the night with bins of 10 min in time and 75 m in range and smoothing of 60 min in time and 300 m in range.

A single example of a retrieved temperature profile is shown in Fig. 6.3. All plots of the temperature as a function of range with comparisons to radiosondes are shown in Fig. 6.4. The red line is the temperature measured from the radiosonde, while the blue line indicates the temperature retrieved using the lidar. The error shown is estimated using the bootstrapping method discussed above. Figure 6.5 shows the same profiles but as a difference between DIAL profiles and radiosonde profiles. The profiles shown in Figs. 6.4 and 6.5 show good agreement with the radiosondes in most cases. The lidar captures the larger aloft temperature inversions well. During the summer months, surface air temperature is highly variable due to strong shortwave/longwave radiative heating/cooling. During the day, intense

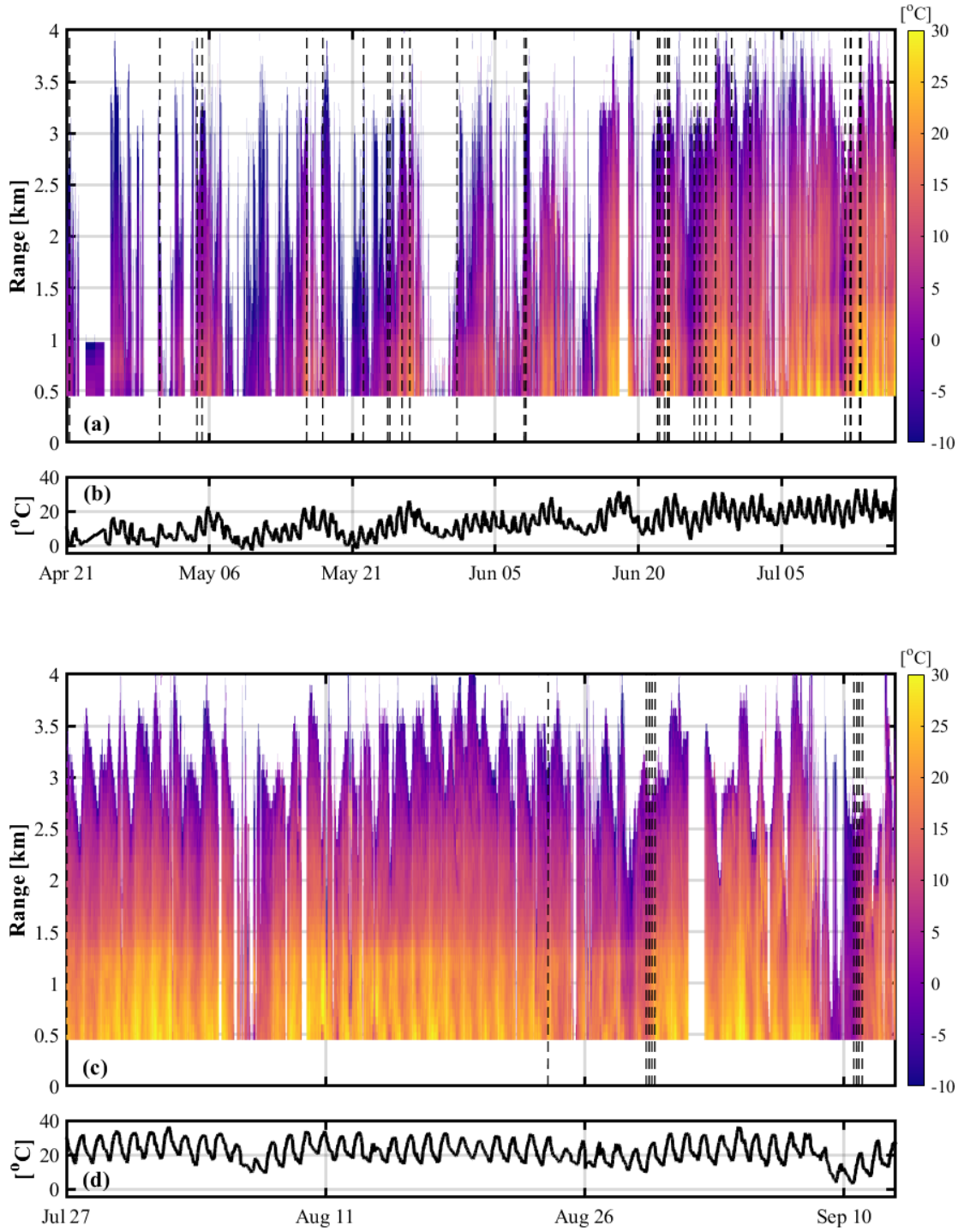


Figure 6.1: Temperature retrieval from the MSU lidar in the summer of 2022. Vertical dashed lines represent radiosonde launches. Areas in white represent a data mask. The data mask is from data availability, clouds, and low signal-to-noise ratio. Time ticks are at 00:00 UTC.

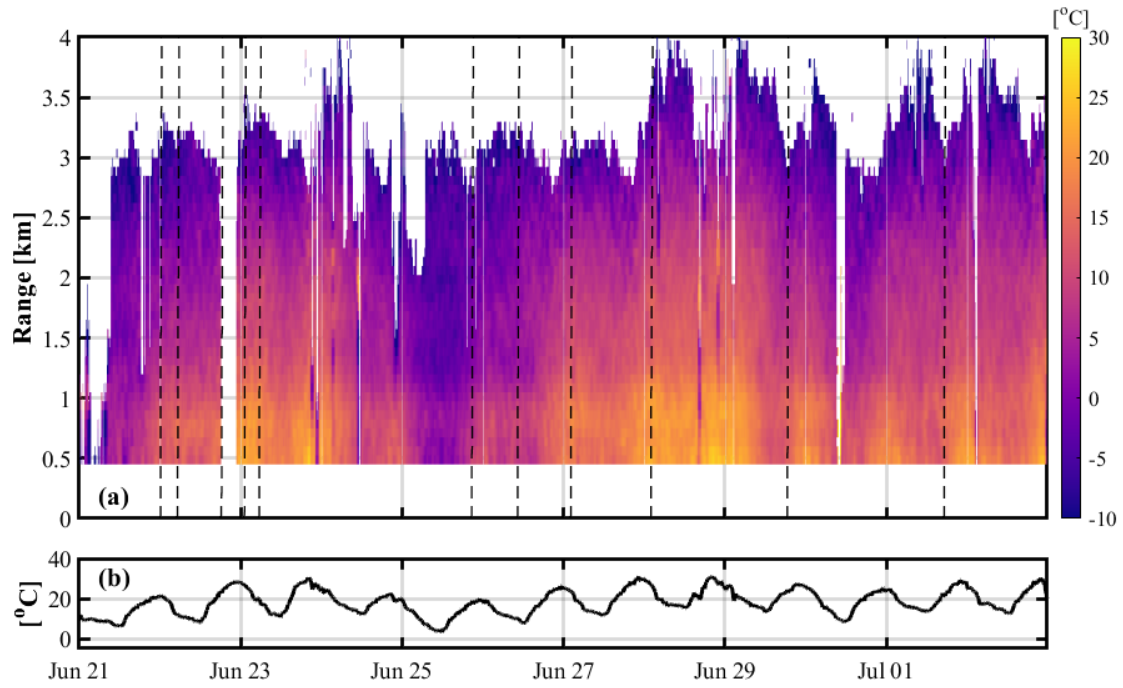


Figure 6.2: A selected section of the measurement period shown in Fig. 6.1.

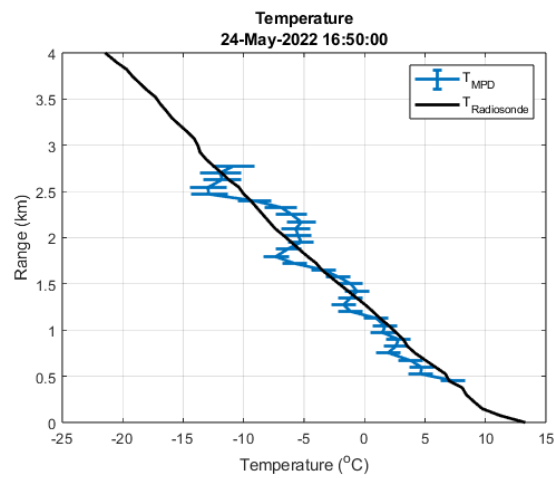


Figure 6.3: A single retrieved temperature profile with an error estimate as errorbars and a corresponding radiosonde profile.

surface heating caused a super-adiabatic lapse rate, and during the night, radiative cooling caused temperature inversions at the surface. These effects are mostly confined below the first measurement bin of the temperature profile at 400 m. This can be seen in the radiosonde profiles between the ground level and 500 m in Fig. 6.4.

The perturbative retrieval of the O_2 absorption coefficient utilizes the retrieved BSR to account for the broadened lineshape of the backscattered signal. A plot of the zero-order absorption, first-order correction, second-order correction, and total absorption are shown in Fig. 6.6a-6.6d, respectively, for the same time period as Fig. 6.2. The BSR is shown in Fig. 6.6e. For the O_2 absorption coefficient retrieval, the zero-order term tends to be too low due to the broadening of the molecularly scattered signal, i.e., observed absorption is less than what would be expected from pure aerosol scattering that would maintain the laser wavelength spectrum because the emitted wavelength is broadened by molecular scatterers. Accordingly, the first-order correction term is mostly positive and is on the order of about 10% to the total absorption coefficient. The second order correction term contributes about 1% to the total absorption coefficient. The first and second-order correction terms tends to contribute most in two distinct scenarios: 1) when there are strong gradients in the BSR (the DIAL technique depends on the gradient in range and a BSR gradient greatly contributes to Rayleigh-Brillouin error) or 2) when the BSR approaches unity and molecular scattering dominates (here the reduction in absorption due to Rayleigh-Doppler broadening is maximized).

A comparison of the radiosonde temperature to the DIAL retrieved temperature is shown in Fig. 6.8. Figure 6.8a (6.8c) is a comparison plot of the temperature retrieved from the lidar and the radiosondes for the data collected using a $1\ \mu\text{s}$ (750 ns) pulse duration, while Fig. 6.8e is a comparison for all 40 radiosondes. Figure 6.8b (6.8d) is a plot of the temperature difference as a function of range for the data collected using a $1\ \mu\text{s}$ (750 nm) pulse duration, while Fig. 6.8e is a plot of the temperature difference for all 40 radiosondes.

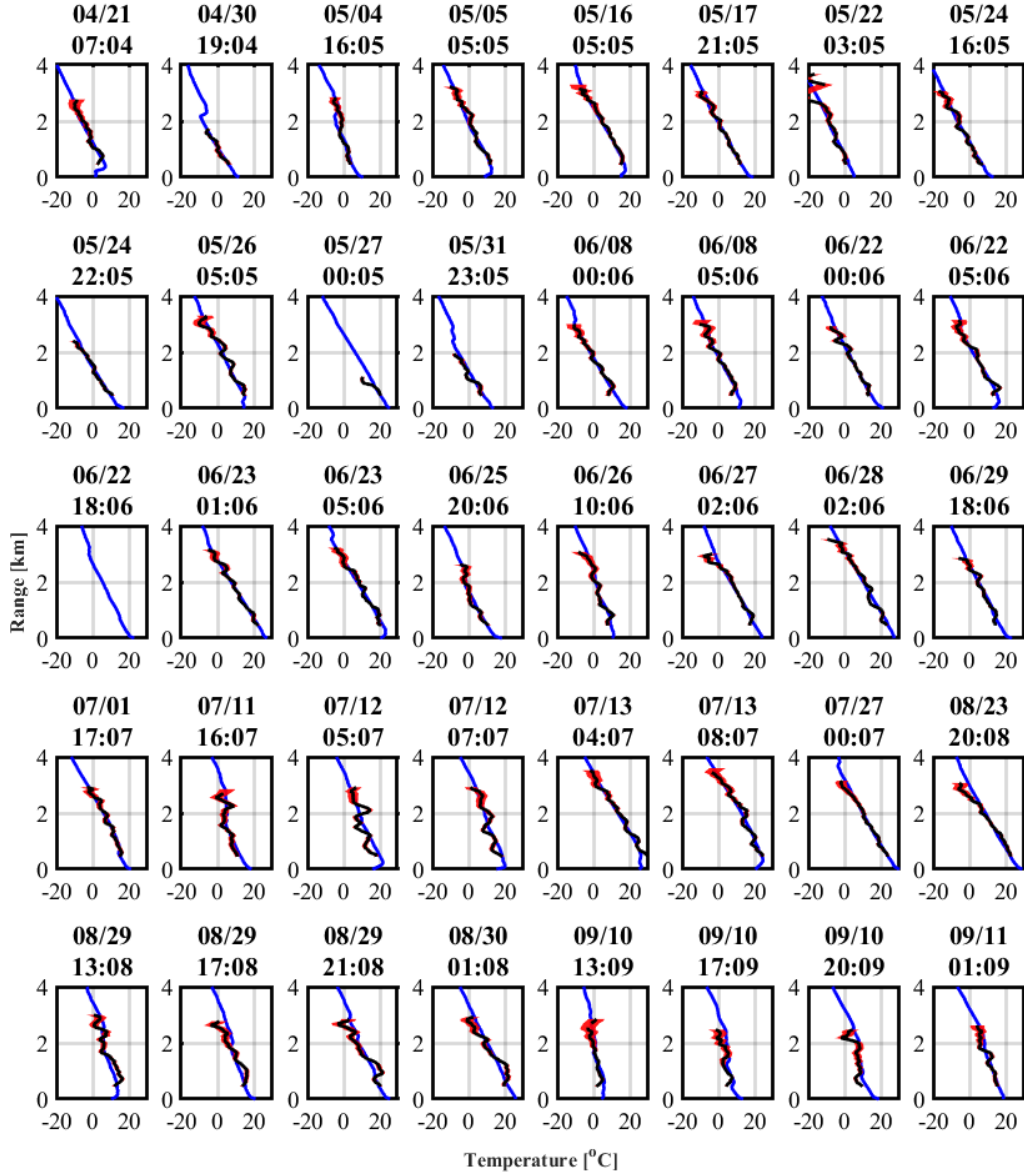


Figure 6.4: All radiosonde profiles from the measurement period with the radiosonde temperature in blue, DIAL temperature in black and error colored in light red shading. The temperature retrieval from the radiosonde profile on 06/22 18:06 was completely masked out from clouds and error masking.

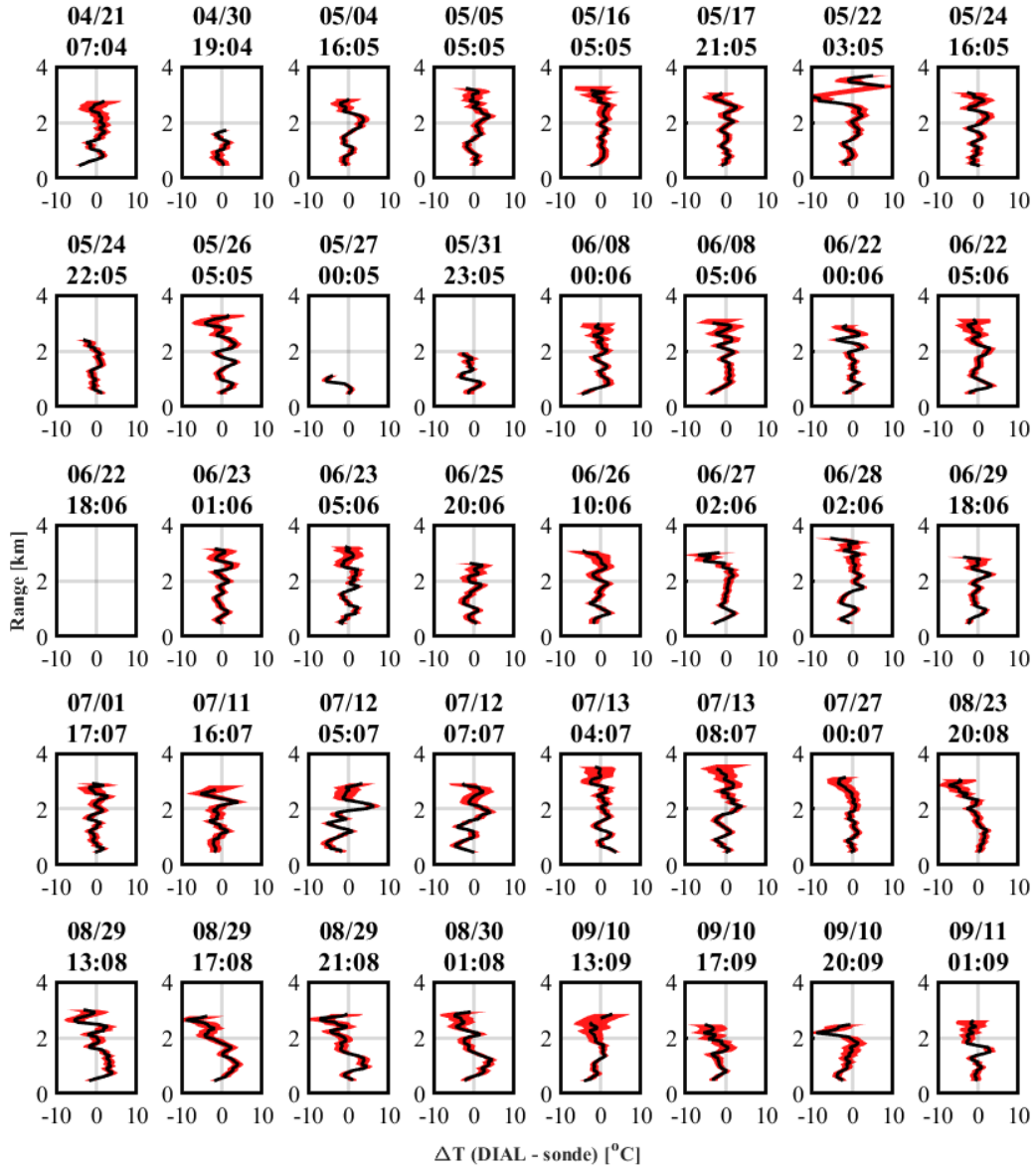


Figure 6.5: Temperature difference between DIAL and radiosonde. Error estimates are light red shading.

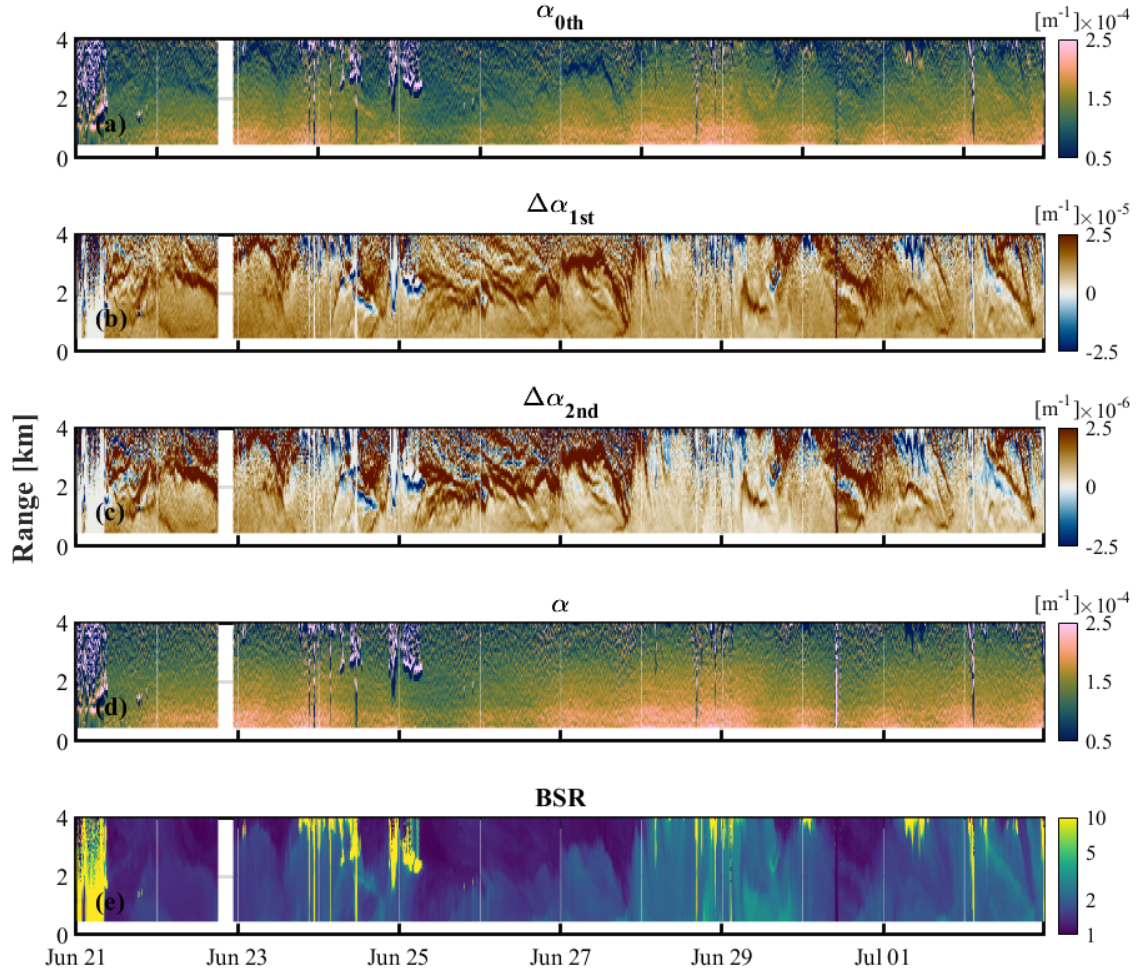


Figure 6.6: A selected section of the MPD data set showing the effect of the backscatter ratio on the O₂ absorption and the perturbative correction. Upper plot (a) shows the zero-order standard DIAL O₂ absorption coefficient. Below that (b) is the first-order correction. Below that (c) is the second-order correction. Next (d) is the total corrected O₂ absorption coefficient. Last (e) is the backscatter ratio. Note the changes in color and scale to represent the data. Time ticks are at 00:00 UTC.

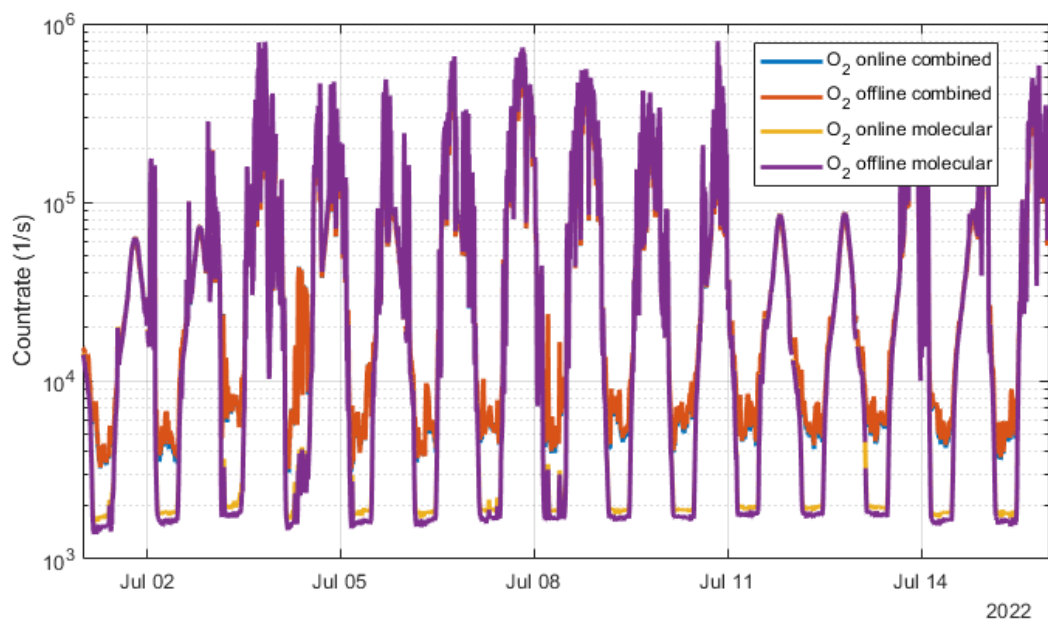


Figure 6.7: Background count rate for each lidar channel. A selection of the wider data is shown. The diurnal cycle can be clearly seen with background increasing in the daytime and going to a minimum at night. July 11 and 12 show clear days with no clouds. Time ticks are at 00:00 UTC.

In Figs. 6.8a, 6.8c, and 6.8e, the dashed black line represents a slope of unity, while the solid black lines represent a slope of 1 with a $\pm 2^\circ\text{C}$ offset and the blue line represents a linear fit. In Figs. 6.8b, 6.8d, and 6.8f, the vertical dashed black line represents a temperature difference of 0°C while the solid black lines represent a temperature difference of $\pm 2^\circ\text{C}$ and the blue line represents the mean and dashed lines are the standard deviation from the mean.

Using a linear fit to the scatter plot of the temperature retrieved from the lidar and the temperature measured using collocated radiosondes shown in Fig. 6.8a, a slope of 0.995 and intercept of 0.0185°C was determined with an $R^2 = 0.919$. The fit in Fig. 6.8c has a slope of 1.00 an intercept of -0.539°C with an $R^2 = 0.830$, in Fig. 6.8e the slope is 0.964 with an intercept of 0.387°C and with an $R^2 = 0.912$. Difference comparisons between radiosonde and lidar temperature as a function of altitude show a consistent bias that swings from positive to negative in altitude approximately 1 km above ground level. This is also seen on time series plots as horizontal banding. Slight horizontal banding can also be observed in water vapor MPD data in previous work [68, 76] suggesting the bias stems from something with MPD hardware architecture. Different instruments and small differences in the alignment of the MPD show different shapes and amplitudes of the bias. In the observational period presented here, the pulse length of the lidar transmitter was changed from $1\ \mu\text{s}$ to $0.75\ \mu\text{s}$ in an attempt to reduce or change the bias. Figs. 6.8b and 6.8d show the bias change between a $1\ \mu\text{s}$ and a $0.75\ \mu\text{s}$ pulse length. We believed that amplified spontaneous emission from the tapered amplifier used in the lidar transmitter, which has a larger divergence angle than the amplified injection seeded beam, results in larger errors at short ranges. This may not be correct. This exact cause of the effect is currently under investigation.

Each comparison bin has dimensions of 75 m and 10 min. Early summer has 977 bins for comparison, late summer has 300 bins for comparison, and in total there are 1277 bins for comparison. The standard deviation of the temperature difference is 2.51°C (mean 0.005°C) for the $1\ \mu\text{s}$ pulse duration, 2.36°C (mean -0.784°C) for the $750\ \text{ns}$ pulse duration, and

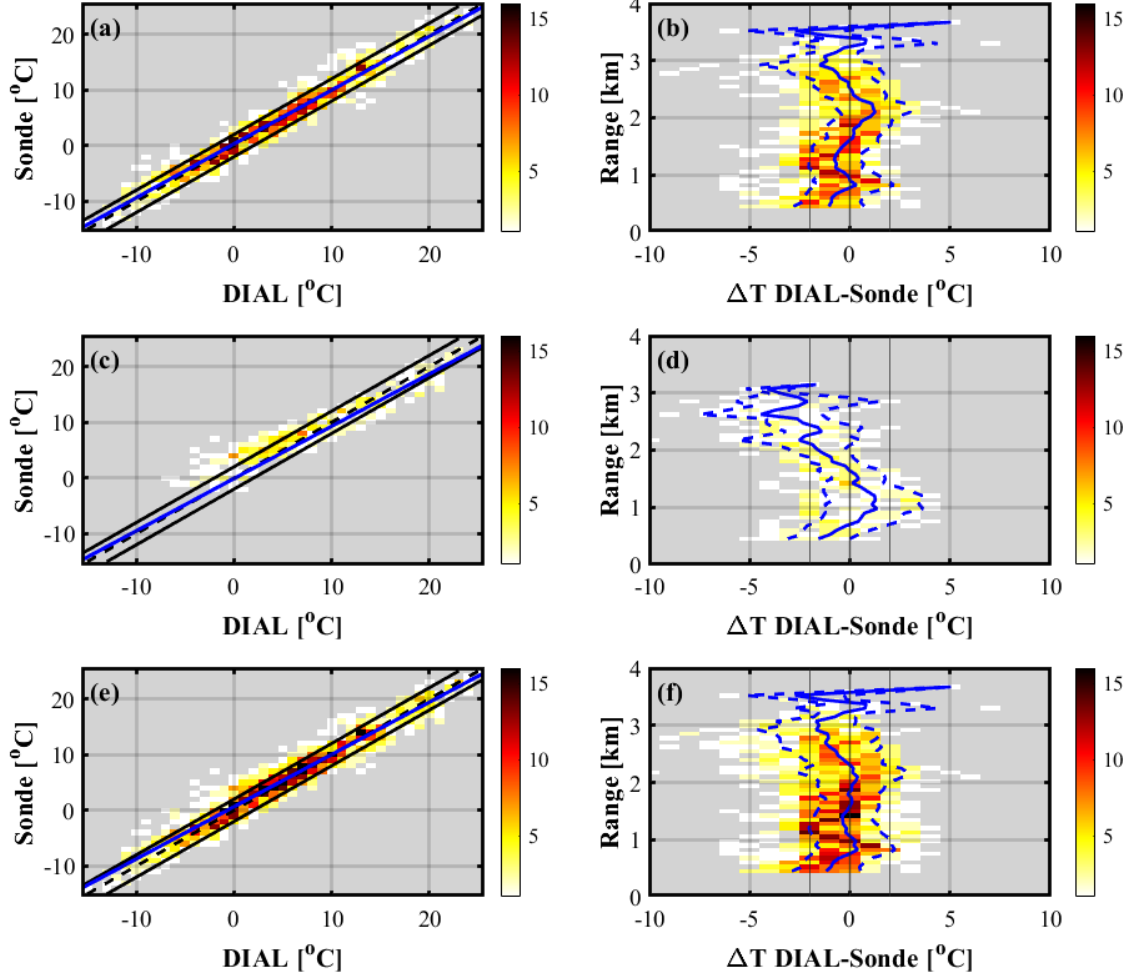


Figure 6.8: (a,c,e) Comparisons of radiosondes and DIAL temperature on a 1:1 plot. The blue line is a linear fit. Black dashed line is along the 1:1 line, and black solid lines are 2K away. (a) Early summer 1 μ s pulse length, (c) Late summer 0.75 μ s, (e) total summer comparison. (b, d, f) Comparisons of radiosonde and DIAL temperature difference as a function of range. Blue line is the mean, and black dashed lines are 1 $^{\circ}$ C away. (b) Early summer 1 μ s pulse length, (d) Late summer 0.75 μ s, (e) total summer comparison.

2.50 °C (mean -0.190 °C) for the combined data. Based on the combined data, this suggests that the error in the temperature retrieval is approximately ± 2.5 °C, however, a small bias in range is present as shown in Fig. 6.8.

The results of the bootstrapping method of error estimation presented in Ch. 3 section 3 is shown in Figs. 6.4 and 6.5. As expected, the error estimate increases with range because of lower signal to noise ratio at farther ranges. The error estimate is primarily used as a mask where temperature profiles are masked based on a threshold of 5 °C in the error estimate. The mask shown in Figs. 6.1 and 6.2 show an expected pattern of masking more during the day because of the higher background noise. The radiosonde comparisons in Fig. 6.8 show few comparison points beyond ± 5 °C meaning the error estimate appears to function well enough to mask data within a threshold.

Discussion of MSU Data

The first step in the temperature retrieval process relies on a perturbative retrieval of the O₂ absorption coefficient that utilizes the retrieved BSR to account for the lineshape of the backscattered signal. A plot of the zero-order absorption, first-order correction, second-order correction, and total absorption are shown in Fig. 6.6. The BSR is also shown in Fig. 6.6. The zero-order absorption term results from the standard DIAL retrieval (Eq. ??) and is in the range of about $1 \times 10^{-4} \text{ m}^{-1}$. For the O₂ absorption coefficient retrieval, the zero-order term tends to be too low due to the broadening of the molecularly scattered signal, i.e., absorption is less than expected because the emitted wavelength is broadened by the backscattering process. The first-order correction term is mostly positive and is on the order of $1 \times 10^{-5} \text{ m}^{-1}$, contributing about 10% to the total absorption coefficient. The first-order correction term tends to contribute most when there are high gradients in the BSR (the DIAL technique depends on the gradient in range and a BSR gradient greatly contributes to the error) or when the BSR approaches unity and molecular scattering dominates. The

second order correction term is on the order of $1 \times 10^{-6} \text{ m}^{-1}$, contributing about 1% to the total absorption coefficient. This second-order term tends to contribute most when the BSR approaches unity and molecular scattering dominates.

The efficacy of temperature retrieval was tested using data provided by the radiosondes in 2 ways. Because the retrieval described is a 2 part process (1: perturbative retrieval of the O_2 absorption coefficient and 2: iterative conversion of absorption to temperature), it is useful to test each step. To test the former, an O_2 absorption profile calculated from HITRAN parameterizations using radiosonde temperature, pressure, and water vapor data was compared to the absorption profile measured using the perturbative retrieval and data from the lidar. A plot of the difference between the absorption coefficient profile measured using the lidar and the absorption coefficient measured using the data from all 40 radiosondes, is shown in Fig. 6.9. Figure 6.9a shows the absorption difference based on the standard DIAL retrieval, i.e., the zero-order absorption term. As expected, the absorption measured by the lidar is about 10% lower than the absorption coefficient calculated using the radiosonde data. This corresponds to a bias of approximately $2.5\text{-}3^\circ\text{C}$. Furthermore, large deviations are observed at distinct heights. These correspond to strong aerosol gradients and are the reason Bösenberg [9] concluded that “the incomplete Rayleigh-Doppler correction is the dominant source of error, making this method practically useless for applications in atmospheric research.” Figure 6.9b shows the absorption difference as a function of range when the total absorption coefficient is calculated with the perturbative method – the sum of the zero, first, and second-order terms. The absorption difference is now centered near zero with no large spikes, indicating that the perturbative retrieval of the absorption coefficient is correcting for the change in lineshape of the backscattered light.

Similar to above, a test of the second step of the temperature retrieval algorithm was conducted using data from the radiosondes. Note, while this does not test the accuracy of the spectroscopic model or the perturbative absorption correction (the first step of the

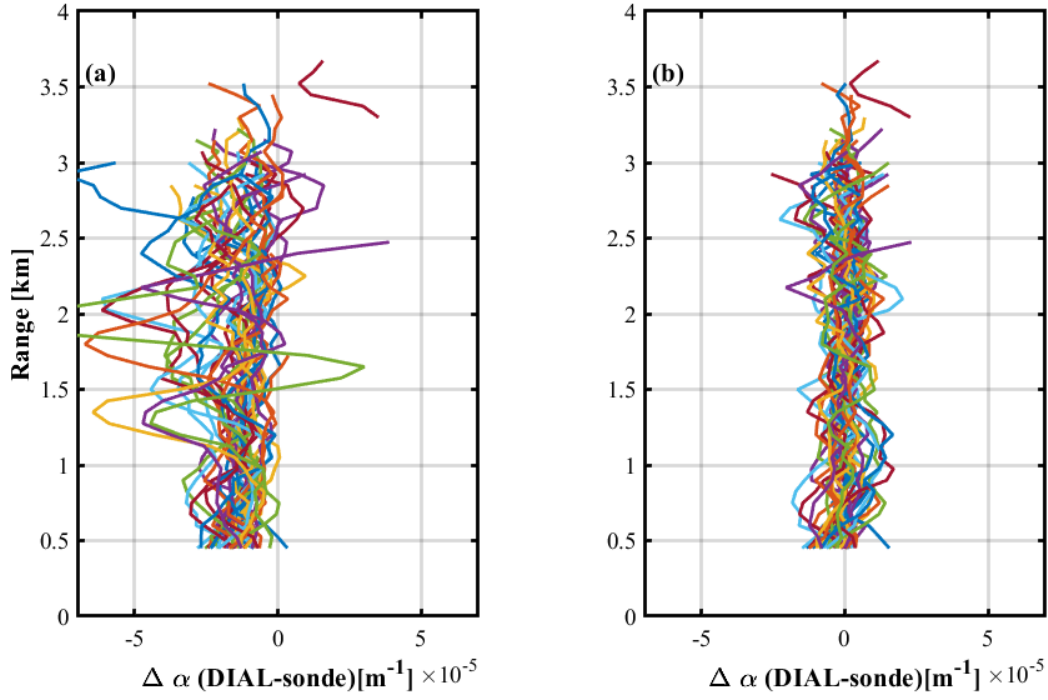


Figure 6.9: Comparison of the DIAL O_2 absorption coefficient and modeled O_2 absorption coefficient from radiosonde data. Each line represents one radiosonde profile. (a) Zero-order O_2 absorption coefficient difference. (b) Total corrected O_2 absorption coefficient difference.

DIAL temperature retrieval), it will highlight in particular the pressure sensitivity in the spectroscopic model. The calculated absorption profiles from the radiosonde temperature and pressure measurements (shown in Fig. 6.9) are used as input into the iterative temperature retrieval. The surface temperature, along with a lapse rate of -6.5 K/km , was used as the initial temperature profile (this is only a starting point because the temperature and pressure model will converge to the final temperature profile). A pressure profile was then calculated using the surface pressure, and the initial guess lapse rate using Eq. 2.34. The initial temperature profile was updated using Eq. 2.48 and iterated until convergence. Once the iterative temperature retrieval converges, a comparison of the retrieved temperature and pressure profiles with the temperature and pressure profiles measured with the radiosondes can be used to assess the efficacy of the iterative temperature retrieval technique. A plot of the temperature and pressure difference (retrieved minus the radiosonde) as a function of range is shown in Fig. 6.10a(6.10b).

The maximum temperature difference in Fig. 6.10 is less than 0.03°C at 5 km, while the maximum pressure difference is less than 0.001 atm up to 5 km. Note the data range exceeds the observed DIAL observation range as all data originates from sonde measurements. This result indicates that if one starts with the correct O_2 absorption profile, the iterative temperature retrieval will converge to provide a good estimate of the temperature and pressure profiles. The addition of the additional absorption line in the temperature retrieval shown in Ch. 2 improved the retrieval-sonde comparison by an average of 1.6°C at 400 m and 0.8°C at 4 km using the same comparisons shown in Fig. 6.10a. The retrieved temperature is higher without the additional line because a lower calculated absorption in Eq. 2.48 will result in a higher temperature. The difference changes in height because the absorption lines have different temperature sensitivities.

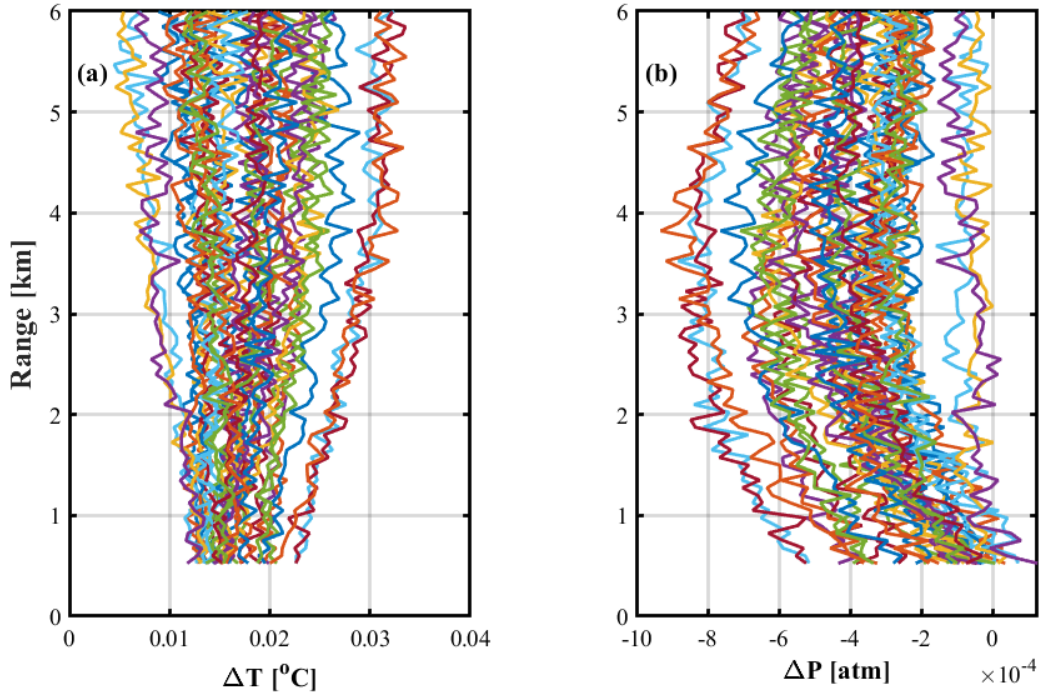


Figure 6.10: Similar to Fig. 6.9 comparing temperature and pressure (a) Temperature difference (retrieval minus sonde). (b) Pressure difference (Eq. (2.34) minus sonde).

Pre-CIP

A field test in Fort Collins, CO near Christman Field run by the National Center for Atmospheric Research (NCAR) generated a dataset with WV DIAL, O₂ DIAL, and HSRL data[45]. Radiosondes were launched and used as a comparison to the MPD retrievals. However, the radiosondes were launched for a separate study and not ideal conditions for lidar comparisons. Radiosondes were launched in convective conditions and launched during the day. This represents difficult conditions for lidar retrievals because of solar background and cloudy conditions. About two months of continuous data were recorded and 42 radiosondes were launched. This dataset is useful for improving the temperature retrieval. This test was the first major test of the combined WV, HSRL, and temperature and can be used to test the retrieval with all components working together. The WV and HSRL retrieval rely on an estimated temperature model. The temperature retrieval can be used to improve the WV and HSRL over the estimated model. The HSRL measurement can also be used to improve the WV retrieval in the same process as the perturbative O₂ temperature retrieval based on the Doppler broadening of the molecular backscatter signal. The analysis presented here is my own and not the full retrieval from NSF NCAR. The water vapor retrieval and backscatter ratio is a simpler version than used by NCAR.

Temperature Retrieval

Figures 6.11 and 6.14 show temperature and absorption profiles for the almost two month test. The background counts are shown in Fig. 6.18 and demonstrates the day and night cycle and background from clouds. Figure 6.14 shows horizontal banding in the upper regions (above 2 km) of absorption. This may be due to ringing due to feedback or backreflections into the TSOA. This has since been corrected in newer iterations of the MPD. Figures 6.12, 6.13, 6.16, 6.15, and 6.17 show comparisons between radiosonde temperature

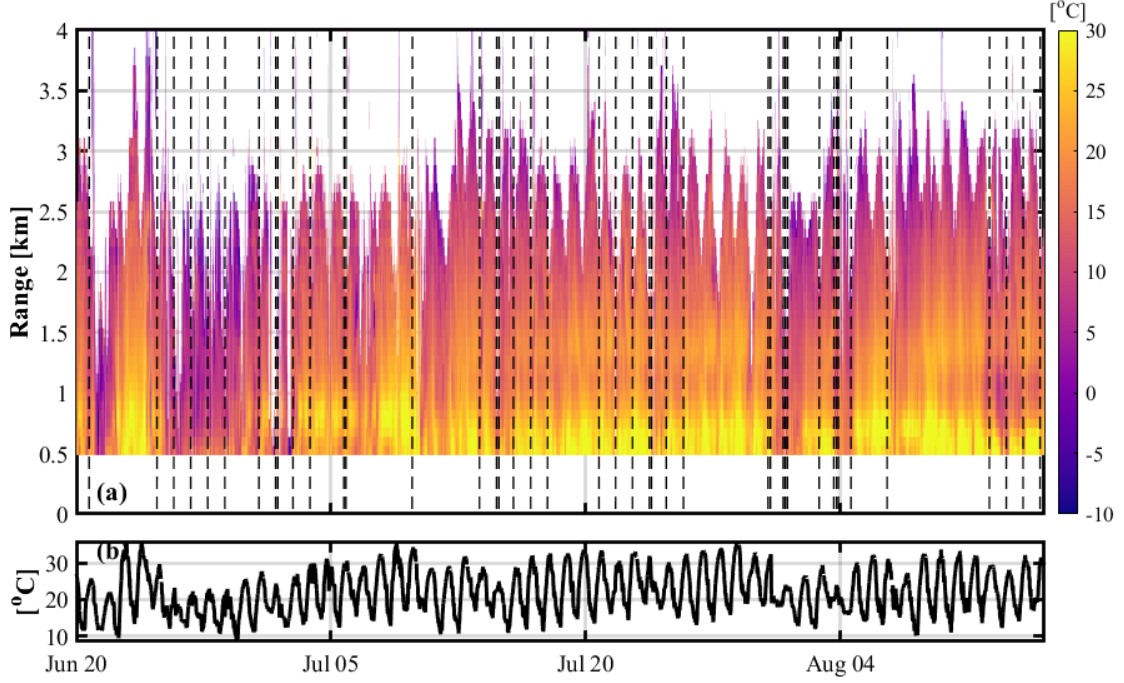


Figure 6.11: Temperature retrieval from the MPD03 in the summer of 2021. Vertical dashed lines represent radiosonde launches. Areas in white represent a data mask. The data mask is from data availability, clouds, and low signal-to-noise ratio. Time ticks are at 00:00 UTC.

profiles, shown as dashed lines in Fig. 6.11, and the MPD temperature retrieval. This test showed promising results for the temperature DIAL system. The bias shown in Figs. 6.17 may be due to a bias in the HSRL retrieval due to insufficient calibration scans of the HSRL receiver. The range dependent bias shown in Figs. 6.11 and 6.16 is a similar bias seen in the MSU 2022 data and the M2HATS data. This effect is still under investigation.

WV Retrieval

Figure 6.19 shows the absolute humidity of the water vapor DIAL retrieval. This is not the full water vapor retrieval used by the NCAR MPD. The photon data is binned to 75m and 10min and the absolute humidity is smoothed to 150m and 10m with an averaging filter. The error and mask is created using the same bootstrapping method for temperature

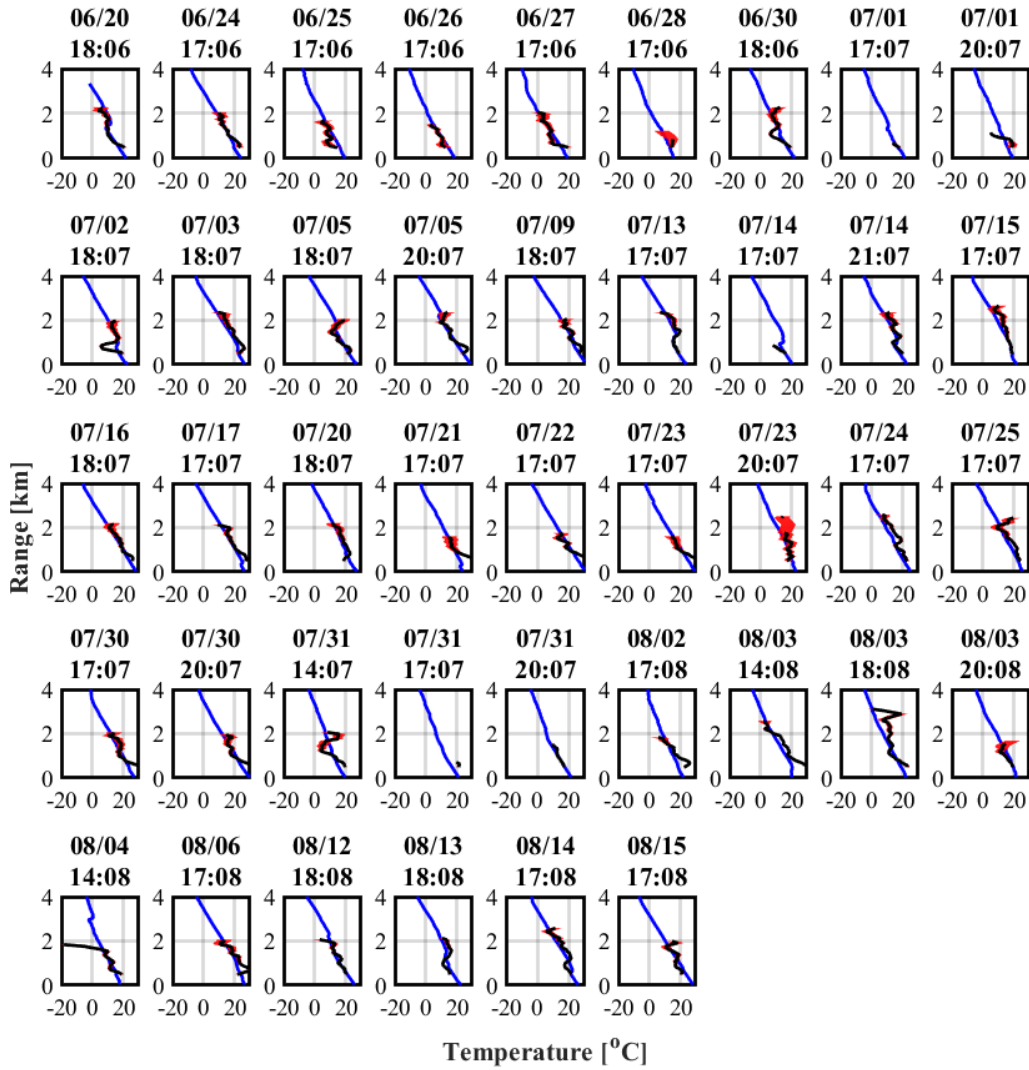


Figure 6.12: All radiosonde profiles from the measurement period in Fig. 6.11 with the radiosonde temperature in blue, DIAL temperature in black and error colored in light red shading.

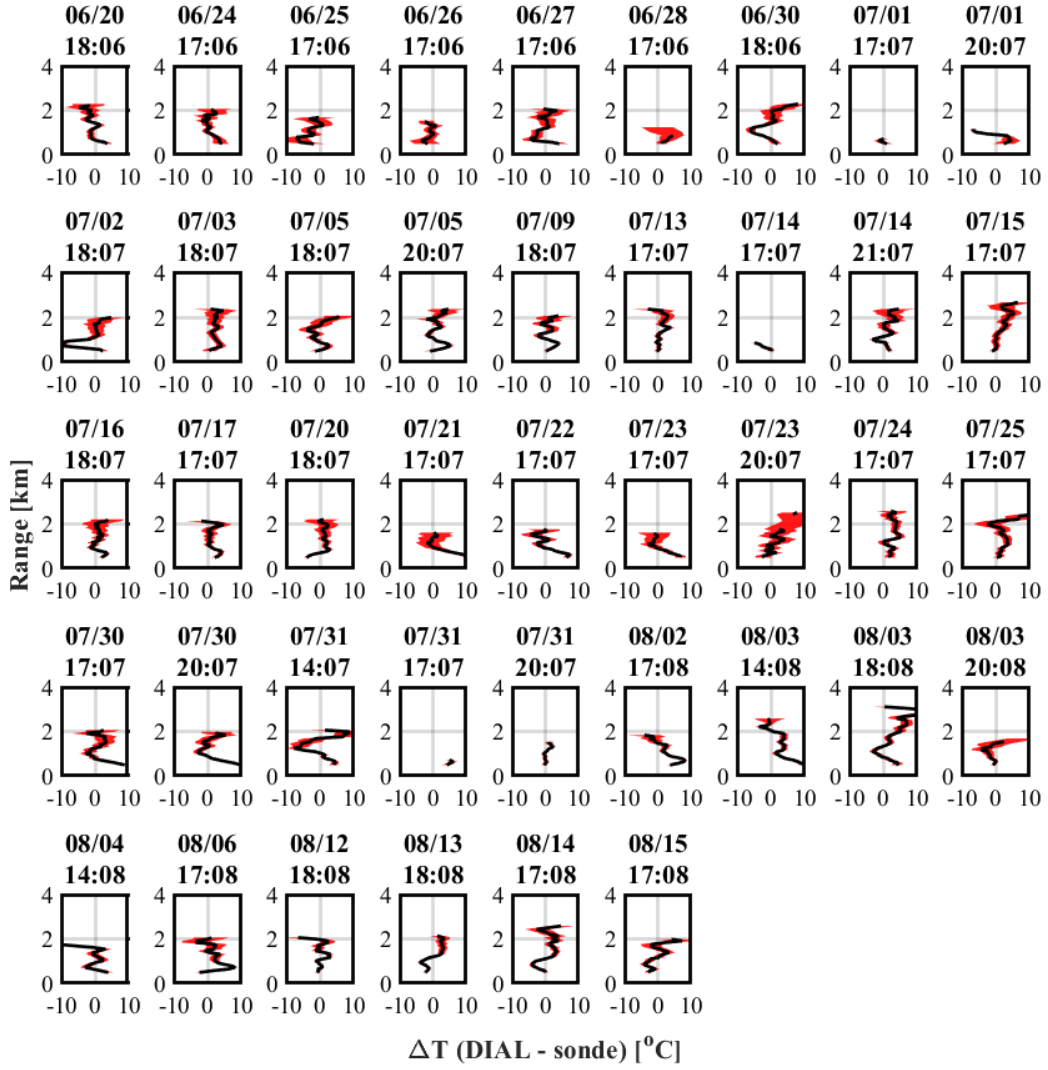


Figure 6.13: Temperature difference between DIAL and radiosondes shown in Fig. 6.12. Error estimates are light red shading.

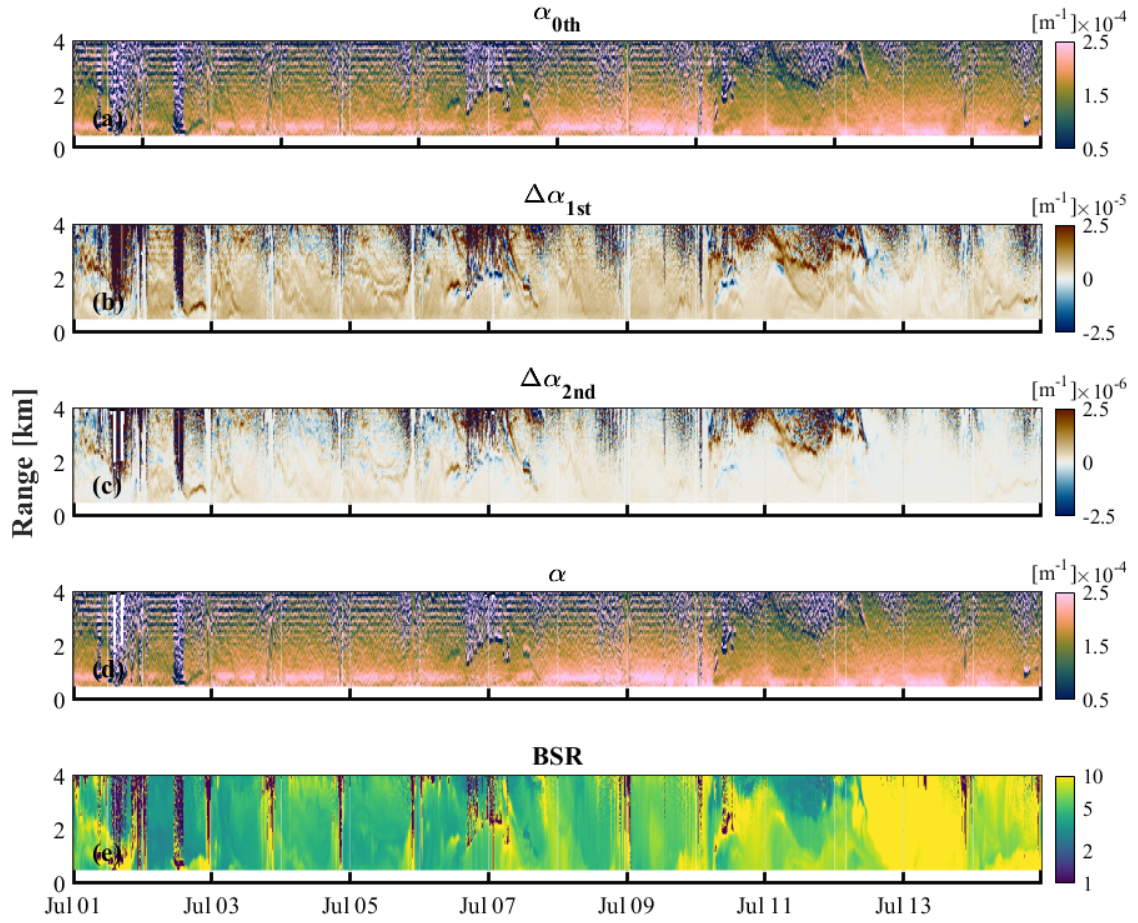


Figure 6.14: The absorption and BSR from Fig. 6.11 showing the effect of the backscatter ratio on the O₂ absorption and the perturbative correction. (a) the zero-order O₂ absorption coefficient. (b) the first-order correction. (c) the second-order correction. (d) the total observed O₂ absorption coefficient. (e) the backscatter ratio. Note the changes in color and scale to represent the data. Time ticks are at 00:00 UTC.

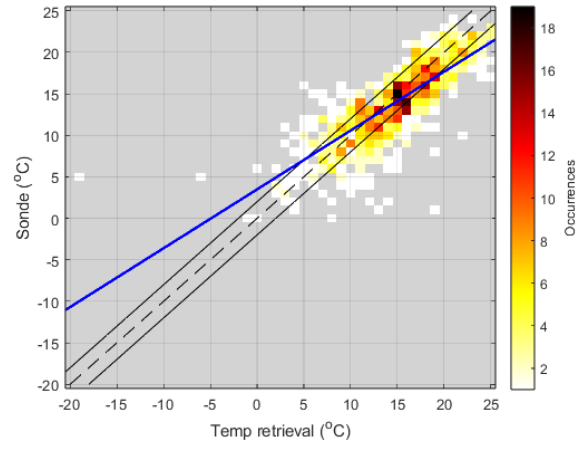


Figure 6.15: Comparisons of radiosondes and DIAL temperature for MPD03 in 2021 on a 1:1 plot. The blue line is a linear fit. Black dashed line is along the 1:1 line, and black solid lines are 2 K away.

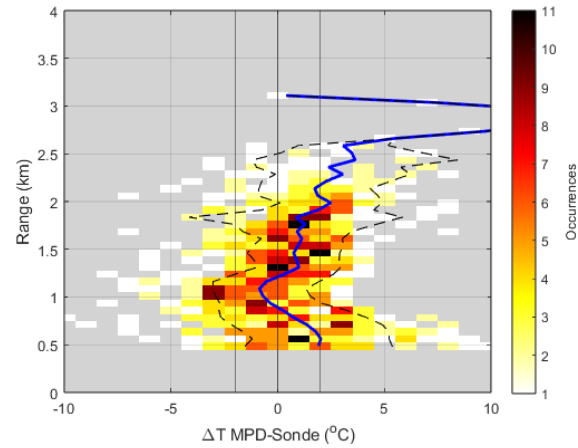


Figure 6.16: Comparisons of radiosonde and DIAL temperature difference for MPD03 in 2021 as a function of range. Blue line is the mean, and black dashed lines are 1 °C away.

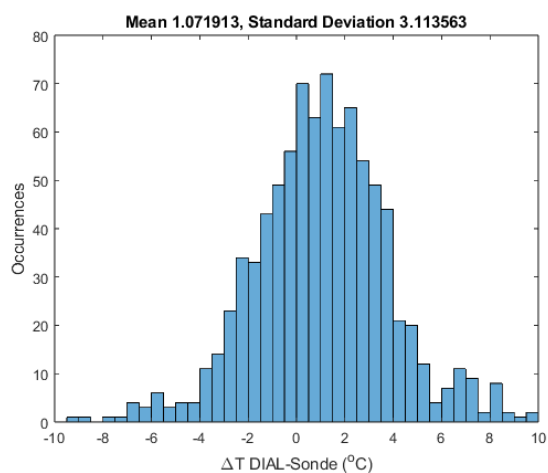


Figure 6.17: Histogram of comparisons of radiosonde and DIAL temperature difference for MPD03 in 2021 as a function of range.

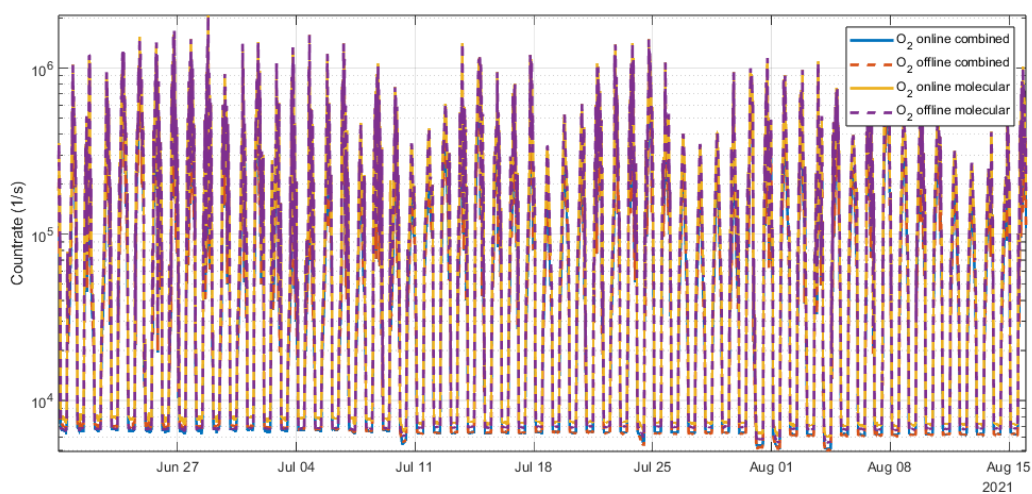


Figure 6.18: The measured background count rate for each receiver channel for MPD03 in 2021.

and is masked at an error threshold of 5 g/m^3 . Radiosonde comparisons are shown in Figs. 6.20, 6.21, 6.22, and 6.23. There is little bias in the water vapor DIAL retrieval. The water vapor dial retrieval may be improved by applying the perturbative absorption correction developed for the O_2 DIAL temperature retrieval in Ch. 2 Section 2. The backscatter ratio must be corrected from 770nm to 828nm. An approximation of the aerosol backscatter $B_a^{828nm} \approx (770/828)^u B_a^{770nm}$, where u can vary from 0 to 4 in a real atmosphere depending on aerosol particle size[32]. For these data, $u = 1$ was used. The molecular backscatter was calculated at 828nm using Eq. 2.55. The difference between the zero order water vapor retrieval and the perturbative water vapor retrieval is shown in Fig. 6.24. The difference of absolute humidity in range for all radiosonde locations are shown as individual lines. Due to the difference in molecular scattering linewidth and water vapor absorption linewidth the perturbative absorption does not have as large of a correction factor as the O_2 DIAL absorption. In times with low aerosol scattering or large gradients in aerosol scattering in range a perturbative correction to the water vapor retrieval may be helpful, but is not necessary for this dataset.

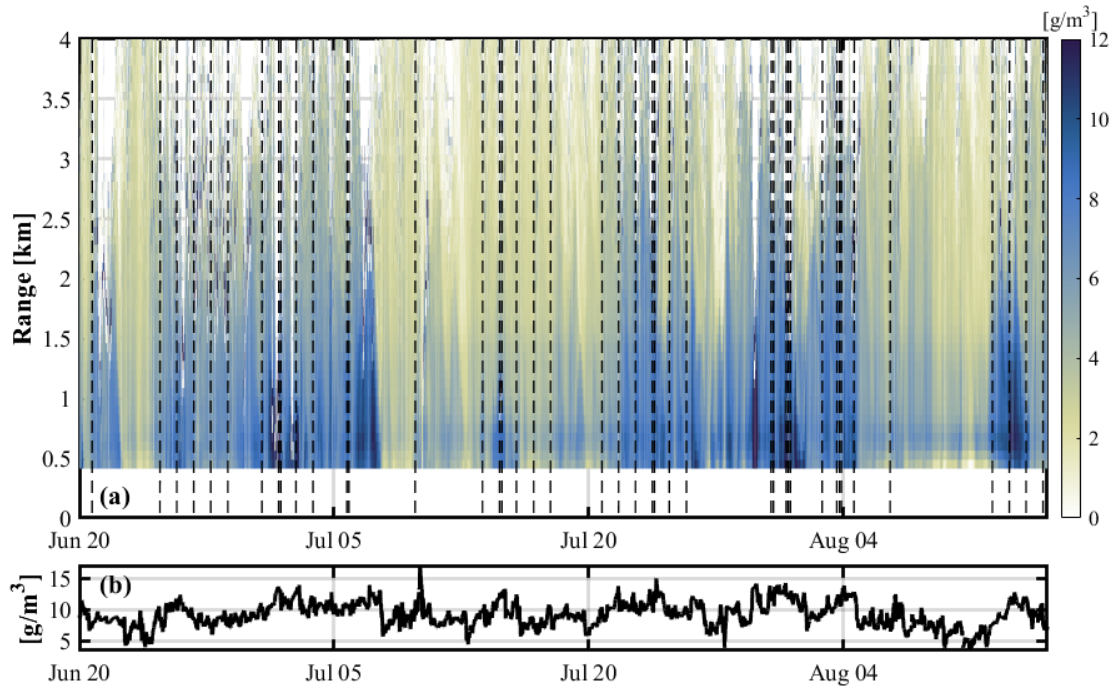


Figure 6.19: Water vapor absolute humidity from the MPD03 in the summer of 2021. Vertical dashed lines represent radiosonde launches. Areas in white represent a data mask. The data mask is from data availability, clouds, and low signal-to-noise ratio. Time ticks are at 00:00 UTC.

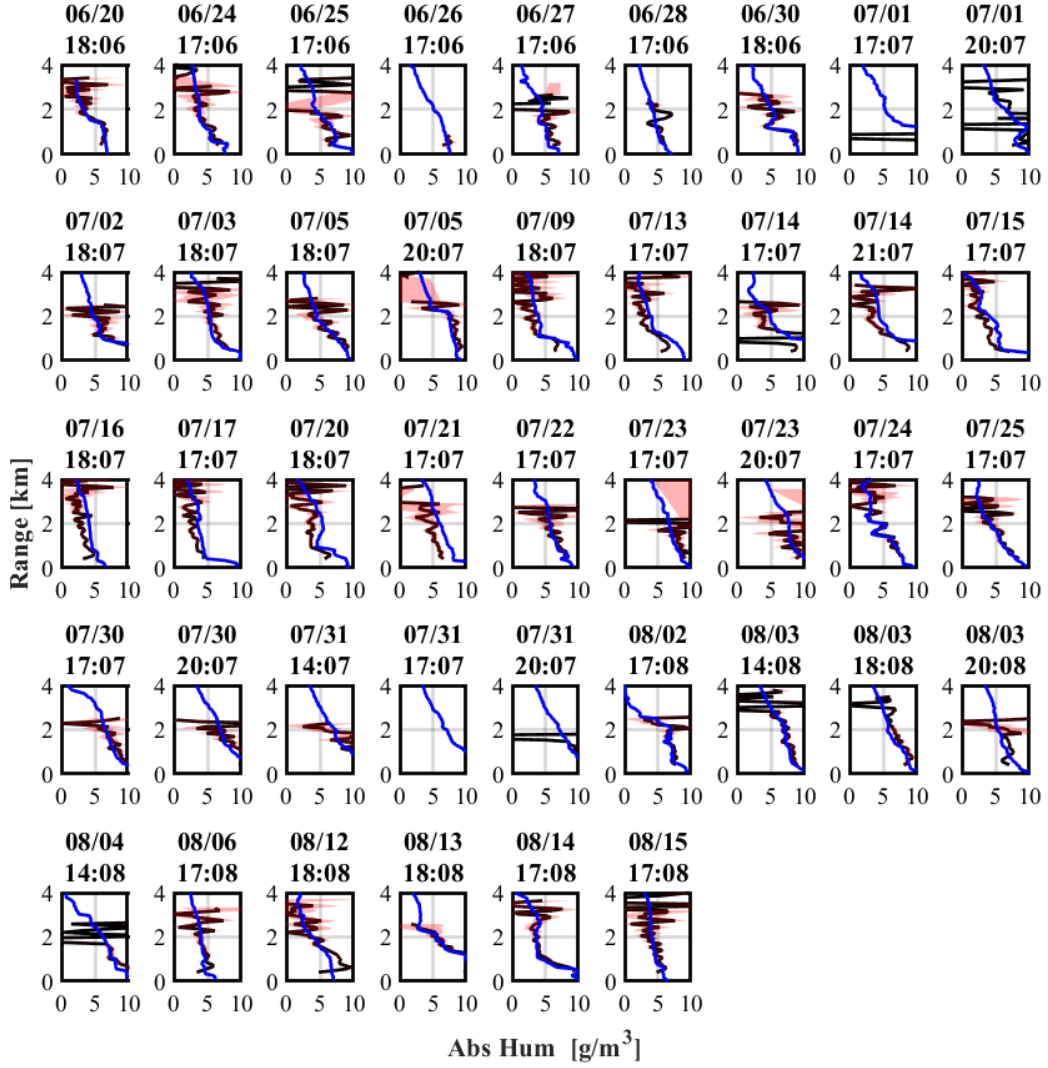


Figure 6.20: All radiosonde profiles from the measurement period in Fig. 6.19 with the radiosonde WV in blue, DIAL WV in black and error colored in light red shading.

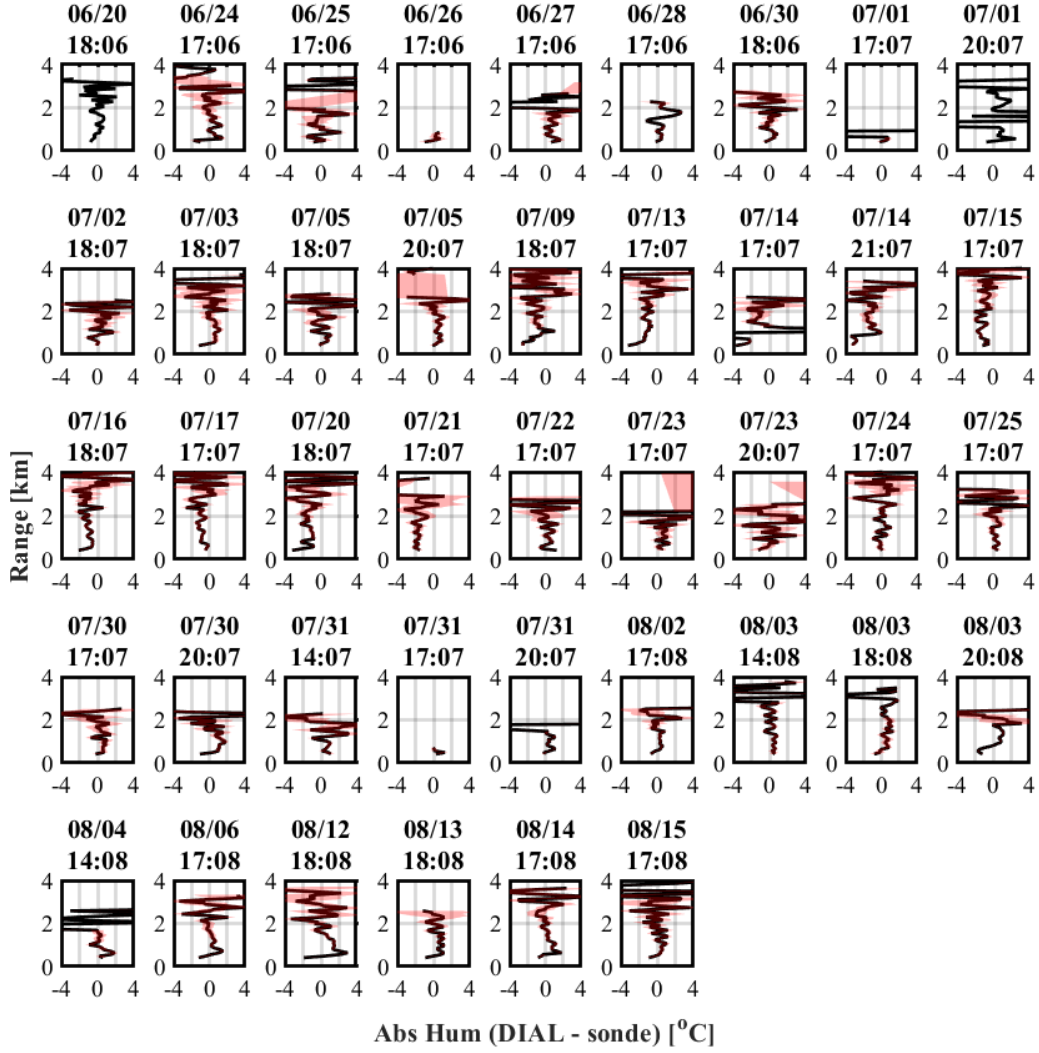


Figure 6.21: Absolute humidity difference between DIAL and radiosondes shown in Fig. 6.20. Error estimates are light red shading.

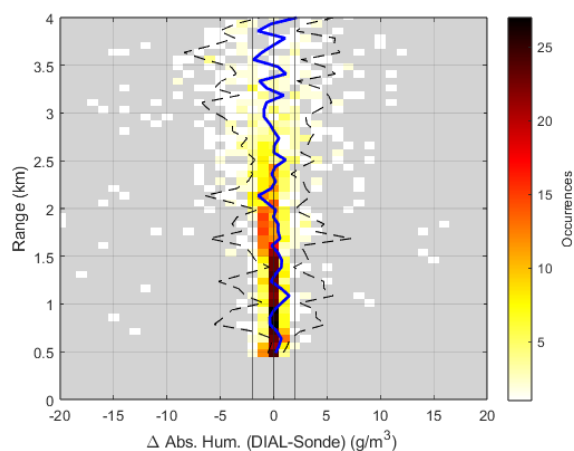


Figure 6.22: Comparisons of radiosonde and DIAL WV difference for MPD03 in 2021 as a function of range. Blue line is the mean, and black dashed lines are 2 g/m^3 away.

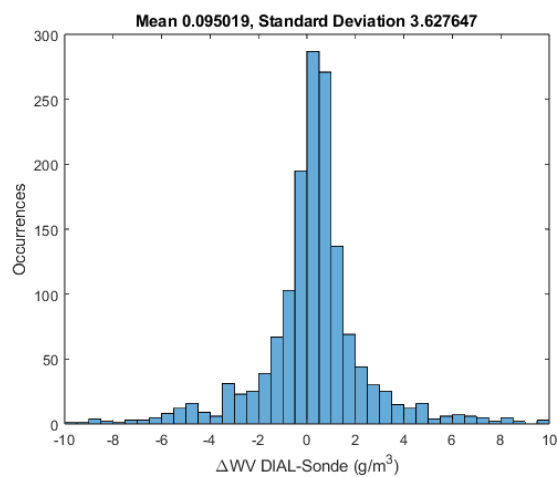


Figure 6.23: Histogram of comparisons of radiosonde and DIAL WV difference for MPD03 in 2021 as a function of range.

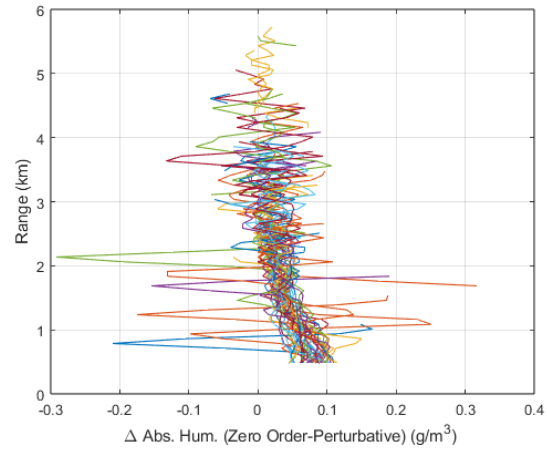


Figure 6.24: Comparisons at all radiosonde locations of DIAL zero order absolute humidity and total perturbative DIAL absolute humidity for MPD03 in 2021.

CONCLUSION

The MPD architecture has been specifically designed to address observational gaps for thermodynamic profiling within the lower troposphere. The O₂ DIAL temperature profiler described here is designed to add temperature and aerosol profiling to the MPD. The temperature retrieval and hardware is described along with results of long term testing in this dissertation.

In the MSU test in 2022, a laboratory-based instrument version, – consisting of a subset of the MPD temperature-profiling architecture – was evaluated to assess the effectiveness of the DIAL temperature retrieval algorithm. This study introduced three key advancements. Firstly, the temperature retrieval was updated by incorporating multiple O₂ absorption lines, thereby enhancing the physical realism. Secondly, an error estimation method for the temperature retrieval was adapted from a technique originally developed for the water vapor MPD. Finally, a total of 40 radiosondes were launched from a collocated station with the lidar system between April 21, 2022 and September 22, 2022. These radiosonde data were utilized to evaluate the efficacy of the temperature retrieval in three stages: initially comparing the perturbative retrieval of absorption (first stage) against the radiosondes, followed by an assessment of the iterative temperature retrieval (second stage), and ultimately comparing the DIAL temperature retrieval against radiosondes.

Another field test was evaluated in 2021 operated by NCAR. This test of the MPD temperature instrument showed promising results. Comparisons with radiosondes showed a constant bias that may be due to insufficient HSRL scans or spectral purity issues. These problems were addressed in later MPD tests. This test also showed the full MPD tested with the water vapor retrieval contributing to the temperature retrieval.

While individual comparisons of the DIAL-based temperature retrieval with radiosondes generally exhibited good agreement (within 2.50 °C), some temperature profiles exhibited

variation in altitude, albeit without significant bias. Notably, difference comparisons between radiosonde and DIAL-based temperature as a function of altitude consistently revealed a characteristic bias in altitude around approximately 1 km above ground level, which is also observable as horizontal banding in the time vs height plots. This slight bias may be attributed to a combination of factors. Identifying the exact mechanism and minimizing this bias will be a focus of future work.

The micropulse DIAL temperature profiling instrument and retrieval shows good promise in field testing and lab testing. The temperature MPD will hopefully be a deployable, low-cost method to improve weather forecasting and weather science. The MPD fills a need for measurements of temperature (and water vapor) in a region between 400m and 4km. This could provide more accurate coverage of the thermodynamic field in combination with passive thermodynamic sensors such as infrared or microwave radiometers. Passive sensors have higher temporal resolution and can resolve low-altitude temperature inversions, but accuracy falls off past 500m.

My contributions to the ongoing work on the MPD are: building a test O₂ DIAL instrument, improving the temperature retrieval algorithm by adding additional O₂ absorption lines and improving the pressure model and adding an estimate of error, writing an advanced temperature retrieval program in MATLAB, operating the MSU DIAL and testing with radiosondes, and modeling the performance of the MPD for testing of factors that contribute to noise or bias.

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APPENDICES

APPENDIX A

CHARATERIZATION OF LASER

In order to characterize the linewidth of the laser after the in-line amplifier a scanning Fabry-Perot cavity was used. The cavity has adjustments for mirror separation and angle relative to each other. Two 2 in diameter mirrors were chosen with the closest wavelength to the lasers at 780 nm. The setup consisted of what was described in Ch. 4 with the seed laser, fiber splitter, polarization controller, and SOA. The fiber output of the SOA was collimated and sent through a 5x beam expander to a diameter of approximately 1 cm. The output of the beam expander was tested using a Thorlabs collimation tester. The beam then passed through two mirrors in a z fold and an iris and then into the FP cavity. The back reflection from the mirrors in the FP cavity was used to align the beam perpendicular to the cavity. The transmission spots were used to align the cavity mirror to converge all the spots into one. A New Focus 2001 detector with a peak response at 900nm was used to detect the transmitted light. An oscilloscope that could send data to a computer was connected to the detector. The cavity was driven by a ramp generator with a 20 ms ramp time and ramp amplitude adjusted so that 2 FP fringes were visible in one ramp on the oscilloscope. The three bias adjustments on the ramp generator peaked the amplitude of the signal on the oscilloscope. The gain of the detector was adjusted to give an output of a few volts on the oscilloscope.

The mirror spacing of approximately 15 cm results in a theoretical free spectral range of the cavity of 1 GHz. Using this FSR we can calibrate the time scale of the oscilloscope to an optical frequency swept by the FP cavity with two fringe peaks. The data taken from the oscilloscope is shown in the figure below. Then the full width at half max line width of the fringes can be measured. Five measurements were taken of the Fabry-Pérot scan with two peaks visible. The FWHM of the peaks were 8.5, 9.3, 11.5, 18.2, 12.4, 10.9, 10.8, 10.5, 10.3, and 9.3 MHz. With a max of 18.2 MHz, min of 8.5 MHz, and an average of 11.2 MHz. The finesse of the cavity measured as $F = (\Delta\nu_{FSR})/(\Delta\nu_{FWHM})$ with values of 117.6, 107.5, 87.1, 54.8, 80.4, 91.7, 92.6, 95, 97.1, and 107.5. With a max of 117.6, a min of 54.8, and an average of 93.1. The measured values of Finesse are close to what the finesse of the cavity mirrors would be so we can assume the measurement of the laser linewidth is most likely limited by the finesse of the cavity with an upper limit of the linewidth as 11.2 MHz. The actual linewidth of the laser should be closest to 1 MHz;

The laser semiconductor optical amplifier (SOA) or travelling wave amplifier spectrum was tested to ensure the seeded linewidth is the same as the laser. The online and offline laser spectrum as well as the seeded SOA spectrum is shown in Figure A.1. The spectrum was measured with an Agilent 86140B with a resolution bandwidth of 0.06 nm. There is no significant difference between the seed laser and the seeded optical amplifier other than slightly increased background.

The TSOA spectrum was measured with the Agilent 86140B with a resolution bandwidth of 0.06 nm. The unseeded and seeded TSOA spectrum is shown in Figure A.2. The seeded TSOA pulse shape is shown in Figure A.3. The TSOA should be seeded properly for narrow linewidth. The TSOA was pulsed with a 1 μ s pulse and a seed power of 12.5 mW. The detector used was a Thorlabs DET100A/M. The total pulse power was calculated by integrating the data in Figure A.3 and is shown in Table A.1.

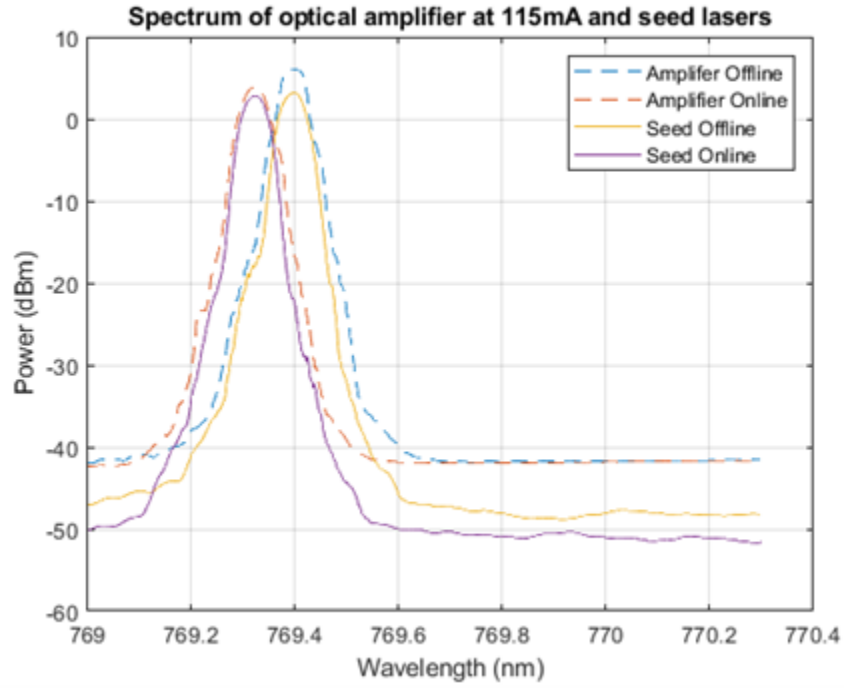


Figure A.1: Spectrum of seed lasers and output of semiconductor optical amplifier at 115 mA. The optical spectrum analyzer is an Agilent 86140B with a resolution bandwidth of 0.06 nm.

Driver Amps	Pulse Energy
5A	25.9 μ J
6A	31.6 μ J
7A	37.2 μ J
8A	42.7 μ J
9A	46.6 μ J

Table A.1: TSOA driver amps and total pulse energy. Seeded power 12.5 mW an 1 μ s pulse length.

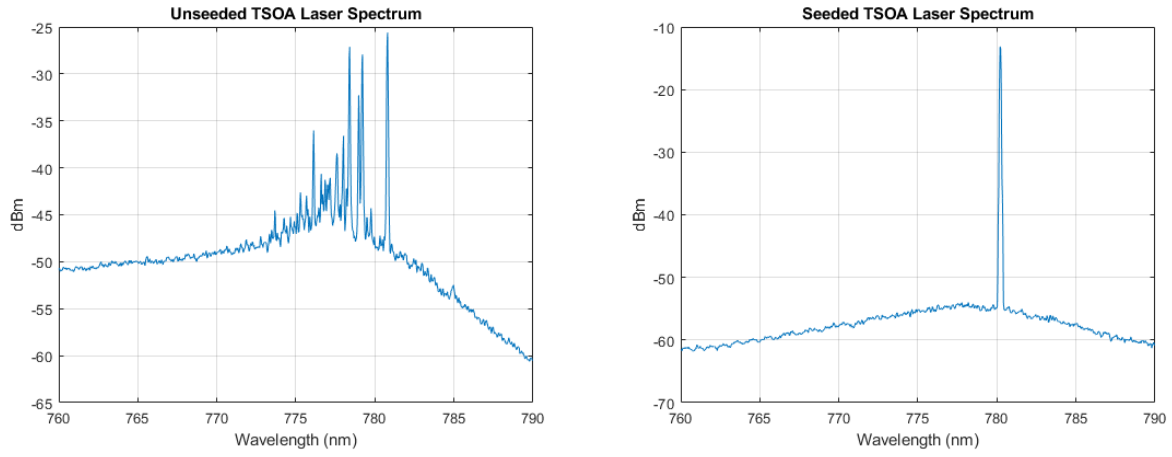


Figure A.2: Measured TSOA laser spectrum from an optical spectrum analyzer. Left: Unseeded. Right: Seeded. Resolution is bandwidth 0.06 nm.

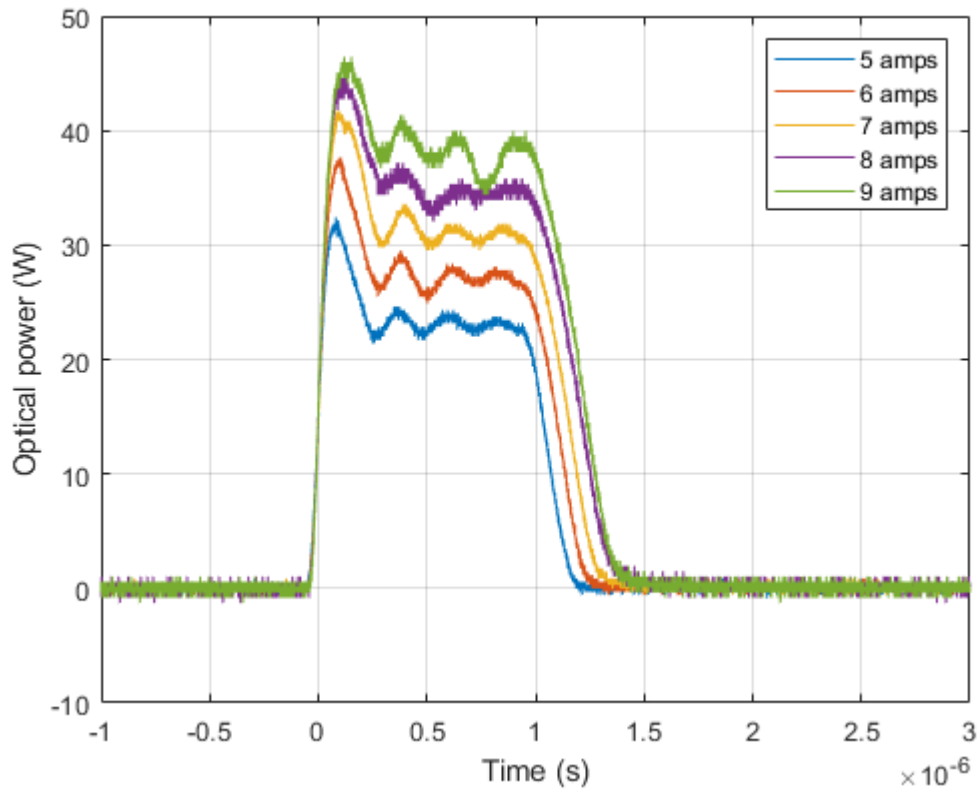


Figure A.3: TOSA pulse power over time with different drive currents.

APPENDIX B

EYE SAFETY CALCULATIONS

The United States Food and Drug Administration lists regulations for eye safety in the Code of Federal Regulations, Title 21: Food and Drugs, PART 1040—PERFORMANCE STANDARDS FOR LIGHT-EMITTING PRODUCTS. According to the code of regulations, the class I accessible emission limits for laser radiation is 2.74×10^{-7} J at 770 nm and a $1 \mu\text{s}$ pulse. The maximum radiant exposure determined with a 7 mm diameter aperture and is therefore $7.12 \times 10^{-7} \text{ Jcm}^{-2}$. The MPD instrument pulse has an energy of $\sim 5 \mu\text{J}$. The transmit beam has an outer diameter of 20 cm and an inner diameter of 10 cm with an area of 235 cm^2 . The radiant exposure of the transmitted beam (at the aperture) is therefore $2.13 \times 10^{-8} \text{ Jcm}^{-2}$. The MPD meets the class I accessible emission limit by a factor of 33.

APPENDIX C

HITRAN ABSORPTION LINES

I	ν	S	A	γ_{air}	γ_{self}	E''	n_{air}	δ_{air}	Q	ref
3	12984.176912	1.020E-29	.02336	.0294	.033	1559.8935	.63	-.009400	0	[18, 36]
1	12984.267206	2.674E-27	.01352	.0507	.052	1600.1301	.73	-.006100	1	[11, 19, 82]
1	12986.261218	3.404E-27	.01705	.0507	.052	1598.1361	.73	-.007100	1	[11, 19, 82]
2	12987.194584	6.211E-29	.02238	.0294	.033	1519.8867	.63	-.009500	0	[18, 36]
3	12988.132766	1.591E-29	.02432	.0303	.033	1470.1824	.63	-.009400	0	[11, 35, 36, 58]
1	12988.479939	3.130E-27	.01449	.0491	.049	1637.0878	.74	-.006150	1	[11, 19, 82]
1	12988.722523	5.059E-26	.02287	.0312	.034	1422.4983	.63	-.009300	0	[18, 36]
2	12988.926630	6.024E-29	.02153	.0294	.033	1518.1547	.63	-.009400	0	[18, 36]
3	12989.866583	1.541E-29	.02336	.0303	.033	1468.4486	.63	-.009300	0	[11, 35, 36, 58]
1	12990.457770	4.889E-26	.02192	.0312	.034	1420.7631	.63	-.009300	0	[18, 36]
1	12990.501832	3.749E-27	.01719	.0491	.049	1635.0659	.74	-.007300	1	[11, 19, 82]
1	12992.295768	3.182E-27	.01509	.0478	.049	1685.4073	.73	-.006200	1	[11, 19, 82]
2	12992.721796	9.286E-29	.02242	.0303	.033	1430.8889	.63	-.009400	0	[11, 35, 36, 58]

Table C.1: All the HITRAN[20] O₂ absorption lines in figure 2.1. I is the isotope where 1=¹⁶O₂, 2=¹⁶O¹⁸O, and 2=¹⁶O¹⁷O. The variables ν is the line center (cm^{-1}), S is the line strength multiplied by isotope abundance ($cm^{-1}/(molec * cm^{-2})$), A is the Eisenstein coefficient (s^{-1}), γ_{air} is the air broadened linewidth ($cm^{-1} * atm^{-1}$), γ_{self} is the self broadened linewidth ($cm^{-1} * atm^{-1}$), E'' is the ground state energy (cm^{-1}), n_{air} is the temperature exponent for the air broadened linewidth, δ_{air} is the pressure induced line shift ($cm^{-1} * atm^{-1}$), v'' is the quanta, and ref is the cited reference for the line.

HITRAN absorption lines are shown in table C.1.