Modeling the performance of a diode laser-based (DLB) micro-pulse differential absorption lidar (MPD) for temperature profiling in the lower troposphere

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Abstract: Ground-based, network-deployable remote sensing instruments for thermodynamic profiling in the lower troposphere are needed by the atmospheric science research community. The recent development of a low-cost diode-laser-based (DLB) micro-pulse differential absorption lidar (DIAL) has begun to address the need for ground-based remote sensing instruments for water vapor profiling in the lower troposphere. Now, taking advantage of the broad spectral coverage of the DLB architecture, an enhancement to the water vapor micro-pulse DIAL (MPD) instrument is proposed to enable atmospheric temperature profiling. The new instrument is based on measuring a temperature-dependent oxygen (O2) absorption coefficient and using this to retrieve the range-resolved temperature profile. In this paper, a retrieval method is proposed based on the recently developed perturbative solution to the DIAL equation that takes into account the Doppler broadening of the molecularly backscattered signal. This perturbative solution relies on an ancillary high spectral resolution lidar (HSRL) measurement of the backscatter ratio. Data from an operational water vapor MPD combined with a DLB-HSRL were used to create an atmosphere model, from which return signals for the O2-MPD were generated. The perturbative retrieval was then applied to these data and a comparison of the retrieved temperature and the model temperature profile allowed the efficacy of retrieval to be evaluated. The results indicate that the temperature profile may be retrieved from a theoretical O2-MPD instrument with a ±1 K accuracy up to 2.5 km and ±3 K accuracy up to 4.5 km with a 150 m range resolution and 30-minute averaging time. Using data from a recently developed O2-MPD in combination with a WV-MPD, and a DLB-HSRL, an initial temperature retrieval is demonstrated. The results of this initial demonstration are consistent with the performance modeling.

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1. Introduction

The importance of thermodynamic profiling has been highlighted in two National Research Council reports [1,2] as well as in a report to the National Science Foundation and National Weather Service [3]. A recent review article details the state of remote sensing of lower tropospheric thermodynamic profiling [4]. In that review paper, it was demonstrated that huge observational gaps exist with respect to thermodynamic profiling in the lower troposphere, and low-cost, ground-based passive and active remote sensing systems are suggested as the best means to close these observational gaps.

One of the currently operational, ground-based, passive remote sensing instruments used for thermodynamic profiling in the lower troposphere is the ‘atmospheric emitted radiance interferometer’ (AERI) [5,6]. The AERI measures the downwelling infrared radiance between 520 cm⁻¹ to 3000 cm⁻¹ (19.2 µm and 3.3 µm) with approximately a 1 cm⁻¹ channel resolution...
and uses two National Institute of Standards and Technology (NIST) traceable blackbodies to ensure the accuracy of the radiance measurements. Retrieving range-resolved information from the AERI is based on the idea that channels close to an absorption line center are more opaque and therefore more sensitive to radiation from the atmosphere directly above the instrument while channels located farther away from the absorption line center are more transparent and can provide information about the atmosphere farther away from the instrument. The temperature and water vapor profiles are obtained through an iterative solution to the radiative transfer equation and are typically retrieved for clear sky conditions up to approximately 3 km with vertical resolution of 50 m, 800 m, 1200 m, and 2500 m at a range of 300 m, 1 km, 2 km, and 3 km, respectively [7,8]. This vertical resolution causes a smoothing of the thermodynamic profiles retrieved by the AERI. In a recent comparison of water vapor profiles retrieved using the passive AERI instrument and an active differential absorption lidar (DIAL), the DIAL was able to better detect the vertical structure of the water vapor profiles and capture elevated moist and dry layers not detectable with AERI [9].

Raman lidar are active remote sensing instruments used for thermodynamic profiling [10–26]. The rotational Raman lidar channels of these instruments use Raman shifted backscatter resulting from rotational energy state transitions in atmospheric nitrogen, N$_2$, and oxygen, O$_2$ for temperature profiling [11,12]. The receiver uses narrow bandwidth filters to detect two bands in either the Stokes or the anti-Stokes branch of the Raman spectrum that have different temperature dependencies resulting from the Boltzmann population distribution. The ratio of the rotational Raman scattered signal in these two channels is temperature-dependent allowing a temperature profile to be retrieved. The major advantage of the rotational Raman lidar for temperature measurements is that a relatively simple laser transmitter may be used; typically the second or third harmonic of an Nd:YAG at 532 nm or 355 nm respectively. Furthermore, the Raman lidar can simultaneously retrieve temperature and water vapor profiles depending on the receiver configuration. The challenges associated with the Raman lidar include the need to calibrate the instrument for both temperature and water vapor profiles [11,12], the need for a high power laser transmitter to compensate for the weak non-linear Raman scattering cross section [11,12], and the difficulty in deployment due to the high power requirements [21,22], eye-safety risk, and staffing typically needed for operations. This safety deployment challenge – coupled with the typical high cost and maintenance needs of Raman lidar – makes it a poor candidate for a large ground-based network.

DIAL is another class of active remote sensing instrument that has the potential for thermodynamic profiling [27–39]. The DIAL technique utilizes a laser transmitter operating at two closely spaced wavelengths, one associated with the absorption feature of interest, referred to as the on-line wavelength, and a second removed from the absorption feature of interest, referred to as the off-line wavelength. The on-line and off-line return signals are used to determine the absorption coefficient for the molecule of interest. By choosing a temperature-insensitive absorption feature, the range-resolved number density of a molecule of interest, such as water vapor, can be retrieved. Several research grade DIAL instruments for water vapor profiling have been developed, including the NASA Lidar Atmosphere Sensing Experiment (LASE) that is based on a high-power injection seeded Ti:sapphire laser transmitter [31], the University of Hohenheim (UHOH) DIAL, also based on a high-power injection seeded Ti:sapphire laser [32], the optical parametric oscillator (OPO) based DIAL located at the Schneefernerhaus high altitude research station in Zugspitze, Germany [33], and the airborne DIAL developed by German Aerospace Center (DLR) that utilizes a frequency double Nd:YAG laser to pump an optical parametric oscillator (OPO) [34]. More recently, diode-laser-based (DLB) micro-pulse DIAL (MPD) have been developed for network-deployable, ground-based unattended operations [35–39]. These instruments employ a laser transmitter that utilizes two diode lasers, one locked to the on-line wavelength and the second locked to the off-line wavelength, to injection seed a
tapered semiconductor optical amplifier to produce a high repetition rate of micro-joule pulses while the DIAL receiver uses efficient photon counting modules to monitor the return signals. The MPD instruments are eye-safe, class 1M, which by definition have a zero nominal ocular hazard distance to facilitate long term autonomous operation.

Temperature profiling using the DIAL technique is based on measuring a temperature-sensitive absorption coefficient for a molecule with a known atmospheric mixing ratio, such as diatomic oxygen ($O_2$) and then extracting the temperature profile from this absorption coefficient measurement [40–43]. While the DIAL technique has been successfully implemented for water vapor profiling, it has not found success for temperature profiling. The difficulty with using DIAL for temperature profiling follows from the need to account for the Doppler broadening of the molecularly scattered return signal in order to minimize the error in the temperature retrieval. Recently, a perturbative retrieval technique based on the full DIAL equation to retrieve the centerline absorption was presented in the literature [44]. The perturbative retrieval technique relies on an ancillary measurement of the aerosol and molecular backscatter to account for the Doppler broadening of the scattered return signal, which can be made using a high spectral resolution lidar (HSRL).

To develop low-cost, ground-based active remote sensing instruments for network-deployable, autonomous deployment, researchers at Montana State University (MSU) and the National Center for Atmospheric Research (NCAR) are actively developing DLB lidar instrumentation for thermodynamic profiling in the lower troposphere [39]. Diode lasers, tapered semiconductor optical amplifiers, and single photon counting modules based on avalanche photodiodes cover a broad spectral range from 650–1000 nm allowing for the development of multiple lidar instruments based on a common instrument architecture. Currently, five WV-MPD instruments for water vapor profiling are operational. These WV-MPD instruments have been deployed at several recent field experiments including FRAPPE, PECAN, Perdigão, LAFE, and RELAMPAGO. More recently, a DLB-HSRL instrument was demonstrated using a similar architecture to the WV-MPD instrument and was also deployed at the LAFE field experiment [45].

In this paper, the performance of an $O_2$-MPD instrument for temperature profiling in the lower troposphere will be modeled. This performance model is based on developing the return signals for the on-line and off-line wavelengths of the $O_2$-MPD and the WV-MPD as well as the molecular and aerosol channels of the DBL-HSRL. Care is taken to add the Poisson noise associated with photon counting, which is the major source of noise associated with return signals for the WV-MPD, $O_2$-MPD and DBL-HSRL. Using these modeled return signals, the perturbative retrieval technique is applied to retrieve the $O_2$ absorption coefficient using the ancillary DBL-HSRL measurements to account for the Doppler broadening of the scattered return signal. An iterative temperature retrieval based on the retrieved $O_2$ absorption coefficient is then applied to obtain a final temperature profile. By modeling the return signals and applying the retrieval, the errors associated with the $O_2$-MPD and the ancillary DBL-HSRL and WV-MPD measurements will propagate, giving a more complete picture of the error estimate with the goal of assessing the potential performance for temperature retrievals using the $O_2$-MPD.

This paper is organized as follows. A discussion of the modeling of the return signals is presented in Section 2. Line selection considerations are presented in Section 3. In Section 4, the perturbative retrieval of the $O_2$ absorption coefficient is discussed. The temperature retrieval is then presented in Section 5. In Section 6, a discussion of the $O_2$-MPD performance is given. In section 7, an initial temperature retrieval is presented. Finally, some brief concluding remarks are presented in Section 8.

2. Modeling the return signal

The MPD instruments utilize a narrow bandwidth laser transmitter with a typical instantaneous linewidth less than 1 MHz while the absorption features for atmospheric molecules, including
where \( m \) and \( \beta \) are the wavelength of 828.187 nm (in vacuum), a line strength of 1.64.

The atmospheric transmission term, \( T_A(r, \nu) \), results from the scattering from atmospheric molecules and aerosols. This term is modeled as

\[
T_A(r, \nu) = e^{-\int_0^\infty \sigma_A(r', \nu) \, dr'}
\]

where \( \sigma_A(r, \nu) \) is the aerosol extinction and \( \sigma_m(r, \nu) \) is the molecular extinction. The atmospheric transmission resulting from molecular absorption is modeled as

\[
T_m(r, \nu) = e^{-\int_0^\infty \alpha(r', \nu) \, dr'}
\]

where \( \alpha(r, \nu) \) is the absorption coefficient. By choosing a temperature-insensitive absorption line, the number density of a molecular species may be retrieved since the absorption coefficient and number density are related via the absorption cross section through \( \alpha(r, \nu) = N_m \sigma_0(r, \nu) \), where \( \sigma_0(r, \nu) \) is the absorption cross section and may be calculated using parameters from the HITRAN database [46]. Furthermore, by choosing a temperature-sensitive absorption line for an atmospheric molecule with a known mixing ratio, the temperature profile can be retrieved.

The water vapor absorption line used by the current WV-MPD instruments has a center feature between 828.193 nm – 828.200 nm depending on the atmospheric conditions. The O\(_2\) absorption line selection will be discussed in Section 3.

Elastically scattered light from the heavy atmospheric aerosols will maintain the laser lineshape while Rayleigh scattered light from the lightweight atmospheric molecules will result in a Doppler-broadened lineshape. The number of photons that scatter at a range \( r \) may be written

\[
N_{\Lambda,bs}(v, r) = N_{\Lambda,bs}(v, r) \beta(r) \gamma(r, \nu)
\]

where \( \beta(r) \) is the total backscatter (integrated over frequency) per unit length and solid angle and the normalized backscatter lineshapes, \( \gamma(r, \nu) \), is given as

\[
\gamma(r, \nu) = \frac{\beta_A(r)}{\beta(r)} \delta(\nu - \nu_L) + \frac{\beta_M(r)}{\beta(r)} l(r, \nu - \nu_L)
\]

where \( \beta_A(r) \) is the aerosol backscatter, \( \beta_M(r) \) is the total molecular backscatter (integrated over frequency), and \( l(r, \nu - \nu_L) \) is the Doppler-broadened lineshape centered at the laser frequency \( \nu_L \). The total number of photons detected by the lidar receiver, \( N_A(r) \), is

\[
N_A(r) = N_0 m \frac{c \tau}{2} \int \int_0^\infty \gamma(r, \nu) \sigma_0(\nu_L) \sigma_D(\nu_L) T_A^2(r, \nu_L) T_m(r, \nu_L) \beta(r) l(r, \nu - \nu_L) T_m(r, \nu) \gamma(r, \nu) E(\nu) d\nu
\]

where \( m \) is the number of outgoing laser pulses that the signal is averaged over, \( c \) is the speed of light, \( \tau \) is the laser transmitter pulse duration, \( A \) is the area of the telescope aperture, \( \sigma(r) \) is the
overlap function, $\varepsilon_0(\lambda)$ is the efficiency of the optics associated with the lidar receiver, $\varepsilon_D(\lambda)$ is the efficiency of the photon counting detector, and $E(\nu)$ is the transmission function of the etalon and narrowband filters in the optical receiver. For the above equation, it was assumed that $\varepsilon_0(\nu_L)$, $\varepsilon_D(\nu_L)$, and $T_A(r, \nu_L)$, are constant over the Doppler-broadened molecular scatter and molecular absorption lineshapes. Furthermore, the overlap function described in Spuler et al. [35] is used for all calculations presented in this paper.

The MPD utilizes a photon counting module in the receiver. Photon counting is a classic Poisson process that can be modeled using a Gaussian distribution when the photon counts are sufficiently large. For a total of $N$ counts, the Poisson distribution will have a half width at half maximum value given by $\sqrt{N}$. Using the total number of detected photons, $N(r)$, a random number from the Poisson distribution with a mean parameter $\sqrt{N(r)}$ is generated to mimic the noise associated with the return signal. The other sources of noise associated with the MPD instruments include dark count rates of less that 200 counts/s and daytime background counts of less than $1 \times 10^6$ counts/s. This background count rate is within the linear operation of the avalanche photodiode’s operating region. The typical signal count at 2 km is on the order of $2 \times 10^2$ counts (summing over the 7 kHz pulse repetition rate for one second).

An atmospheric model that includes a temperature, pressure, water vapor number density, molecular backscatter, and aerosol backscatter profile is needed to estimate the return signals described in the above equation. Four atmospheric models will be used to assess the performance of the temperature retrieval of the O$_2$-MPD based on data collected during the Land Atmosphere Feedback Experiment (LAFE). During this experiment, the WV-MPD and DLB-HSRL were deployed and the retrieved water vapor number density and aerosol backscatter profiles will be used as a part of the model atmosphere. Furthermore, temperature and pressure profiles are processed NCEP data interpolated to the instrument site and will be used, while the molecular backscatter profile will be calculated using the temperature profile. A summary of these models is shown in Fig. 1 with the four atmospheric models, labeled M1, M2, M3 and M4, represented by the black, red, blue and purple lines respectively. Figures 1(a)–1(d) show the temperature, pressure, aerosol backscatter coefficient, and water vapor number density profiles, respectively.

![Fig. 1. The atmospheric models used. The black, red, blue and purple lines refer to the M1, M2, M3, and M4 models respectively. In Fig. 1(a), the temperature profiles are shown while Fig. 1(b) shows the pressure profiles. The aerosol backscatter profiles are shown in Fig. 1(c) and the water vapor number density profiles are shown in Fig. 1(d).](image-url)
The instrument parameters used in the modeling are based on the current WV-MPD [39], DLB-HSRL [45], and O$_2$-MPD [47,48]. The instrument parameters are summarized in Table 1. Using the LAFE data, a comparison between the measured return signal averaged over two seconds of data collection for the off-line WV-MPD and the calculated returns averaged over two seconds using the M1 and M2 models were used to adjust the optical efficiency of the receiver so that these return counts agreed. This optical efficiency, shown in Table 1, is then used for each of the instruments.

Table 1. Instrument parameters for the WV-MPD [35], O$_2$-MPD [47,48], and DLB-HSRL [45].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>WV-MPD</th>
<th>O$_2$-MPD</th>
<th>DLB-HSRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Transmitter</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength (nominal)</td>
<td>828.2 nm</td>
<td>769.8 nm</td>
<td>780.4 nm</td>
</tr>
<tr>
<td>On-Line</td>
<td>828.187 nm</td>
<td>769.796 nm</td>
<td></td>
</tr>
<tr>
<td>Side-Line</td>
<td>828.195 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off-Line</td>
<td>828.287 nm</td>
<td>770.107 nm</td>
<td></td>
</tr>
<tr>
<td>Freq. Stability</td>
<td>±44 MHz</td>
<td>±51 MHz</td>
<td>±49 MHz</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>5 µJ</td>
<td>5 µJ</td>
<td>5 µJ</td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>1 µs</td>
<td>1 µs</td>
<td>1 µs</td>
</tr>
<tr>
<td>Range Resolution</td>
<td>150 m</td>
<td>150 m</td>
<td>150 m</td>
</tr>
<tr>
<td>Pulse Rep. Freq.</td>
<td>7 kHz</td>
<td>7 kHz</td>
<td>7 kHz</td>
</tr>
<tr>
<td>Linewidth</td>
<td>&lt; 1 MHz</td>
<td>&lt; 1 MHz</td>
<td>&lt; 1 MHz</td>
</tr>
<tr>
<td>Spectral Purity</td>
<td>&gt; 99.95%</td>
<td>&gt; 99.95%</td>
<td>&gt; 99.95%</td>
</tr>
<tr>
<td>Optical Receiver</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Telescope Aperture Area</td>
<td>970 cm$^2$</td>
<td>970 cm$^2$</td>
<td>970 cm$^2$</td>
</tr>
<tr>
<td>Narrowband Filter Bandwidth</td>
<td>0.75 nm</td>
<td>0.75 nm</td>
<td>0.75 nm</td>
</tr>
<tr>
<td>Etalon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free Spectral Range</td>
<td>0.1 nm (44 GHz)</td>
<td>0.311 nm (157 GHz)</td>
<td>0.5 nm (250 GHz)</td>
</tr>
<tr>
<td>Finesse</td>
<td>40</td>
<td>15.4</td>
<td>17</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>0.0025 nm (1.1 GHz)</td>
<td>0.0202 nm (10 GHz)</td>
<td>0.03 nm (15 GHz)</td>
</tr>
<tr>
<td>Blocking Filter Bandwidth</td>
<td>Rubidium Cell</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Receiver Optics Efficiency</td>
<td>0.025</td>
<td>0.025</td>
<td>0.02</td>
</tr>
<tr>
<td>Molecular Channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Channel</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detector Efficiency</td>
<td>0.70</td>
<td>0.66</td>
<td>0.65</td>
</tr>
<tr>
<td>Averaging Time</td>
<td>5 minute</td>
<td>30 minute</td>
<td>1 minute</td>
</tr>
<tr>
<td>On-Line</td>
<td>2.5 minute</td>
<td>15 minute</td>
<td></td>
</tr>
<tr>
<td>Off-Line</td>
<td>2.5 minute</td>
<td>15 minute</td>
<td></td>
</tr>
<tr>
<td>Oversampling</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

3. O$_2$ absorption line selection considerations

The temperature retrieval, discussed in detail in Sections 4 and 5, is a two-step process that first uses the O$_2$-MPD on-line and off-line return signals to retrieve the O$_2$ absorption coefficient, then uses the retrieved O$_2$ absorption coefficient to retrieve the temperature profile. Accurate temperature retrievals require choosing a molecular absorption feature with an appropriate line strength and temperature sensitivity. However, line strength and temperature sensitivity both
depend on the ground state energy level, a higher ground state energy level will result in a higher temperature sensitivity and a weaker line strength due to the thermal population of this ground state energy level. Four absorption lines in the A-band of O$_2$ considered for temperature profiling are detailed in Table 2 [46]. A plot of the absorption cross section as a function of wavelength is shown in Fig. 2. The black line represents the O$_2$ absorption cross section while the red line indicates the water vapor cross section.

![Graph showing absorption cross section vs. wavelength](image)

**Fig. 2.** A plot of the absorption cross section as a function of wavelength. The black line represents the O$_2$ absorption cross section while the red line indicates the water vapor absorption cross section.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Line Strength (cm$^{-1}$/molecule cm$^{-2}$)</th>
<th>Linewidth (cm$^{-1}$)</th>
<th>Linewidth Temp. Dependence</th>
<th>Ground State Energy (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>770.5878</td>
<td>$2.18 \times 10^{-25}$</td>
<td>0.218</td>
<td>0.63</td>
<td>1608.066</td>
</tr>
<tr>
<td>769.7958</td>
<td>$4.89 \times 10^{-25}$</td>
<td>0.489</td>
<td>0.63</td>
<td>1420.763</td>
</tr>
<tr>
<td>769.2333</td>
<td>$1.11 \times 10^{-25}$</td>
<td>0.111</td>
<td>0.63</td>
<td>1248.201</td>
</tr>
<tr>
<td>768.4870</td>
<td>$2.19 \times 10^{-25}$</td>
<td>0.219</td>
<td>0.63</td>
<td>1083.433</td>
</tr>
</tbody>
</table>

The error in the retrieved absorption coefficient will be minimized when the one-way molecular optical depth at the maximum range of interest is approximately 1.1 [49]. Using a simple atmospheric model with a surface temperature of 296 K, a lapse rate of 6.5 K/km, and a surface pressure of 1 atm, the molecular optical depth is plotted as a function of range in Fig. 3. The vertical black line indicates an optical depth of 1.1. The maximum range for the O$_2$-MPD temperature retrieval is expected to be between 3 and 5 km thus indicating that the most appropriate O$_2$ absorption line to minimize the error in the retrieved absorption coefficient would be the line centered at 769.2333 nm.

The temperature retrieval requires the selection of a temperature sensitive O$_2$ absorption line. Following the work of Theopold and Bosenberg [42], the temperature sensitivity may be written

$$\frac{d\alpha}{\alpha} = \frac{1}{T} \left( \frac{\epsilon hc}{k_B T} - \frac{5}{2} + \Xi(\Lambda) \right)$$

where $\epsilon$ is the ground state energy and $\Xi(\Lambda)$ is a value dependent on the lineshape, which in the limit is zero for pure Doppler broadening and one in the limit of pure collisional broadening. Since the goal of the O$_2$-MPD is temperature retrievals in the lower troposphere where collisional broadening dominates, $\Xi(\Lambda) = 1$ is used for the calculations in this section. A plot of the temperature sensitivity as a function of temperature is shown in Fig. 4 for the four absorption...
The molecular optical depth for the four absorption lines summarized in Table 2. The vertical line indicates an optical depth of 1.1 and provides an estimate of the maximum range the absorption coefficient can be retrieved with minimal error.

The absorption line with the highest ground state energy has the largest temperature sensitivity, as expected.

The temperature sensitivity as a function of temperature. Because of the ground state thermal population, the lines with higher temperature sensitivity typically have a smaller line strength.

Because the temperature retrieval is a two-step process that first requires the retrieval of the absorption coefficient that then allows the temperature to be retrieved, the trade-off between line strength and temperature sensitivity must be considered. From Eq. (7), the temperature deviation, $dT$, may be given as

$$dT = T \frac{d\alpha}{\alpha} \left( \frac{1}{T} + \frac{\Xi(\Lambda)}{\frac{5}{2} + \Xi(\Lambda)} \right)$$

For a photon counting receiver, a differential error analysis [39] based on the standard DIAL retrieval can be used to estimate the term $d\alpha$ and leads to the expression for the temperature deviation, $dT$, where

$$dT = \frac{T}{2\alpha \Delta r} \left[ \frac{1}{N_{on}(r)} + \frac{1}{N_{on}(r + \Delta r)} + \frac{1}{N_{off}(r)} + \frac{1}{N_{off}(r + \Delta r)} \right]^{0.5} \frac{1}{\frac{\hbar c}{k_B T} - \frac{5}{2} + \Xi(\Lambda)}$$

Using the M2 model atmosphere from the LAFE data set, the return counts were calculated and the temperature deviation for the four absorption lines were plotted as a function of range with the results shown in Fig. 5. The results of this calculation indicate that the absorption lines at
769.2333 nm and 769.7956 nm will produce a temperature deviation less than \(+/-1 K\) below 4 km. This result suggests that minimizing the error in the retrieval of the absorption coefficient is important provided a reasonable temperature sensitivity of greater than about 1.5%/K is used. These two absorption features are candidates for DIAL temperature retrievals and instrument design considerations may play a role in the choice of the absorption feature to be used.

![Fig. 5.](image)

The modeling of the performance for the O\(_2\)-MPD discussed in Sections 4, 5, and 6 will utilize the O\(_2\) absorption line centered at \(\lambda_0 = 769.7956 \text{ nm}\), which has been identified as a suitable absorption feature for DIAL-based temperature measurements in the lower troposphere [43]. The absorption line parameters include a line strength of \(S_0 = 0.489 \times 10^{-25} \text{ cm}^{-1}/(\text{molecule cm}^{-2})\), a collisional halfwidth \(\gamma_L = 0.0312 \text{ cm}^{-1}\), and a ground state energy \(E = 1420.763 \text{ cm}^{-1}\) [46].

4. Perturbative retrieval of the absorption coefficient

The first step in the temperature retrieval is to use the perturbative solution to the DIAL equation to retrieve the O\(_2\) absorption coefficient. The perturbative solution requires an initial guess at the temperature profile. For calculations presented in this paper, the initial guess at the temperature profile will consist of the surface temperature and a simple moist adiabatic lapse rate of 6.5 K/km. 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 DLB-HSRL data.

The perturbative retrieval technique utilizes an expansion of the absorption coefficient at the on-line wavelength, \(\alpha_{m,1}(r)\), so that [44]

\[
\alpha_{m,1}(r) = \alpha_{0th}(r) + \Delta \alpha_{1st}(r) + \Delta \alpha_{2nd}(r)
\]

where \(\alpha_{0th}(r)\) is the zeroth order term and \(\Delta \alpha_{1st}(r)\) and \(\Delta \alpha_{2nd}(r)\) are the first and second order correction terms.

The zeroth order absorption coefficient term, \(\alpha_{0th}(r)\), is found from the on-line and off-line return signals [44]

\[
\alpha_{0th}(r) = \alpha_{m,2}(r) - \ln \left( \frac{N_1(r + \Delta r)N_2(r)}{N_1(r)N_2(r + \Delta r)} \right)
\]

where \(\alpha_{m,2}(r)\) is the molecular absorption coefficient at the off-line wavelength. This term is typically very small and may be approximated using the assumed temperature profile. The zeroth order term is simply the standard DIAL equation.
The first and second order correction terms account for the Doppler broadening of the molecularly scattered light and rely on the normalized backscatter lineshape, \( g_s(u, r) \), which may be written

\[
g_s(u, r) = \frac{\beta_A(r)}{\beta_A(r) + \beta_M(r)} h_s(u) + \frac{\beta_M(r)}{\beta_A(r) + \beta_M(r)} (h_s(u) \otimes l(u, r))
\]  

(12)

where \( h_s(u) \) is the laser lineshape, \( l(u, r) \) is the Doppler-broadened lineshape [50], and the subscript \( x \) is either 1 for the on-line wavelength or 2 for the off-line wavelength. For the work described in this paper, the laser lineshape is assumed to be a delta function. The normalized backscatter lineshape is known from the HSRL retrieval of the aerosol backscatter coefficient and the molecular backscatter coefficient model which uses a Doppler-broadened lineshape model.

The first order correction to the absorption coefficient, \( \Delta \alpha_{1st}(r) \), may be written [44]

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

(13)

where

\[
\Delta W_{1st}(r) = \frac{\int \xi_1(u, r) [1 - f(v, r)] dv}{\int \xi_1(u, r) dv}
\]  

(14)

and

\[
\Delta G_{1st,1}(r) = \frac{\int \eta_1(u, r) dv}{\int \xi_1(u, r) dv}
\]  

(15)

where \( f(v, r) \) is the molecular absorption lineshape with a maximum value of 1 at line center. The terms \( \xi_1(u, r) \) and \( \eta_1(u, r) \) are given by

\[
\xi_1(u, r) = g_s(u, r) E(v) T_{m0th,1}(u, r)
\]  

(16)

and

\[
\eta_1(u, r) = \frac{dg_s(u, r)}{dr} E(v) T_{m0th,1}(u, r)
\]  

(17)

where \( E(v) \) is the normalized lineshape of the transmission function of the optical filter in the receiver of the DIAL instrument, \( T_{m0th,1}(u, r) = \exp(- \int_0^r \alpha_{0th}(r') f(v, r') dr') \) and \( T_{m0th,2}(u, r) = \exp(- \int_0^r \alpha_{m}(r') f(v, r') dr') \). In contrast to the theory presented in Bunn et al. [44], the term \( \Delta G_{1st,2}(r) \) has been included here and is important for the correct retrieval of the absorption coefficient, particularly in regions where the backscatter has a high gradient such as in the M2 and M4 models. Furthermore, it should be noted that in regions where the aerosol backscatter coefficient is small and changing rapidly, care must be taken in estimating \( \frac{dg_s(u, r)}{dr} \) since the instantaneous derivative may be different than an estimate of this derivative based on a difference between points separated by a finite \( \Delta r \).

The second order correction to the absorption coefficient, \( \Delta \alpha_{2nd}(r) \), is found from [44]

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

(18)

Where

\[
\Delta W_{2nd}(r) = \frac{\int \xi_1(u, r) [1 - f(v, r)] dv}{\int \xi_1(u, r) dv} \frac{\int \xi_1(u, r) [1 - f(v, r)][1 - T_{m1st,1}(R)] dv}{\int \xi_1(u, r) dv}
\]  

\[
- \frac{\int \xi_1(u, r) [1 - f(v, r)][1 - T_{m1st,2}(R)] dv}{\int \xi_1(u, r) dv}
\]  

(19)

and

\[
\Delta G_{2nd,1}(r) = \frac{\int \eta_1(u, r) dv}{\int \xi_1(u, r) dv} \frac{\int \xi_1(u, r) [1 - T_{m1st,1}(R)] dv}{\int \xi_1(u, r) dv} - \frac{\int \eta_1(u, r) [1 - T_{m1st,1}(R)] dv}{\int \xi_1(u, r) dv}
\]  

\[
\frac{\int \eta_1(u, r) [1 - T_{m1st,2}(R)] dv}{\int \xi_1(u, r) dv} - \frac{\int \eta_1(u, r) [1 - T_{m1st,2}(R)] dv}{\int \xi_1(u, r) dv}
\]  

(20)

where \( T_{m1st,1}(u, r) = \exp(- \int_0^r \Delta \alpha_{1st}(r') f(v, r') dr') \) and \( T_{m1st,2}(u, r) = 1 \). The first order correction to the offline atmospheric transmission resulting from molecular absorption, \( T_{m1st,2}(u, r) = 1 \),
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 $T_{m1r,2}(ν, r) = 1$, $ΔG_{2nd,2}(r) = 0$ implying that only $ΔG_{2nd,1}(r)$ need be considered.

The major sources of error in the retrieval of the $O_2$ absorption coefficient result from the aerosol backscatter coefficient retrieval using the DLB-HSRL data and the perturbative retrieval technique using the $O_2$-MPD data. The first major source of error is that associated with the retrieval of the aerosol backscatter coefficient from the DLB-HSRL data. These errors result from counting statistics associated with the return signals and from uncertainty in the molecular backscatter model. Typically, the molecular backscatter model requires a temperature profile and deviations in the assumed temperature profile model from the actual temperature profile will result in errors for both the molecular and aerosol backscatter profiles. The second major source of errors is associated with the retrieval of the absorption coefficient from the $O_2$-MPD. These errors include those resulting from the counting statistics associated with the return signals, which are referred to as Poisson noise, as well as the errors from the difference between the assumed temperature profile model and the actual temperature profile, the errors in the normalized lineshape resulting from the DLB-HSRL retrieval, and the errors in the perturbative retrieval method.

A plot of the retrieved $O_2$ absorption coefficient as a function of range is shown in Fig. 6. The modeled $O_2$ absorption coefficient is shown as the black solid line while the retrieved $O_2$ absorption coefficients, including terms through the zeroth, first, and second order, are shown as the blue dot-dashed, blue dashed, and blue solid lines respectively. From Fig. 6, it is seen that the zeroth order retrieval of the $O_2$ absorption coefficient – which is the standard DIAL retrieval – results in significant errors, particularly where the aerosol backscatter coefficient has large gradients. Including the first and second order correction terms improves the retrieval of the $O_2$ absorption coefficient; as seen in Fig. 6, there is good agreement between the modeled $O_2$ absorption coefficient and the retrieved $O_2$ absorption coefficient when the correction terms are applied.

Plots of the retrieved absorption coefficients for the four atmospheric models are shown in Figs. 7(a)–7(d) for the M1-M4 models. The solid lines represent the modeled $O_2$ absorption coefficient, the dashed line represents the retrieved $O_2$ absorption coefficient with the Poisson noise turned off, and the dot-dashed line represents the retrieved $O_2$ absorption coefficient with the Poisson noise turned on. The error in the retrieved $O_2$ absorption coefficient as a function

![Fig. 6. The retrieved $O_2$ absorption coefficient as a function of range for the M3 model. The black solid line represents the model $O_2$ absorption coefficient. The dot-dashed, dashed, and solid blue lines represent the zeroth, first, and second order perturbative retrieval of the $O_2$ absorption coefficient.](image-url)
of range is shown in Fig. 8 as the black, red, blue, and green lines for the M1, M2, M3, and M4 models. The black vertical dashed lines in both plots indicate an error of ± 2%. Reducing retrieval error will be considered when the temperature retrievals are discussed below in Section 6.

**Fig. 7.** The retrieved O$_2$ absorption coefficient as a function of range for the M1, M2, M3, and M4 atmospheric models are shown in Figs. 7(a), 7(b), 7(c), and 7(d) respectively. The solid line represents the model O$_2$ absorption coefficient while the dashed line represents the retrieved O$_2$ absorption with the Poisson noise turned off while the dot-dashed line represents the retrieved O$_2$ absorption with the Poisson noise turned on.

**Fig. 8.** The error in the retrieved O$_2$ absorption coefficient as a function of range. The black, red, blue and purple lines represent the M1, M2, M3, and M4 models. The vertical dashed black lines represent a ± 2% error.

5. **The iterative temperature retrieval**

The temperature retrieval requires an initial guess at the temperature profile to seed the retrieval (typically, the initial guess uses the surface temperature and a lapse rate of 6.5 K/km). Using the retrieved absorption coefficient and the initial guess at the temperature, an updated temperature profile is estimated. This updated temperature profile is then used as the new seed temperature
profile and, again using the retrieved O2 absorption coefficient, a new updated temperature profile is estimated. This iterative process is repeated until the updated temperature profile matches the seed temperature profile.

The updated temperature profile may be estimated starting with the O2 absorption coefficient profile, which may be written as [42]

\[
\alpha_{O_2}(r) = S(T_0) \frac{T_0}{T(r)} \exp \left[ \frac{\epsilon}{kT_0} - \frac{\epsilon}{kT(r)} \right] g(v - v_0, r)n_{O_2}(r)
\]  

(21)

where \( S(T_0) \) is the line strength at the temperature \( T_0 \), \( \epsilon \) is the ground state energy, \( k \) is the Boltzmann constant, \( g(v - v_0, r) \) is the absorption lineshape function, \( n_{O_2}(r) \) is the O2 number density, and \( T(r) \) is the temperature profile. The O2 number density may be written as a function of temperature in the following manner. Start with

\[
n_{O_2}(r) = q_{O_2}(n_L(r) - n_{wv}(r)) = q_{O_2}(1 - q_{wv}(r))n_L(r)
\]  

(22)

where \( q_{O_2} \) and \( q_{wv}(r) \) are the atmospheric mixing ratios of O2 and H2O, respectively, and \( n_L(r) \) is Loschmidt’s number and is a function of both temperature and pressure, which are both functions of range, \( r \). Next, the water vapor mixing ratio, \( q_{wv}(r) \), is provided by the retrieval from the water vapor MPD and Loschmidt’s number can be written \( n_L(r) = \frac{P(r)}{kT(r)} \). Furthermore, using the barometric formula, the pressure can be written \( P(r) = P_0 \left( \frac{T_i}{T_i + \Delta T(r)} \right) \) where \( g_0 \) is the acceleration due to gravity, \( M \) is the molar mass of air, \( R \) is the universal gas constant and \( \Delta T \) is the lapse rate and is negative in the lower troposphere. Using the above relationships, the absorption coefficient may be written as

\[
\alpha_{O_2}(r) = \frac{S(T_0)T_0P_0 \exp \left( \frac{\epsilon}{kT_0} \right)}{kT_i^{\frac{7}{2}}} g(v - v_0, r)q_{O_2}(1 - q_{wv}(r))T(r)^{\frac{7}{2}} - 2 \exp \left( \frac{-\epsilon}{kT(r)} \right)
\]  

(23)

where \( \gamma = \frac{g_0M}{R} \).

The updated temperature profile, \( T_{i+1}(r) \), may be written as

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

(24)

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. (23) can be expanded to first order such that \( T_{i+1}(r)^{\frac{7}{2}} - 2 \approx T_i(r)^{\frac{7}{2}} - 2 \left( 1 + \left( \frac{7}{2} - 2 \right) \frac{\Delta T(r)}{T_i(r)} \right) \) and \( \exp \left( \frac{-\epsilon}{kT_i(r)} \right) \approx \left( 1 + \frac{\epsilon}{kT_i(r)} \Delta T(r) \right) \). Substituting these approximations into Eq. (23) and keeping terms to first order in \( \frac{\Delta T(r)}{T_i(r)} \), one can show that

\[
\Delta T(r) = \frac{\alpha_{O_2}(r)C_1C_2(r)g(v - v_0, r)q_{O_2}(1 - q_{wv}(r))}{C_1C_2(r)C_3(r)g(v - v_0, r)q_{O_2}(1 - q_{wv}(r))} \]

(25)

where

\[
C_1 = \frac{S(T_0)T_0P_0 \exp \left( \frac{\epsilon}{kT_0} \right)}{kT_i^{\frac{7}{2}}},
\]

(26a)

\[
C_2(r) = \frac{T_i(r)^{\frac{7}{2}} - 2 \exp \left( \frac{-\epsilon}{kT_i(r)} \right)}{C_3(r)g(v - v_0, r)q_{O_2}(1 - q_{wv}(r))},
\]

(26b)
and

$$C_3(r) = \frac{-\gamma}{T(r)} - 2 + \frac{\epsilon}{kT^2_i(r)},$$

(26c)

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, which is necessary to complete the next iteration of the temperature profile update.

The temperature retrieval as a function of range is shown in Figs. 9(a)–9(d) for the M1-M4 atmospheric models. The solid black lines represent the model temperature profile while the dashed black lines indicate a ±1 K temperature deviation from the model temperature. The blue dot-dashed line represents the initial guess at the temperature profile while the red line indicates the retrieved temperature profile. The temperature deviation – the retrieved temperature minus the model temperature – as a function of range is shown in Fig. 10. The vertical dashed (dot-dashed) lines indicate a ±1 K (±3 K) temperature deviation while the black, red, blue, and purple lines represent the results for the M1, M2, M3, and M4 models. 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, as in the M4 model, the temperature retrieval results in a larger temperature deviation as seen in Figs. 9 and 10.

The temperature retrieval used a total of 20 iterations. For each iteration, a linear fit to the temperature profile allows for an estimate of that temperature profile’s lapse rate which is needed for the iterative temperature retrieval. A plot of the lapse rate as a function of iteration is shown in Fig. 11 with the black, red, blue, and purple lines representing the M1, M2, M3, and M4 atmospheric models. Each lapse rate reaches a steady state value after approximately eight iterations, indicating that the temperature retrieval can be terminated after eight iterations.
Fig. 10. The temperature deviation a function of range. The dashed (dot-dashed) vertical black lines indicate ±1 K (±3 K) temperature deviation. The black, red, blue, and purple lines represent the M1, M2, M3, and M4 models.

Fig. 11. The retrieved temperature lapse rate as a function of the iteration number for the M1, M2, M3, and M4 models is shown as the black, red, blue, and purple lines. After approximately eight iterations, the retrieved lapse rate reaches a steady state value.

6. Discussion

The major source of error associated with the retrieved temperature profiles results from errors in the retrieved O$_2$ absorption coefficient. These errors are associated with the Poisson noise that originates from the photon counting used by the instrument architecture. There are four potential methods to decrease the Poisson noise. First, one can increase the output power. The trade-off with increasing the output power includes eye-safety concerns and decreased lifetime of the optical amplifier. Second, one can increase the integration time. The trade-off here is that as the integration time is increased to improve the accuracy and precision of the retrieved temperature profile, the ability to resolve the temporal changes in the temperature profiles diminishes. Third, one can increase the pulse repetition frequency of the laser transmitter. The current WV-MPD and DLB-HSRL operate at a pulse repetition frequency of 7 kHz. However, in the past, these instruments have operated at a 10 kHz pulse repetition frequency. Changing to the higher pulse repetition frequency would increase the number of return photons over an integration time. However, increasing the pulse repetition frequency results in the potential of the return signal from one pulse at a large range adding to the return signal from the next pulse at a closer range. The fourth method of improving the temperature retrieval involves maintaining a shorter range resolution where the aerosol backscatter is stronger and a longer range resolution where the aerosol backscatter is weaker. The effect of using the longer range resolution in regions of weak
aerosol backscatter is the improvement of the temperature retrieval, however this is achieved at the cost of range resolution.

To attain a better understanding of the potential for the O$_2$-MPD to retrieve temperature profiles, 25 temperature, pressure, water vapor number density and aerosol backscatter profiles were selected from the LAFE data set to constitute 25 atmospheric models. Each atmospheric model was selected from a different day and at a random time with the caveat that no clouds were present below 5 km. Plots of the temperature deviation as a function of range are shown in Figs. 12(a)–12(c) with Fig. 12(a) representing the temperature deviation using a 150 m range resolution and Fig. 12(b) representing the temperature deviation using a 300 m range resolution. Figure 12(c) representing the temperature deviation using a range resolution of 150 m and etalon transmission bandwidth of 1.7 GHz as opposed to the etalon transmission bandwidth of 10 GHz used for Figs. 12(a) and 12(b). It should be noted that the etalon bandwidth for the water vapor DIAL channel is 1.1 GHz. The red vertical dashed (dot-dashed) lines indicate a ±1 K (±3 K) temperature deviation. The use of a longer range resolution results in decreasing the Poisson noise and, as seen in Fig. 12(b) compared to Fig. 12(a), a modest improvement in the accuracy of the temperature retrieval. Decreasing the etalon bandwidth, as seen in Fig. 12(c) compared to Fig. 12(a), the temperature retrieval accuracy improves.

The temperature deviation for the 150 m range resolution using the 1.7 GHz etalon bandwidth is within ±1 K for 96.9%, 95.0%, 80.1%, and 51.9% of the retrievals between 0.5 and 1.5 km, 1.5 and 2.5 km, 2.5 and 3.5 km, and 3.5 and 4.5 km. The temperature deviation is within ±3 K for 99.7%, 98.2%, 95.6%, and 91.7% of the retrievals between 0.5 and 1.5 km, 1.5 and 2.5 km, 2.5 and 3.5 km, and 3.5 and 4.5 km. These results indicate that the temperature retrieval can be achieved to within ±1 K below 2.5 km using a 150 m range resolution and an averaging time of 30 minutes. Furthermore, the temperature retrieval can be achieved to within ±3 K below 4.5 km. It should be noted that the World Meteorological Organization requirements for using observational temperature data in high resolution numerical weather prediction models requires a threshold (breakthrough, goal) accuracy of 3 K (1 K, 0.5 K) with a temporal resolution 2 hours (30 minutes, 15 minutes), a vertical resolution of 1 km (250 m, 100 m) and a horizontal resolution of 25 km (5 km, 1 km) [51]. Furthermore, requirements for using observational temperature data for nowcasting requires a threshold (breakthrough, goal) accuracy of 3 K (1 K, 0.5 K) with a temporal resolution 1 hours (10 minutes, 5 minutes), and a vertical resolution of 1 km (300 m 100 m) and a horizontal resolution of 50 km (10 km, 5 km) [51].

Fig. 12. The temperature deviation for 25 atmospheric models using the LAFE data set. The red dashed (dot-dashed) lines indicate a ±1 K (±3 K) temperature deviation. Figure 12(a) represents data using a 150 m range resolution while Fig. 12(b) represents data using a 300 m range resolution. Figure 12(c) represents data using a 150 m range resolution and an etalon bandwidth a factor of six narrower than the data represented in Figs. 12(a) and 12(b).
7. First O$_2$-MPD temperature retrieval

Recently, a prototype O$_2$-MPD was developed [47,48] and, along with the DLB-HSRL and WV-MPD, provided data for demonstrating initial temperature retrievals. Using a 225 m range resolution and a 30-minute averaging time, the absorption coefficient and temperature profile was retrieved. The absorption coefficient as a function of range is shown in Fig. 13. The black line is the calculated absorption coefficient using data from a co-located radiosonde. The blue dot-dashed line is the retrieved absorption coefficient using just the 0$^{th}$ order term in the retrieval. It should be noted that the 0$^{th}$ order term in the perturbative retrieve represents the retrieval based on the standard DIAL equation and results in significant error in the retrieved absorption coefficient. This error in the retrieved absorption coefficient results in a temperature deviation on the order of 10 K, which is in line with modeling presented by Bosenberg et. al [43]. The red dashed line represents the retrieved absorption coefficient using the 0$^{th}$, 1$^{st}$, and 2$^{nd}$ order terms in the retrieval.

![Fig. 13.](image)

**Fig. 13.** The absorption coefficient as a function of range. The black line is the calculated absorption coefficient using data from a co-located radiosonde. The blue dot-dashed line is the retrieved absorption coefficient using just the 0$^{th}$ order term in the retrieval while the red dashed line represents the retrieved absorption coefficient using the 0$^{th}$, 1$^{st}$, and 2$^{nd}$ order terms in the retrieval.

![Fig. 14.](image)

**Fig. 14.** The left hand plot shows the temperature as a function of range. The dashed red line indicates the retrieved temperature profile using the O$_2$-MPD data while the solid black line indicates the temperature profile measured using the co-located radiosonde. The dot-dashed blue lines indicate ± 1 K temperature deviation and are shown for reference. The right hand plot shows the corresponding temperature deviation as a function of range as the solid black line. The dashed (dot-dashed) vertical lines indicate ± 1 K (± 3 K) temperature deviation.
The temperature as a function of range is shown in Fig. 14(a). The black line represents the temperature profile measuring by the co-located radiosonde while the red dashed line represents the retrieved temperature profile. The blue dot-dashed lines represent a ± 1 K temperature deviation and are shown for reference. The temperature deviation is shown as the black line in Fig. 14(b). The red dashed (dot-dashed) vertical lines represent a temperature deviation of ± 1 K (± 3 K). Good agreement between the retrieved temperature profile using the O\textsubscript{2}-MPD data and the temperature profile measured using the radiosonde is seen to about 4.2 km and is in agreement with the performance modeling discussed in this paper.

8. Conclusions

The O\textsubscript{2}-MPD along with the WV-MPD and DLB-HSRL may be used to provide thermodynamic profiles of the lower troposphere and aerosol backscatter profiles. Both the WV-MPD and DLB-HSRL have demonstrated long-term autonomous operation during several recent field experiments. The proposed O\textsubscript{2}-MPD is based on the same architecture as the WV-MPD and has the potential to provide temperature profiling capabilities in the lower troposphere. Thus, this set of instruments has the promise of providing thermodynamic profiling capabilities needed by both the climate and weather forecasting research communities.

A retrieval algorithm for temperature profiling was developed in this paper. First, a perturbative retrieval of the O\textsubscript{2} absorption coefficient is retrieved using both the first and second order perturbative correction terms. This retrieval technique relies on the retrieval of the aerosol backscatter coefficient using an ancillary measurement based on the DLB-HSRL that can be used to account for the Doppler broadening of the light scatter from atmospheric molecules. Care must be taken when applying this perturbative solution in regions where the gradient of the normalized lineshape, $\frac{dg_{\nu,r}}{dr}$, is large since this term can vary as $dr$ varies when a finite difference is used to estimate this derivative. Once the O\textsubscript{2} absorption coefficient is retrieved, an iterative retrieval of the temperature profile can be completed. This iterative approach starts with an assumed temperature profile and after each iteration produces an updated temperature profile. For the atmospheric models used for the performance modeling, it was found that the temperature profile converged after approximately eight iterations.

Recently, a combined DLB-HSRL and WV-MPD instrument was deployed at the LAFE field experiment. Using data collected by this instrument, along with the temperature and pressure profiles provided with the LAFE data, modeling of the temperature retrieval performance of an O\textsubscript{2}-MPD was studied based on the retrieval technique described above. The design of theoretical O\textsubscript{2}-MPD is based on the DLB architecture. The modeling results indicate that the temperature profile may be retrieved from an O\textsubscript{2}-MPD instrument with a ±1 K accuracy up to 2.5 km and ±3 K accuracy up to 4.5 km with a 150 m range resolution and 30-minute averaging time. Finally, an initial temperature retrieval from an operation O\textsubscript{2}-MPD was presented and the results from this initial measurement are in agreement with the theoretical modeling.

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