Survey of Atmospheric Remote Sensing Techniques Leveraging Information in Passive IR Spectral Radiance Measurements

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Abstract— **Several techniques exist for using ground-based measurements of IR radiance to characterize the atmosphere, especially the boundary layer. These methodologies, in contrast to space based observations or active probing techniques, offer a safe, continuous measure of atmospheric parameters at a single location that are highly accurate at altitudes very near the ground (<500m) and can be obtained without the need for human monitoring.**

Herein we demonstrate the use of data from a BOMEM MR140 spectroradiometer for estimation of temperature and water vapor profiles. Temperature profiles are calculated using a simple process based on temperature invariant spectral points of downwelling mid-wave IR (MWIR) radiance; the basic algorithm was reported in 2000. Results reported here include an update to the fit algorithm as well as qualitative comparisons to field test data obtained in 1999 where an active Raman LIDAR and a balloonsonde measured the vertical temperature profile and vertical water vapor profile during an MR data collection.

Once the vertical temperature profile is known, the vertical water vapor profile can be calculated using the same radiometric data. Water vapor profiles are calculated in much the same way as temperature profiles, using a simple inversion process, except different altitude points are based on temperature dependent absorption lines instead of temperature invariant points.

Keywords-remote atmospheric sensing, temperature profile, water vapor profile, spectroradiometery

I. INTRODUCTION

Passive remote sensing techniques offer a relatively new approach to measuring species concentration and atmospheric temperature [1,2]. Such sensors are reliable, have a moderate cost, have no radiation hazard and feature good performance. Temperature and water vapor profiles are important for understanding the dynamics of the atmospheric boundary layer [3]. To obtain the best results for models of these processes, high fidelity measurements of low altitude temperature and humidity as a function of altitude are required. However, current measurement techniques for obtaining these quantities have severe limitations, such as cost, safety or low spatial resolution that could be mitigated by using a ground based passive radiometric measurement technique. In this paper, algorithms for determining temperature and water vapor profiles, based on measurements of the downwelling radiance of the atmosphere are presented. The algorithms are based upon radiometric data collected over a 5 year period between 1999 and 2004 using a BOMEM MR-140 dual channel spectroradiometer.

II. TEMPERATURE PROFILING

An algorithm for using downwelling radiance measurements to determine the temperature profile of the atmosphere at lower altitudes ($z < 3$km) was previously reported [4]. Figure 1 illustrates the geometry of a downwelling measurement. The algorithm is based on using measured radiance at temperature invariant spectral lines of CO_2 and N_2O within the mid-wave IR region to invert the radiation transfer equation. By using absorption lines of gases with known mixing ratios and varying absorbance strength, one can infer the temperature of the atmosphere at different discrete altitudes. A continuous profile is then completed by calculating a piecewise linear fit between the different altitude points. This low spatial resolution profile is intended as an initial estimate to begin iterative procedures using the temperature dependent spectral points.

To check the fidelity of this model, results from a downwelling measurement made in Philadelphia were compared to balloonsonde data taken at the same time. The two data sets were not in sharp agreement at low altitudes due to the low spatial resolution of the balloonsonde data. Resolution issues are considered symptomatic of the smoothing caused by the balloon as it rises. Figure 2 visually confirms this conclusion by comparing balloonsonde data with Raman LIDAR data taken at the same location and time. Data from the LIDAR show very complex structure in the temperature profile where the balloonsonde data show little to no change. Further, the inversion near 100m is completely obscured. For a higher fidelity comparison, data from a Raman LIDAR are considered. Figure 3 shows the temperature profile generated by the LIDAR, plotted on the same axis as the downwelling based profile. The agreement between the two is very good at both the low and high altitudes. One notable problem is the missing structure at 2800m detected by the LIDAR but not the downwell. With increased spatial resolution, that feature may have been identified by the passive method, but the resolution is currently fixed by the number of temperature invariant points in the mid-wave spectrum. In the future, temperature sensitive points will be incorporated to increase the number of available fit points.

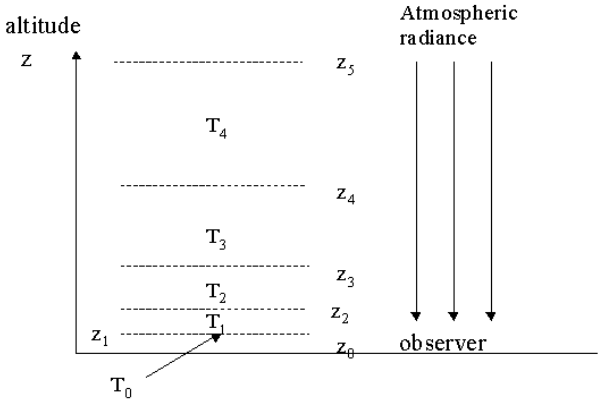

Figure 1: Down-welling radiance in a vertically stratified 4-layer medium with each layer at a path averaged temperature of T_i.

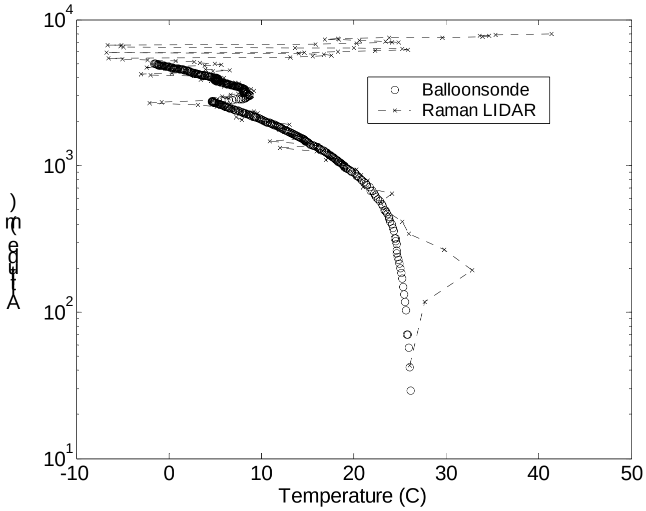

Figure 2: Comparison of nighttime balloonsonde and LIDAR generated temperature profiles.

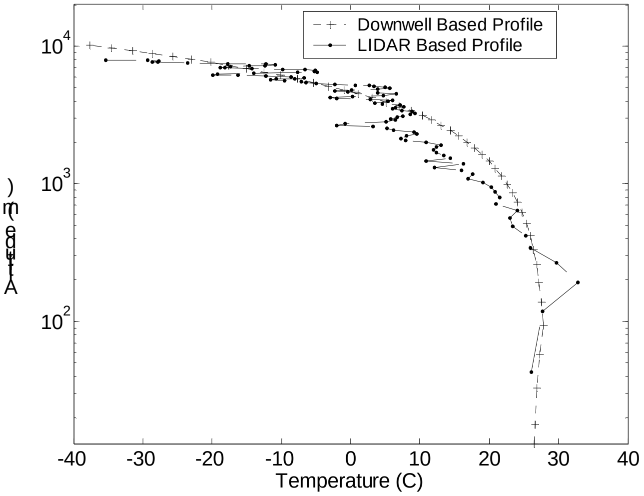

Figure 3: Comparison of nighttime downwell measurement based profile and Raman LIDAR generated profile.

III. WATER VAPOR PROFILING

Determination of vertical water vapor profile in the atmosphere is of great importance in many fields of atmospheric study [3]. Passive spectroradiometers typically measure absorber amount (concentration times path length) of an atmospheric species. Thus knowledge of the spatial structure can not be obtained directly. Range resolved concentration requires additional information about the absorbing species.

A new and computationally fast approach that yields range resolved profiles of an absorbing species within the lower boundary layer of the atmosphere is described below. Assuming a single atmospheric layer, a measurement of the downwelling path radiance leads to the layer transmittance, τ, according to the formula,

$$\tau(\nu,T)=\exp(-C_{abs}(\nu,T)u)=1-\frac{L_{measured}(\nu)}{L_{bb}(\nu,T)} \qquad (1)$$

where ν is the frequency in wave numbers, T is the temperature in Kelvin, C_{abs} is the absorption cross section, u is the absorber amount for the absorbing species, $L_{measured}$ is the measured down welling path radiance and L_{bb} is the blackbody radiance. The HITRAN database is used to compute the absorption cross section of the absorbing species, water vapor [5]. The absorption cross section varies with wave number. Thus, we expect strong absorption features will limit the optical path (layer thickness) to short distances and weak absorption features will allow longer paths to greater altitudes. The key assumption in this inversion algorithm is that the layer thickness is inversely proportional to the absorption cross section, as given by

$$\Delta z(\nu) = \frac{x_{WV}}{C_{abs}(\nu, T(\frac{\Delta z_0}{2} + z_0))} \tag{2}$$

where x_{wv} is a proportionality constant and Δz_0 is defined as Eq. 2 solved using a representative altitude independent temperature. Solving Eq. 1 for the absorber amount and dividing by the layer thickness leads to the absorbing species concentration in units of number density or partial pressure. Note that the layer thickness is spectrally dependent. This means that a range of spectral points covering different emission (absorption) levels is desired.

The above scheme is applied to water vapor profiling in the atmosphere. An initial value for the constant x_{WV} can be determined by using a strong absorption feature and a ground based hygrometer. This usually is close to the value that connects the lowest altitude data point for the partial pressure of water vapor to the hygrometer measurement. A mid-wave infrared downwelling radiance measurement is used for $L_{measured}$ in the spectral region of interest, 1902 to 1979 cm^{-1}. Local water vapor emission features of varying strength dominate this part of the spectrum. Results are plotted in Figure 4 along with balloonsonde and Raman LIDAR data. Good agreement between the LIDAR and the spectroradiometers is demonstrated and the two instruments produce data sets that are complementary. The balloonsonde seems to have a problem measuring water vapor in the lower region of the atmosphere because the response time of the hygrometer is too slow for the rate of ascent of the balloon.

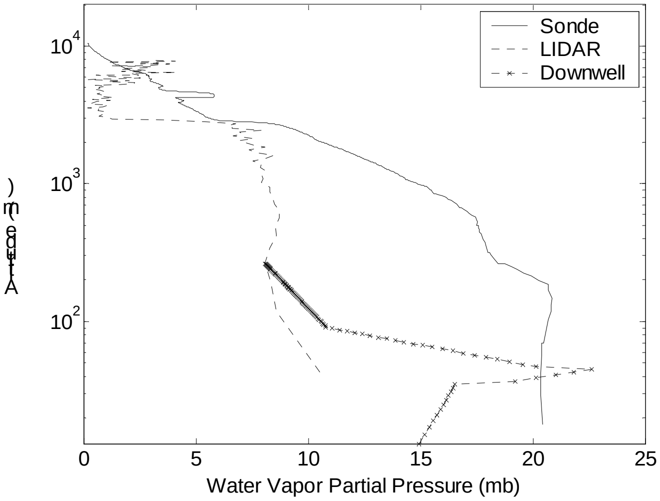

Figure 4: Comparison of 3 different measurement techniques to obtain the vertical water vapor partial pressure of the nighttime atmosphere.

IV. INSTURMENT SELECTION

It is important to realize that no one method is appropriate to calculate temperature and water vapor profiles at all altitudes under all conditions. Table 1 shows the parameters for each of the instruments whose data products are presented here. Depending on time resolution requirements, altitudes of interest, spatial resolution requirements, etc., each of these devices have their place. The distinct advantage of using the passive data to generate profiles at lower altitudes is that a single measurement made every 2.5 minutes generates both a temperature and water vapor profile that is highly resolved at altitudes less than 300m with little to no noticeable processing time.

Table 1: Instrumentation comparison.

Instrument	Time Resolution	Altitudes	Spatial Resolution
Balloonsonde	2 hours	Surface to 10 km	30m (z < 1km) 10m (z >1km)
Raman LIDAR	1 min (water vapor) 30 min (temperature)	43m to 8 km	75 m
Spectroradiometer	2.5 minutes	Surface to 500m (water vapor) Surface to 3km (temperature)	10 m (z < 30 m) 200 m (z >100m)

V. CONCLUSION

Through the comparison of data collected using a Raman LIDAR, it has been shown that passive measurements of the downwelling radiance of the atmosphere can contain large amounts of information about the temperature and water vapor profiles near the surface of the Earth. The advantage of using this technique lies in both the complementary nature of the data to high altitude LIDAR measurements and the safety and ease of using an instrument that can be fully automated and left to run autonomously. Automation also allows for long time series of data to be taken, not only during different times of day to study water evaporation cycles, but also over the course of months to study seasonal variations in the atmosphere.

The next step in refining these algorithms for more detailed analysis is to add more spatial resolution to the temperature profiles by using temperature dependent lines. Higher fidelity in the temperature profile will then lead to better water vapor profiles with smaller discrete layers capable of showing “faster” variations in the atmosphere. Beyond extending the resolution of the models, error analysis should be conducted to find the effects of instrument noise and to determine wave number resolution required to provide useful profiles.

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