Rotational temperatures retrieval from the Arecibo Observatory Ebert-Fastie spectrometer and their inter-comparison with Lidar and SABER measurements

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Abstract

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1. Introduction

The Mesosphere and Lower Thermosphere (MLT) region (approximately from 80 km to 120 km altitude) is a unique part of the terrestrial atmosphere where both the neutral dynamics and plasma electrodynamics play crucial roles in governing the overall motion. This region is affected by dynamical processes from the lower altitudes, such as atmospheric gravity waves, tides, planetary waves, etc., and external forcing from the higher altitudes, such as solar activity and geomagnetic storms. The MLT region plays a crucial role in the atmospheric vertical coupling
processes, and it is essential to understand and quantify the variabilities of this region at different temporal and spatial scales.

It has been challenging to investigate the MLT temperatures since this region is too high for balloon sounding and too low for sustainable in-situ measurements by satellites (Bittner et al., 2002 and references therein). Limited in-situ measurements obtained with sounding rockets and falling spheres provide valuable MLT temperature information (Lubken, 1999; Nordberg et al., 1965). Space based remote sensing instruments onboard low earth-orbiting satellites and ground-based remote sensing instruments, such as the meteor radar, incoherent scatter radar, and lidars, have helped to accumulate important MLT temperature data base in the past few decades (e.g., Fricke & Von-Zahn, 1985; Hocking, 1999; Russell III et al., 1994; Tepley & Mathews, 1978; Höffner & Lautenbach, 2009). The discovery of the OH band emissions in the nightglow spectrum by Meinel (1950), provided another tool to remotely monitor MLT temperatures. Since then, ground-based optical instruments, such as the Ebert-Fastie spectrometer (EFS), have been employed to observe the intensity of these vibrational-rotational OH emission lines and estimate the temperatures in the this region (e.g. Bittner et al., 2002; Sigernes et al., 2003).

EFS is capable of recording airglow emissions coming from different altitudes in the MLT region (e.g. O$_2$(0,1) atmospheric band and OH Meinel bands) in a single scan and in turn, allows temperature estimation from these altitudes. The temperatures obtained from EFS are naturally weighted by the volume emission rate (VER) profile of the corresponding emission. Therefore, knowledge of the shape and peak altitude of these VER profiles are essential to understand these temperatures in a better way. Also, information about these two parameters of the VER is crucial for the inter-comparison between instruments that measure altitude-integrated measurements (such as EFS) and altitude-resolved measurements (such as Lidar, Meteor radar, and satellite).

One of the first comprehensive studies on the OH Meinel band VER was conducted by Baker and Stair Jr. (1988), who observed that the peak altitude occurs between 86.8 ± 2.6 km and the full width at half maximum (FWHM) to be 8.6 ± 3.1 km. Since then, several researchers have studied the peak altitude and FWHM of the OH Meinel band VER from different locations and found considerable temporal and spatial variabilities in these two parameters (Liu & Shepherd, 2006; Mulligan et al., 2009; Takahashi et al., 2005).
To date, most of the observations with EFS have been carried out from either the high latitudes or the mid-latitudes stations (Bittner et al., 2002; Myrabø et al., 1984; Sigernes et al., 2003; Sivjee et al., 1972). Some of these stations have been operating the EFS continuously for several decades and have acquired valuable long-term MLT temperature data sets. To our knowledge, the EFS at the AO is the only one that continuously monitored MLT temperatures in the low latitude regions. This EFS was brought to the AO from the Kitt Peak National Observatory, Arizona, USA, in the 1970s and since then, it has been utilized to measure different airglow emissions. For example, it has been used to study the nightglow emission lines of OI 6300 Å and NI 5200 Å (Burnside et al., 1977), (0,1) band of N\textsuperscript{+} nightglow emission (Meriwether Jr. & Walker, 1977), the nightglow triplet emission of OI 7774 Å (Burnside et al., 1980), evening twilight emission of O\textsuperscript{+} ions (Meriwether Jr. et al., 1978) and twilight Ca\textsuperscript{+} emission (Tepley et al., 1981).

During its ~40 years of operation, the AO EFS has been utilized to mostly observe the O\textsubscript{2}(0,1) atmospheric band and OH(6,2) and OH(8,3) Meinel band emission lines of the nightglow spectrum. Despite the extensive database, only a few studies had been published based on a single night or a few nights of observations of these MLT region emissions (Hecht et al., 1993; Kane et al., 1993; Meriwether, 1979; Zhou et al., 1997; Walterscheid et al., 2000). No previous study has comprehensively used such an extensive AO EFS MLT region emissions database.

This work is the first step of a new initiative at AO that plans to investigate long-term trends in the MLT region using the vast AO EFS MLT database and study their relationship with other geophysical parameters and atmospheric variations. We present a methodology to estimate the rotational temperatures in the MLT region using the P1 lines of the OH(6,2) Meinel band measured by the AO EFS. A comparison with the co-located Potassium temperature Lidar (henceforth referred to as K-Lidar) data has been conducted to validate our results. After that, the EFS and K-Lidar temperatures are combined to retrieve the temporal variation of the peak emission altitude of the OH(6,2) Meinel band over AO and compare it with satellite observation and theoretical results. No such detailed investigation of the OH Meinel band VER parameters has been carried out at AO except by Hecht et al. (1993), where two days of EFS and Sodium Lidar data were used. This motivated us to investigate how the peak of the OH(6,2) Meinel band VER
varies with local time over AO using a larger database of the EFS and K-Lidar temperatures. The AO EFS data used in this work have not been explored before.

2. Instruments

A detailed description and working principle of the AO EFS can be found in Meriwether Jr. and Walker (1977) and Meriwether (1979). The AO EFS consists of a concave mirror with a one-meter focal length. The EFS is fitted with a mirror system at the top, allowing it to look at different elevation and azimuth angles. During the period of our study, the instrument was pointed towards the zenith, and it was operated in the first order with a slit width of 0.6 mm × 8 mm. These settings provide a spectral resolution of ~4.5 Å and a field of view of ~1° × 8° (Kerr et al., 2001). This spectral resolution is sufficient to resolve the P1 rotational lines of OH(6,2) Meinel band. The integration time per spectral point varies between 1.7 sec to 3.3 sec on different nights during the study period, resulting in variable data cadence between 6.8 min and 13.2 min. Dark count data for a particular night is obtained with a similar integration time per spectral point as the airglow data. An Argon (Ar) lamp was used to calibrate the AO EFS wavelength coverage.

The K-Lidar used in this work has been continuously operated at AO since early 2000 (Friedman et al., 2003). It sends out pulses of an Alexandrite Ring Laser that is injection seeded by a continuous wave (CW) laser and collects the backscattered laser light from the atmosphere with an 80 cm mirror, as described in detail by Friedman (2003). The well-established three-frequency technique measures mesospheric temperature from the potassium (K) spectra by switching between three laser frequencies (She & Yu, 1994; Friedman, 2003). The CW seed laser is locked to a Doppler-free feature at the K-D1 line near the peak of the K fluorescence to establish the frequency reference. An acousto-optic modulator setup generates and switches to the two wing frequencies. The signal is integrated for 1000, and 500 laser pulses at the reference frequency and the two wing frequencies, respectively, with a range resolution of 150 m. In routine operation, the raw data are processed to extract temperature profiles with a resolution of 30 minutes and 450 m. The resulting temperature errors are about 2–3 K and <50 K at the peak and edge of the K layer, respectively (Friedman & Chu, 2007). However, temperatures utilized in this study are processed with a temporal resolution of 15 minutes to better match the EFS data.
resolution, resulting in an increased error by ~1.5-2 times at the peak and by ~2-3 times at the edge of the K layer in comparison to the 30 min resolution data. Data gaps in the temperature profiles due to weak signals (e.g., edge of the K-layer, clouds, or “bad” laser pulses) are rare. Friedman and Chu (2007) describe the instrument improvements implemented in 2003 to extract reliable and precise raw data by discrimination against spectrally “bad” pulses from the Alexandrite Ring laser or secondary frequencies bleeding of the single-frequency CW seed laser.

In this study, data from the Sounding of the Atmosphere by Broadband Emission Radiometry (SABER) instrument onboard NASA’s Thermosphere Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite has also been used. A detailed description of the SABER instrument and the parameters it can measure is documented by Russell III et al. (1994). We have utilized the SABER 2.07 version of the channel A and channel B VER data which are estimated at 2.0 \( \mu \text{m} \) and 1.6 \( \mu \text{m} \) wavelength, respectively. The SABER channel A data is constituted of OH(9,7) and OH(8,6) Meinel band line emissions, while channel B contains the OH(5,3) and OH(4,2) Meinel band emissions. The altitude resolution of the SABER 2.0 \( \mu \text{m} \) and 1.6 \( \mu \text{m} \) VER data between 80 km and 95 km altitude is ~0.4 km.

3. Methodology and Data Analysis

EFS and K-Lidar data during the period of February-April 2005 are considered in this work. This period is characterized by good weather with more clear sky nights over Arecibo, resulting in more simultaneous EFS and K-lidar observation than in other months. A total of 15 nights of simultaneous EFS and K-Lidar data are available during the study period, which results in ~90 hrs of concurrent good quality data.

3.1. Rotational temperature estimation from EFS data

Rotational temperatures in the MLT region are estimated by processing the raw airglow intensity data recorded by the AO EFS. An example of a raw data file obtained on February 11, 2005 is shown in Figure 1(a), where the intensity values are represented in photomultiplier detector counts. Each EFS data file consists of 240 spectral points during this study period. Each spectral point of the data file is hereafter referred to as a channel (ch.). To determine which ch.
in the raw data corresponds to which wavelength of the airglow spectrum, we used the wavelength calibration data. If wavelength calibration data for a particular night is unavailable, then the calibration data available on the nearest previous night is considered. Figure 1(b) shows the wavelength calibration data used to process the raw EFS data shown in Figure 1(a).

![Figure 1: (a) An example of raw EFS data taken between 20:44 AST and 20:57 AST on February 11, 2005 from AO (AST = Universal Time Coordinate (UTC) + 4 hr). (b) Example of a wavelength calibration of the AO EFS performed by using an Argon lamp between 18:56 AST and 18:58 AST on February 10, 2005.](image)

It can be noticed from Figure 1(b) that four prominent Argon (Ar) lines are present in the calibration data. The channel number (ch.no.) and corresponding known wavelengths of these Ar lines are noted in the first and second columns of Table 1, respectively. At times, the intensity profile for a particular Ar line peak appears to be slightly asymmetric with respect to the peak (e.g. the second Ar line peak in Figure 1(b)). Thus, to better estimate the Ar line peak locations, we have applied intensity weighted ch.no. method following Equation 1.

\[
Ch_p = \frac{\sum_{i=1}^{n} \text{ch. no.}(i) \times I(i)}{\sum_{i=1}^{n} I(i)} \quad \text{Eq. 1}
\]
where, $Ch_p$ represents estimated peak ch.no. of an Ar line, $I$ represents the intensity counts within the FWHM of a particular peak, and $n$ represents the number of data points within the FWHM of that peak. A linear fit between the Ar line wavelengths and $Ch_p$ (column 3, Table 1) are performed. By using the fitting coefficients, it is found out that on February 10 2005, ch. 1 and ch. 240 of the raw data correspond to 8726.3 Å and 8321.21 Å, respectively. This results in a data resolution of 1.688 Å/ch. Wavelengths corresponding to the $Ch_p$ are shown in column 4 of Table 1. The wavelength differences shown in column 5 of Table 1 are within ±1.3 Å for all the nights during our study period. The five prominent peaks observed between ch.no. 100 and 200 in Figure 1(a) belong to the P1 lines of the OH(6,2) Meinel band.

**Table 1:** Details of the wavelength calibration performed with the help of Argon lamp on February 10, 2005.

<table>
<thead>
<tr>
<th>Peak ch.no. (raw data)</th>
<th>Standard Ar line Wavelength (Å)</th>
<th>Intensity weighted ch.no. ($Ch_p$)</th>
<th>Fitted wavelength to $Ch_p$ (Å)</th>
<th>Difference of Columns 2 and 4 (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>8667.944</td>
<td>35.098</td>
<td>8668.504</td>
<td>-0.560</td>
</tr>
<tr>
<td>124</td>
<td>8521.442</td>
<td>122.596</td>
<td>8520.2</td>
<td>1.242</td>
</tr>
<tr>
<td>178</td>
<td>8424.647</td>
<td>179.275</td>
<td>8424.134</td>
<td>0.513</td>
</tr>
<tr>
<td>188</td>
<td>8408.210</td>
<td>187.965</td>
<td>8409.404</td>
<td>-1.194</td>
</tr>
</tbody>
</table>

After that, dark counts and background intensity have been deducted from the raw airglow data. Usually, dark counts are measured on every night of the airglow observation. If dark counts are unavailable for a particular night, then dark counts from the nearest previous night are considered. Typical root mean square (RMS) dark count on a night lies in the range of 1 to 10 counts. We considered the average intensity of the first 20 channels as the background intensity since they have the lowest values compared to all other channels in the data, and there is no prominent rotational line peak in those channels. In addition, the EFS data files contaminated by clouds or haze conditions have not been considered for temperature estimation. Data from a co-
located all-sky imager operated by the Boston University is utilized to detect sky conditions over AO.

Rotational temperature estimation using the AO EFS data is based on the assumption that the P1 lines of OH(6,2) Meinel band follow the Boltzmann distribution. Considering the collision frequency and lifetime of the OH*($v'$=6) state, only those rotational lines with rotational quantum number (K) <6 follow the Boltzmann distribution (Holmen et al., 2014; Pendleton Jr. et al., 1993). Therefore, we utilize only the P1 (K=2 to K=5) line intensities in the rotational temperature estimation. In addition, it is assumed that the vibrational-rotational states of OH* are in Local Thermodynamic Equilibrium (LTE), which allows the rotational temperature to represent the neutral atmospheric temperature.

Assuming that the P1 rotational lines OH(6,2) band follow the Boltzmann distribution, the peak intensity ($I$) of each of these lines can be expressed as,

$$I_{v',J'\rightarrow v'',J''} = N_{v'} A_{v',J'\rightarrow v'',J''} [\frac{2(2J'+1)hcB_v}{k_BT}] \times \exp(-\frac{F(J')hc}{k_BT})$$

Eq. 2

Here, $J$, $h$, $c$, $k_B$, and $T$ represent rotational quantum number, Planck’s constant, speed of light in space, Boltzmann constant and rotational temperature, respectively. $N_{v'}$ represents the total concentration of OH* molecules at rotational level $v'$ while $A_{v',J'\rightarrow v'',J''}$ represents Einstein coefficient for a particular line transition. $B_v$ is a rotational constant and $F(J')$ represents the rotational term whose value is computed following Krassovsky et al. (1962).

By taking logarithm of both sides of Equation 2 and rearranging the terms, the following expression can be obtained,

$$\ln\left(\frac{I}{2A(2J'+1)}\right) = \ln\left(\frac{N_{v'}hcB_v}{k_BT}\right) - \frac{F(J')hc}{k_BT}$$

Eq. 3

The plot of $\ln\left(\frac{I}{2A(2J'+1)}\right)$ against the rotational term $F(J')$ is called the Boltzmann plot. An example of a Boltzmann plot is shown in Figure 2. The rotational temperature is estimated from the slope of the linear fit (i.e. $\frac{hc}{k_BT}$). A chi-square test is performed to evaluate the goodness of
the fitting in the Boltzmann plots. To ensure that the assumption of Boltzmann distribution is valid for our calculations, only those rotational temperatures are considered in this study where the chi-square coefficient is less than 0.02.

Figure 2: An example of a Boltzmann plot corresponding to the P1 (K=2 to K=5) rotational lines shown in Figure 1a. The red color line denotes the linear fit.

The uncertainties in the rotational temperature (σ_T) are calculated following the noted error propagation method (Vargas, 2019). The RMS value of σ_T varies between 5.8 K and 10.7 K during our study period. An example of the variation of rotational temperatures derived from the AO EFS during a night is shown in Figure 3, along with the corresponding measurement uncertainties.
Figure 3: Variation of rotational temperature with time on the night of March 10, 2005. The circles represent magnitude of rotational temperature and the vertical lines represent measurement uncertainties.

3.2. Weighted temperature calculation from K-Lidar temperature profiles

The AO K-Lidar provides temperatures between 80 km and 100 km with an altitude resolution of 0.45 km. Since the K-Lidar provides altitude resolved temperature measurements, the K-Lidar temperature profiles are required to be weighted by the OH(6,2) band VER to compare them with the EFS temperatures (Vargas et al., 2021). Any direct measurement of the OH(6,2) band VER is unavailable. Therefore, the SABER 1.6 µm VER profiles are utilized as the weighting function on those nights when SABER passes are concurrently available with the EFS and K-Lidar data. The SABER 1.6 µm VER is chosen as the proxy of OH(6,2) band VER since their peak emission altitudes are expected to be close by (Von Savigney et al., 2012). SABER passes within ±2.5° latitude and longitude range of the AO and between 18:00 AST and 30:00 AST (i.e., 06:00 a.m. AST the next day) are only considered here. Out of the fifteen nights when EFS and K-Lidar data are available concurrently, only on five nights the SABER passes satisfy these two selection criteria. Since the altitude resolution of the K-Lidar and SABER 1.6 µm VER data is different, the SABER 1.6 µm VER data is interpolated to the altitudes of the K-Lidar temperature profiles on these five nights. A Gaussian function is used to weight the K-Lidar temperatures on
the remaining ten nights. Previous studies indicate that a Gaussian is a good approximation of
the OH VER profile (e.g., Dunker, 2018 and references therein). The peak altitude and FWHM of
the Gaussian function are the average values of the corresponding parameters obtained from
the five nights of SABER 1.6 µm VER: 87.05 km and 6.46 km, respectively. The standard deviations
are 1.46 km and 0.9 km, respectively. We have not considered those SABER 1.6 µm VER profiles
that exhibit double peaks to estimate the average peak altitude and FWHM.

Reliable temperature retrieval from the K-Lidar below 82-83 km is frequently hindered
due to very low K atom densities on the edge of the K-layer. To ensure symmetric weighting on
both sides of the Gaussian peak altitude, the minimum weighting factor limit is set at 0.5. In
addition, Lidar profiles where temperatures are unavailable at any altitudes having a weight
factor of ≥ 0.8 are not considered in the calculation to make sure that there is no bias in the
weighted K-Lidar temperatures due to data gaps. In Figure 4, an example of a K-Lidar temperature
profile obtained on the night of March 11, 2005 is shown along with a SABER 1.6 µm VER profile
acquired on the same night. The weighted K-Lidar temperature corresponding to the K-Lidar
profile shown in Figure 4 turns out to be 168.29 K.

Figure 4: An example of a K-Lidar temperature profile obtained on March 10, 2005 at 22:19 AST from AO. The red
open circles represent the magnitude of the Lidar temperatures (lower x axis), and the horizontal red lines represent
measurement uncertainties in the Lidar temperatures. The solid blue line (upper x axis) represents a SABER 1.6 µm
VER data recorded on March 11, 2005 at 00:47 AST over AO. The SABER VER data has been normalized with respect to the peak of the VER data.

4. Results and Discussion

4.1. Comparison between EFS and K-Lidar temperatures using a fixed weighting function

The primary purposes of this paper is to validate the rotational temperatures derived from the AO EFS data. This is accomplished by comparing the EFS rotational temperatures with the weighted K-Lidar temperatures. The time resolution of the EFS and K-Lidar data is not equal, and at times, there are data gaps in both of these data sets. Thus, to better compare these two data sets, we looked for EFS temperature values within ±7.5 min of a K-Lidar temperature value and then averaged those EFS temperatures.

In Figure 5(a), a comparison between the weighted K-Lidar temperature and averaged EFS temperature for the night of February 10-11, 2005 is shown. The uncertainties in the weighted Lidar temperatures are the weighted mean of the individual temperature uncertainty at each altitude. The same weighting function which is used to weight the K-Lidar temperatures, is also used to weight the temperature uncertainties. The uncertainties in the EFS temperatures shown in Figure 5(a) are the mean of all the EFS temperature uncertainties within ±7.5 min of a K-Lidar temperature value. The difference between these two data sets are plotted with respect to time in Figure 5(b). It can be seen clearly from Figure 5(a) that the temporal trends of both these data sets show a very good match. Their magnitudes exhibit a very good match at certain times, while at other times, the difference of 10s of K between the two data sets is observed. Also, it is apparent from both panels of Figure 5 that the averaged EFS temperatures are generally greater than the weighted K-Lidar temperatures during most of the night.
Figure 5: (a) Comparison of the EFS rotational temperature (blue color) and weighted K-Lidar temperature (red color) for February 10 – 11, 2005. Vertical lines of the corresponding color show the uncertainties in these two temperature data. (b) The difference of the EFS rotational temperatures and weighted K-Lidar temperatures values shown in Figure 5(a).

To understand the statistical relationship between the EFS and K-Lidar temperatures, we have analyzed the differences between the averaged EFS and weighted K-Lidar temperatures on all the fifteen nights when they are simultaneously available. All the temperature differences are grouped into bins of 5 K irrespective of their local time distribution. Temperature differences within ±2.5 K of the central temperature of a bin are grouped in that bin. We have plotted the number of points (i.e., occurrence) in each of those bins with respect to their central temperatures in Figure 6. We found that out of all the temperature differences, there are 45.56 %, 59.6 % and 74.3 % points within the temperature difference range of ±10 K, ±15 K and ±20 K, respectively. Considering the ~6-10 K uncertainties in the EFS temperatures and larger
uncertainties in the K-Lidar temperatures, the results obtained here indicate that, in general, there is a good agreement between the EFS and K-Lidar temperature magnitudes. Also, it is evident from Figure 6 that on most the occasions, the EFS temperatures are greater than the K-Lidar temperatures. A Gaussian fit to the occurrence of the bins shown in Figure 6 reveals that, on average, the average EFS temperature is warmer than the weighted Lidar temperatures by 10.46 K. The Gaussian fit's standard deviation is 23.29 K, which shows that the temperature differences are mostly spread over the range of -10 K to 30 K.

Figure 6: Plot of the distribution of differences between average EFS and weighted K-Lidar temperatures during February-April 2005. The size of the individual bin is 5 K. The red line represents a Gaussian fitting to the occurrence of the bins and parameters of the Gaussian fit are mentioned in the upper right corner of the Figure.

4.1.1. Comparison of results with previous studies

We could find out only two previous works where temperatures estimated by EFS and Lidar have been compared. Friedman et al., (2003) compared one night of temperature data obtained from the same set of instruments used in the present study. They did not quantify the temperature difference between these two instruments. Rather, they observed that the EFS temperatures compare well with the K-Lidar temperatures when K-Lidar temperatures at different altitudes are considered at different times. In other words, the EFS and K-Lidar temperatures compare poorly when a fixed altitude Lidar temperature is considered for the
whole night. Yu et al. (1991) compared temperatures estimated by an EFS onboard a scientific flight with temperatures obtained by a ground-based Na-Lidar. They noted temperature differences of ~5-10 K during the closest approach of the flight to the Na-Lidar location.

In four more studies comparison of MLT temperatures retrieved from Lidar and spectrometer data is made by using spectrometers with differing configurations than the EFS. Von Zahn et al. (1987) analyzed three nights of MLT temperatures obtained from a Czerny-Turner spectrometer and a co-located Na-Lidar. They found the difference between the hourly averaged spectrometer and Na-Lidar temperatures to be between -10 K to 5 K while their nightly mean values are almost equal except on one night. She and Lowe (1998) have compared MLT temperatures estimated by a Fourier transform spectrometer and a Na Lidar where the instruments were located at similar latitudes but 24° apart in longitudes. They reported differences of ~6-11 K between the seasonal mean of the spectrometer and Lidar temperature at 87 km during all the seasons except spring. They also obtained an average difference of 9 K while comparing the nightly mean temperatures estimated by these two instruments when they were operating concurrently. Burns et al (2003) have conducted a comparative study of the temperatures derived by a Czerny-Turner spectrometer and a Na-Lidar where these two instruments are located at a distance of ~1500 km. They noticed that on one set of nights (~56%) the average nightly mean temperature differences were close to zero while in the other set of nights (~44%), the average differences turned out to be greater than 10 K. Dunker (2018) studied temperature difference between a co-located Czerny-Turner spectrometer and Na-Lidar. By employing a Gaussian function with fixed peak altitude and fixed shape to weight the Na-Lidar, they obtained nightly mean temperature differences in the range of -20 K to 12 K.

We have not employed hourly averages or nightly means of the EFS and K-Lidar temperatures in our analysis as has been done in the comparison studies mentioned in the previous paragraphs. Therefore, the EFS and K-Lidar temperatures used in our analysis contain perturbations due to waves and tides of different spatial and temporal scales. Despite that, we find good agreement between the average temperature difference obtained in our study and the values reported in the previous studies. However, the standard deviation is larger in our case in comparison to theirs.
4.1.2. Discussion about the EFS and K-Lidar temperature difference

Several factors could contribute to the temperature differences observed in the present study. The peak altitude of the weighting function applied on the K-Lidar temperature profiles plays a crucial role in the inter-comparison of EFS and K-Lidar temperatures since the maximum weighting are contributed by the altitudes surrounding the peak. Some previous studies have indicated that OH Meinel bands' peak altitude varies considerably over a night (e.g., Takahashi et al., 2005; Zhao et al., 2005). Therefore, it is very unlikely that a single fixed peak VER (i.e. a single SABER 1.6 µm or a single Gaussian VER) could truly represent the OH(6,2) band VER for the entire night. Also, previously it has been shown that different vibrational bands of the OH emission have different peak emission altitudes (Von-Savigny et al., 2012; Xu et al., 2012). As per these reports, the peak of the OH(6,2) band VER should be located at slightly higher altitude in comparison to the SABER 1.6 µm VER peak altitude. Therefore, the weighting functions used in this analysis (i.e. a single SABER 1.6 µm or a single Gaussian VER) appear to be an important controlling factor of the temperature difference.

The choice of Einstein transition coefficients for the OH(6,2) vibrational lines also could lead to some degree of ambiguity in the EFS temperature estimation. We have adopted the Einstein coefficients prescribed by Langhoff et al., (1986), which have been shown to produce more reliable rotational temperatures in the MLT region (Liu et al., 2015; Phillips et al., 2004). On the other hand, the field of view (FoV) of the EFS, K-Lidar, and SABER are very different. Therefore, the assumption that the airglow intensity and temperature field are uniform over all these three FoVs would not essentially be correct, especially in the MLT region, which is very dynamic at all times. Also, She and Lowe (1998) have mentioned that the OH band intensity varies non-linearly with the temperature. Therefore, direct application of a weighting function that mimics the OH VER to obtain weighted Lidar temperature from a Lidar temperature profile may lead to discrepancy of a few K.
4.2. Investigation of OH(6,2) band peak altitude and FWHM variation

It is already mentioned that several studies have reported considerable variations in the peak altitude of the OH band VER. In addition, significant variation in the FWHM of the OH band VER has also been observed previously (Baker & Stair Jr., 1988). It motivates us to investigate what sort of variations are present in the OH(6,2) band peak altitude and FWHM during our study period. We have utilized SABER 1.6 $\mu$m and 2.0 $\mu$m ch. VER data and a model equation to obtain OH(6,2) VER parameters.

4.2.1. Study of OH(6,2) band VER peak altitudes during February-April 2005

Since both the SABER 1.6 $\mu$m and 2.0 $\mu$m ch. do not measure the OH(6,2) band, we have adopted the method suggested by Liu et al., (2015) to derive the OH(6,2) band VER peak altitudes using these two SABER ch. data. The main assumption of this method is that peak altitudes of different vibrational bands of OH emission are equally spaced in altitude, and the higher vibrational levels of OH bands have their peaks at higher altitudes (Von-Savigny et al., 2012; Xu et al., 2012). In this analysis, all the SABER passes available between February 01, 2005 and April 30, 2005 within the area of AO $\pm$ 2.5° latitude-longitude during the nighttime are considered irrespective of the availability of EFS and K-Lidar data. Peak altitudes of the SABER 1.6 $\mu$m and 2.0 $\mu$m VER are considered when there is only one peak within the half maxima of the peak VER. To obtain the seasonal mean peak altitude (SMPA) of the two SABER channels at any particular time, all the peak altitudes available within the ± 30 min interval of that time are averaged. Such SMPAs for the two SABER channels are estimated at 1 hour intervals between 18:00 AST and 30:00 AST. The SMPAs of the two channels of SABER, along with their standard deviations and SMPAs of the OH(6,2) band are shown in Figure 7(a). The occurrence of peak altitudes of the two ch. of SABER within each 1 hour time bin between 18:00 AST and 30:00 AST are shown in Figure 7(b). It can be seen from Figure 7(b) that the occurrences are not uniform in all the time bins and this could cause a bias in the estimated SMPAs of the OH(6,2) band at certain hours. Thus, to obtain the mean seasonal trend (MST) of the OH(6,2) peak altitudes, a polynomial fitting is performed to the SMPAs of the OH(6,2) band and the same is shown in Figure 7(a).
Figure 7: (a) Temporal variation of SMPAs of the SABER 1.6 μm and 2.0 μm VER are shown in blue and green color open circles, respectively. The standard deviations in their mean altitudes are shown as vertical lines of the same color. SMPAs of the OH(6,2) band are represented as red stars, while their MST is shown as a red dotted line. The model-derived SMPAs of the OH(6,2) band are shown in black stars along with their corresponding standard deviations. (b) The occurrence of the peak altitudes of SABER 1.6 μm and 2.0 μm VER within each 1 hour time bin during our study period is depicted here. Only those peak altitudes are considered here that satisfy our criteria (see text for more details).

The peak altitude of the OH(6,2) VER is also obtained by analyzing the OH(6,2) VER profiles derived with the help of Equation 4 adopted from the work of Liu and Swenson (2003).

\[
OH_{VER} = \frac{f_{(6)}[O][O_2](k_6^{O_2}[O_2] + k_6^{N_2}[N_2])}{(260 + 2 \times 10^{-11}[O_2])}
\]

Eq. (4)

where, the coefficients are, \(k_6^{O_2} = 5.96 \times 10^{-34} \times \left(\frac{300}{T}\right)^{2.37}\) and \(k_6^{N_2} = 5.7 \times 10^{-34} \times \left(\frac{300}{T}\right)^{2.62}\).

Here, \(f_{(6)}=0.08\) is the fractional yield of OH* in the level \(v'=6\). The neutral density parameters for Equation 4 are obtained by using the NRLMSISE-00 model where the Ap and F10.7 index have been provided manually. Single Ap and F10.7 indexes pertaining to the date of the evening hours have been used for the whole night. The OH(6,2) peak altitudes are calculated at a one hour interval between 18:00 AST and 30:00 AST on the fifteen nights when EFS and K-Lidar data are
available concurrently. All the peak altitudes available at a particular time are averaged to obtain
the SMPAs at that time. The temporal variation of these SMPAs provides the MST of the OH(6,2)
peak altitude during our study period. These model derived SMPAs are plotted in Figure 7(a),
along with their corresponding standard deviations. Since NRLMSISE-00 is a climatological model,
it does not produce much day-to-day variability in the temporal variation of the OH(6,2) peak
altitudes within a month. Some monthly variabilities are observed in the model derived OH(6,2)
peak altitudes during our study period. However, these monthly variabilities are much smaller in
comparison to the variabilities of the SABER derived SMPAs and have not been further discussed
here.

It can be seen from Figure 7(a) that the OH(6,2) SMPAs obtained from the SABER
observation are smaller than the model-derived values by ~4-6 km during the evening and pre-
midnight hours and by ~2-3 km during the post-midnight and early morning hours. They are only
decreasing during the midnight hours. Further, the model-derived SMPAs exhibit a gradual
depending trend with time, whereas the values obtained from SABER exhibit an increasing trend
until midnight and a decreasing trend after midnight. The most likely reason for these differences
could be the day to day variability caused by the atmospheric waves in the MLT region since the
NRLMSISE-00 model is expected to reproduce the dominant tidal components (Picone et al.,
2002). Takahashi et al. (2005) have reported a similar temporal variation in the OH(6,2) band
peak altitudes from Shigaraki, Japan (35°N, 136°E), as has been obtained by using the SABER data
in this work. They observed that the largest peak altitudes occurred between 22:00 LT and 23:00
LT, which is about an hour earlier in comparison to our SABER observation. Zhao et al. (2005)
studied the temporal trend of the OH(6,2) band peak altitudes from Maui, Hawaii (20.8°N,
156.2°W). They reported a monotonically decreasing trend which is similar to the model results
obtained here, although the slope of the trend is much larger in their study. One potential factor
for different temporal trends at different locations could be the variable latitude and longitude
dependence of the peak altitudes. Also, the solar activity level was different during the study
period of our work and the other two works (F10.7=150 to 270 for Zhao et al. (2005); F10.7=120
to 140 for Takahashi et al. (2005); F10.7=70 to 120 for the present study). Since the background
atmosphere varies with the solar activity level, the wave and tidal influence on the atmosphere
differed during the period of all these three works. However, a detailed study with more data is required to understand the underlying causes of such variation.

4.2.2. Study of OH(6,2) band VER FWHM during February-April 2005

The FWHM of the OH(6,2) VER is studied here with the help of SABER 1.6 μm and 2.0 μm ch.VER and the model OH(6,2) VER with the help of Equation 4. To obtain the seasonal mean FWHM (SMFWHM) of the two channels of SABER, the same methodology of section 4.2.1. is followed, which is applied to derive the SMPAs of these two channels. The exact relation of the OH(6,2) VER FWHM to the SABER 1.6 μm and 2.0 μm VER FWHM is unknown. Therefore, the average of the SMFWHMs obtained from the two channels of SABER is assumed to represent SMFWHMs of the OH(6,2) band VER. A polynomial fitting is performed on the OH(6,2) band SMFWHMs to obtain the MST of the FWHM. The distribution of the occurrence of SABER 1.6 μm and 2.0 μm VER FWHM values in a 1 hr time bin is the same as shown in Figure 7(b). The SMFWHMs of the two channels of SABER along with their standard deviations, SMFWHMs and the MST of FWHM of the SABER derived OH(6,2) band are shown in Figure 8. The MST of the SABER derived OH(6,2) band FWHM exhibit an increasing trend in the evening hours followed by a decreasing trend in the pre-midnight and midnight hours. A peak is observed in the SABER derived OH(6,2) band FWHM MST at ~21:00 AST and after that, it remains ~7km during the post-midnight and early morning hours. The model derived OH(6,2) band SMFWHMs are also shown in Figure 8. They exhibit an increasing trend in the evening hours with a peak ~20:00 AST, and a monotonic decreasing trend after 20:00 AST until the morning hours. Therefore, the SABER and model-derived OH(6,2) SMFWHMs exhibit similar temporal trends before midnight, while their behavior is slightly different after the midnight. However, the magnitude of the model-derived OH(6,2) SMFWHMs is larger than the SABER-derived SMFWHMs by 3-5 km at all hours of the night.
Figure 8: Temporal variation of the SABER 1.6 \( \mu \text{m} \) and 2.0 \( \mu \text{m} \) VER SMFWHMs during February-April 2005 are shown in blue and green color open circles, respectively, along with their corresponding standard deviations. SABER derived SMFWHMs of the OH(6,2) band are represented by red stars, while the MST of the SABER derived OH(6,2) band FWHM is shown by a red dotted line. Model derived SMFWHMs of the OH(6,2) band during our study period are shown with black color stars along with their standard deviations.

4.3. Comparison between EFS and K-Lidar temperatures using a variable weighting function

It is evident from Figure 7(a) and Figure 8 that there are significant temporal variations in the SMPAs and SMFWHMs of the OH (6,2) band. It is quite possible that similar or even larger temporal variabilities could occur in these two parameters on a day-to-day basis. These results also indicate that a single SABER OH VER profile or a single Gaussian function is not the best representation of the OH VER profiles for the whole night. Therefore, we reanalysed the difference between the EFS and K-Lidar temperature by using Gaussian weighting functions which have time-varying peak altitude and FWHM. The peak altitudes and FWHM for the Gaussian are adopted from the SABER derived MST of the peak altitudes and FWHMs of the OH(6,2) band, respectively. The minimum weight factor limit and the selection criteria K-Lidar profiles based on the weight factor is the same as has been described in section 3. The weighted K-Lidar temperatures are then subtracted from the average of EFS temperatures within \( \pm 7.5 \) min of a K-Lidar temperature data. The temperature differences are grouped into 5 K bins in the same way as has been done for Figure 6. We have plotted the occurrence in each of those bins with
respect to their central temperature in Figure 9. A Gaussian fit to the occurrence of the bins in Figure 9 shows that the mean temperature difference between the average EFS and weighted K-Lidar is 8.59 K while the standard deviation is 23.85 K. Also, it is observed from the new analysis that out of all the temperature differences, there are 50.42 %, 64.17 % and 75.83 % points within the temperature difference range of ±10 K, ±15 K and ±20 K, respectively. Compared to the results shown in Figure 6, the mean temperature difference in the new analysis has decreased by ~2 K but the standard deviation has increased slightly. On the other hand, there is a improvement in the percentage of points within the temperature difference range of ±10 K, ±15 K and ±20 K. All these results show that the use of Gaussian functions having time varying peak altitude and FWHM provides a better comparison between EFS and K-Lidar temperatures instead of using a single weighting function of fixed peak altitude and fixed FWHM for the whole night. The mean temporal trend of the OH(6,2) peak altitudes and FWHM could be improved by considering a larger satellite database which will help to understand the solar activity level and seasonal dependence of these parameters in more detail. Also, the time resolution of the seasonal mean values could be further improved with the help of a larger data set. Even though such mean temporal trends may not exactly replicate the actual magnitude of these parameters on some occasions, it is the second best available option that could significantly improve the inter-comparison of altitude-resolved and altitude-integrated measurements.
Figure 9: Difference between EFS and weighted K-Lidar temperatures during February-April 2005. The analysis is performed using MST of OH(6,2) peak altitude and FWHM obtained from the SABER observations. The size of the individual bin is 5 K. The solid red line represents a Gaussian fitting to the occurrence of the bins and parameters of the Gaussian fit are mentioned in the upper right-hand side. The green dotted line represents the Gaussian fitting shown in Figure 6.

4.4. Computation of OH(6,2) band peak altitudes by comparing EFS and K-Lidar temperatures

It has been previously mentioned that the peak altitude of the weighting function is a crucial parameter that controls the weighted K-Lidar temperature. It is possible to match the EFS and weighted K-Lidar temperatures by only varying the peak altitude of the weighting function. Several researchers have used this methodology to obtain an indirect estimate of the OH peak altitude by comparing temperatures from two different ground-based instruments where one provides altitude-resolved measurements, and the other one provides altitude-integrated measurements (Dunker, 2018; Zhao et al., 2005). Typically, a Gaussian function is employed as the weighting function where the FWHM and peak altitude of the Gaussian function are the free parameters. The same methodology is applied here to investigate how much variations in the peak altitude are required to match the EFS and K-Lidar temperatures and, in turn, to have an estimation of the peak altitude of OH(6,2) VER.

In our analysis, the FWHM of the Gaussian function is assumed to be fixed at 6.46 km. This value is the average FWHM of the SABER 1.6 µm VER profiles on the five nights when SABER, EFS, and K-Lidar data are available concurrently. The lower and upper limit of the peak altitudes for the Gaussian function has been determined separately for each K-Lidar temperature profile. This approach is adopted because there are frequent data gaps on the edges of the K-layer. As a result, temperatures are available over a variable range of altitudes for each K-Lidar temperature profile. Since we plan to employ a symmetric Gaussian weighting function at all the peak altitudes with a minimum weighting factor of 0.5, selection of such a varying peak altitude range becomes necessary. The peak of the Gaussian function is varied in steps of 0.1 km between these lower and upper limits. In this analysis, those peak altitudes are not considered where lidar
temperatures are unavailable at any altitudes having weighting factor ≥ 0.8. Differences between the weighted K-Lidar temperature and averaged EFS temperature (i.e., an average of EFS temperatures within ± 7.5 min of a lidar temperature) is tracked while shifting the peak altitude of the Gaussian. The peak altitude of the Gaussian should represent the peak altitude of the OH(6,2) VER where the temperature difference turns out to be zero. On many occasions, the absolute value of the minimum temperature difference turns out to be much larger than zero. Thus, to estimate the OH(6,2) peak altitude with more certainty, only those Gaussian peak altitudes are considered where temperature differences turn out to be ≤ 0.5 K.

Figure 10 shows the probable peak altitudes of OH(6,2) band obtained at different times on March 17, 2005 using this method. Most of the time, temperature differences of ≤ 0.5 K span over a range of altitudes in Figure 10 instead of a single altitude, leading to some ambiguity in determining the actual peak altitudes of the OH(6,2) band. In a recent study, Dunker (2018) has adopted the same method used in this study to estimate the peak altitude of the OH(3,1) band but in that work, both the peak altitudes and FWHM of the Gaussian are treated as free parameters. The results shown in Figure 10 (particularly around 26:00 LT, 27:30 LT and 28:30 LT) match very well with the findings of Dunker (2018) if a single FWHM and temperature differences within ± 0.5 K is considered (see panel c of Figure 2 in Dunker, 2018). Therefore, our analysis supports the conclusion of Dunker (2018) that peak altitudes of OH Meinel band VER could not be obtained unambiguously by only comparing a height resolved and a height integrated measurements.
But, we suggest here that if a MST of the peak altitudes of the OH band of interest is available, then it could be used as a reference to determine the most probable peak altitudes from the range of peak altitudes shown in Figure 10. As a next step, we consider the MST of the peak altitudes of the OH(6,2) band derived from the SABER data during February-April 2005 as the reference for the peak altitudes. Now, only those peak altitudes are selected out of all the probable peak altitudes shown in Figure 10, which are closest to the reference OH(6,2) peak altitude with respect to time. The OH(6,2) peak altitudes selected using this method are plotted with respect to time in Figure 11, along with the reference peak altitudes. It is evident from Figure 11 that the selected peak altitudes of the OH(6,2) band are showing larger variation in comparison to the reference peak altitudes. Since the reference peak altitudes represent average magnitude over a period of three months, it is most likely that the effect of the atmospheric waves in them might have been averaged out to a certain extent. Therefore, this exercise shows that it is possible to get a better estimation of the OH band VER peak altitudes by using the methodology adopted in this work. Even though use of such a reference peak altitude will not be able to provide OH band peak altitudes with 100% certainty, it can help to reduce the ambiguities associated with this methodology.
Figure 11: Temporal variation of the selected OH(6,2) peak altitudes (shown as black stars) from the probable OH(6,2) peak altitudes shown in Figure 10 for the night of March 17, 2005. The reference OH(6,2) peak altitudes derived from SABER data is presented as red open circles.

5. Summary and Conclusion:

In this work, we have discussed in detail the analysis methodology adopted to retrieve rotational temperatures in the MLT region from the AO EFS OH(6,2) Meinel band data. Then, the results are validated by an inter-comparison between the AO EFS and K-Lidar temperatures for the period of February-April 2005. First, a single weighting function is applied on the K-Lidar temperature profiles for the whole night. In this case, either a SABER 1.6 μm VER profile or a Gaussian function having average SABER parameters is considered as the weighting function. After that, the MST of OH(6,2) VER peak altitude and FWHM during the study period is investigated with the help of SABER 1.6 μm and 2.0 μm VER profiles and model equation run by using NRLMSISE-00 inputs. Time-varying weighting functions constructed from the MST of OH(6,2) band peak altitude and FWHM obtained from SABER, are then used to reanalyze the AO EFS and K-Lidar temperature differences. Finally, peak altitudes of the OH(6,2) VER are estimated.
from the inter-comparison of AO EFS and K-Lidar temperatures. Drawbacks of this method and a way to improve it is also discussed.

The main findings of this study are noted down below.

1) The mean temperature difference between the AO EFS and K-Lidar is comparable with the results reported in the previous studies from different locations. When using a single weighting function on the K-Lidar temperature profiles for the whole night, the mean temperature difference between the EFS and K-Lidar is found to be 10.49 K with a standard deviation of 20.8 K.

2) The MST of the OH(6,2) band peak altitudes and FWHMs estimated by using the SABER 1.6 μm and 2.0 μm VER profiles show that there are considerable temporal variabilities in these two parameters during the study period. It is also found that there are significant discrepancies in the magnitude of these two parameters obtained from SABER observations and model equation run by using NRLMSISE-00 inputs.

3) Inter-comparison between altitude-resolved and altitude-integrated measurements improve while using time varying weighting functions instead of a weighting function having fixed peak altitude and fixed FWHM for the whole night. The mean temperature difference between the AO EFS and K-Lidar turns out to be 8.59 K with a standard deviation of 23.85 K when weighting functions constructed by using the MST of the OH(6,2) peak altitudes and FWHMs obtained from SABER is considered. Further, the occurrence within the temperature difference of ±10 K and ±15 K increase considerably in this analysis in comparison to the previous analysis.

4) It is not possible to accurately estimate the peak altitudes of the OH Meinel band VER from the inter-comparison of EFS and K-Lidar temperatures since there are two free parameters involved in this methodology. But, our study shows that if a MST of OH(6,2) peak altitudes obtained from observation (such as SABER) is available then, it could help to reduce the ambiguities associated with this method.
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Data Availability Statement:
The AO EFS raw data files used in this work and rotational temperature retrieved from them have been uploaded to the open source Zenedo repository and can be accessed from https://doi.org/10.5281/zenodo.7301836. The AO K-Lidar data can be accessed through the AO madrigal data from http://www.naic.edu/madrigal. Boston University all sky imager data can be accessed from http://sirius.bu.edu/dataview/. The SABER data can be accessed from http://saber.gats-inc.com/browse_data.php#. NRLMSISE-00 model outputs are available from https://ccmc.gsfc.nasa.gov/modelweb/models/nrlmsise00.php. Ap and F10.7 indexes are available from https://omniweb.gsfc.nasa.gov/form/dx1.html.

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