CWV.2

Tropospheric Water Vapor Concentrations Measured on a Penn State/ARL Lidar

S. C. McKinley and C. R. Philbrick

Department of Electrical Engineering
Penn State University, State College, Pennsylvania 16802

The use of lidar for measuring water vapor concentration has developed into the most useful technique for studying water vapor distribution. A brief analysis has been done for results obtained over an altitude range of a few hundred meters to 5 km. The theory of Raman scattering is briefly reviewed as background to a discussion of the optical design. The contribution of water vapor to index of refraction is examined.

Researchers have been demonstrating the use of lasers to make measurements of water vapor content in the atmosphere since the 1960's. Some of the first measurements were made by Melfi et al. (1969) and Cooney (1970). These researchers pioneered the technique of using Raman scattering which is described later in this report. Their results showed good agreement between their lidar derived water vapor profiles and those taken by radiosondes up to an altitude of around 2 km. Melfi (1989) has more recently shown how newer and more advanced equipment allows greater temporal and spatial resolution. Penn State/ARL's LADIMAS (Latitudinal Distribution of Middle Atmosphere Structure) campaign and subsequent equipment upgrades have clearly demonstrated the capability of the LAMP lidar instrument to obtain accurate, high resolution measurements of water vapor below 5 km. This allows frequent measurement of water vapor profiles for meteorological purposes.

The first significant results from the ARL/PSU lidar were generated during the LADIMAS campaign which took place aboard the German research ship *Polarstern*, while it traveled from Norway to Antarctica during the last three months of 1991. The measurements of the LADIMAS campaign were based on using several data channels, each having a filter to select a particular frequency of the scattered light collected by the telescopes. The 532 nm laser radiation is scattered by both the molecular and particulate constituents of the atmosphere. A percentage of light scattered by each molecular species is re-emitted at a lower (Stokes) or at a higher (anti-Stokes) frequency, in a process called Raman shifted scattering. The magnitude of the frequency shift depends upon the vibrational energy states of the molecule and therefore the signal is specific to the species selected. The LAMP lidar data collection system measures the signals gathered in up to 8 channels by photomultiplier tubes (PMT's). Photon counting techniques are used to detect the photons which are scattered by N_2 and H_2O, measured at 607 nm and 660 nm wavelengths in each successive 75 m range interval of the atmospheric path. Typical integration periods of 30 minutes are used to obtain profiles. The concentration of H_2O for any given layer is given by the following equation,

$$H_2O\ (\mathrm{g/kg}) = K \times \frac{660\ \mathrm{nm\ Signal}\ (H_2O)}{607\ \mathrm{nm\ Signal}\ (N_2)}$$

where, water vapor is measured in gm per kg of atmosphere and K is a constant described below.

The constant factor K takes into account the difference in the backscattering cross-sections of H_2O and N_2, correction for the fact that N_2 makes up 78% of the atmosphere, the difference in transmission attenuation between 607 nm and 660 nm, and instrument sensitivity differences in the LADIMAS system in collecting photons at 607 nm and 660 nm. The transmission difference between the 660 and 607 nm wavelengths is constant for the molecular attenuation but may vary slightly in the aerosol and cloud layers present. Part of the current research activity is detetermining the possible error and corrections based upon the 2-color backscatter (355 and 532 nm). The instrument measurement constant, K, is found by correlating data from the lidar with weather balloon data. Due to system modifications during the sea voyage, the value of K used while processing the raw data occasionally needed to be updated in order to obtain agreement between balloon and lidar. When

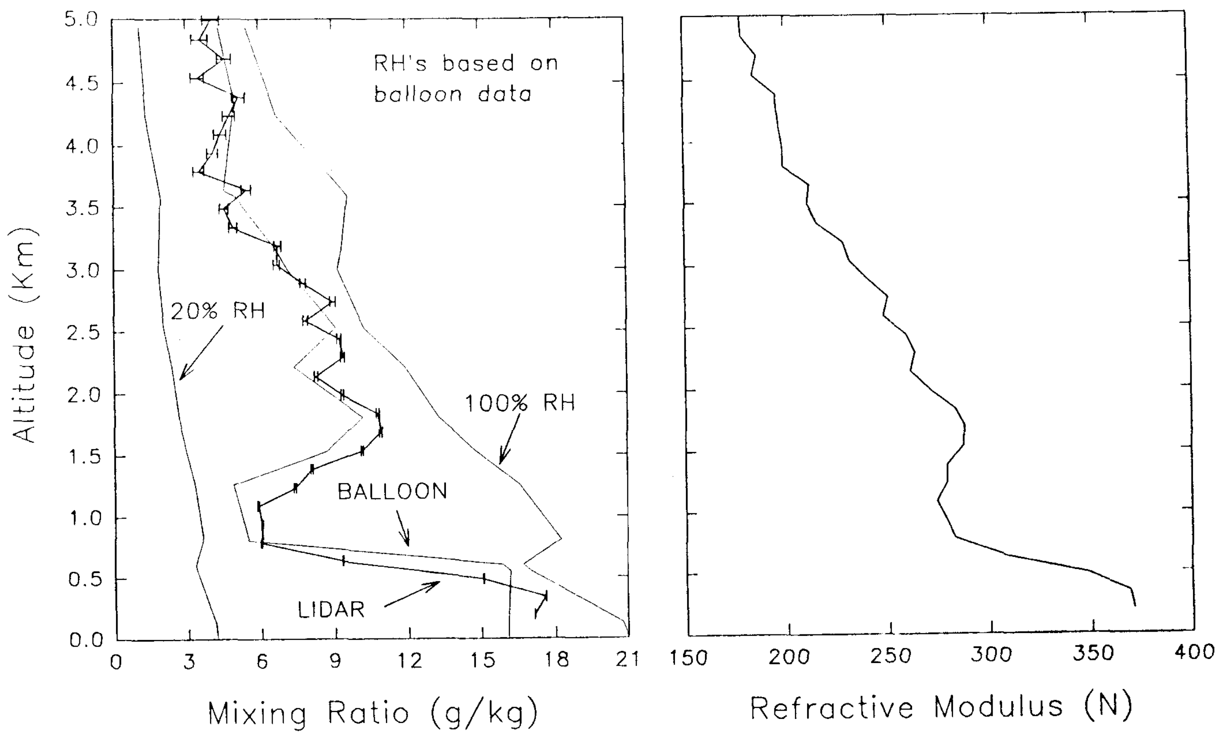

Figure 1 - Water vapor and refractivity graphs for a 30 minute lidar run starting on 11-26-91 02:38 UT. The balloon was launched on 11-26-91 03:00 UT.

instrument system conditions are constant, the balloon data comparisons will be used to serve to serve as a routine check and validation, perhaps on a monthly basis.

Figure 1 shows the close agreement obtained between lidar and weather balloon measurements While Figure 1 shows data going down to 200 meter, the vast majority of the data runs aboard the POLARSTERN were limited below 1 km due to the saturation of the N_2 channel below about 1 km. This fact was discovered when the data analysis was performed on the raw data and can be avoided by several approaches now in use. Figure 1 also shows the statistical error bars, one standard deviation, calculated for each altitude increment, based on Poisson statistics (Measures, 1984).

Figure 1 also shows a graph of atmospheric refractive modulus on the right side. This particular date was selected due to a large inversion in the water vapor concentration profile centered around 1 km. An easier way to deal with atmospheric refractivity is the use of a parameter called the refractive modulus defined,

$$N = (n-1) \times 10^6 ,$$

where n is the index of refraction of air.

The equation relating the modulus of refractivity to the observable physical parameters is,

$$N = \frac{77.6 \times P}{T_K} + \frac{373000 \times P_{WV}}{(T_K)^2} ,$$

where,

P is pressure in millibars
P_{WV} is the partial pressure of water
T_K is temperature in degrees Kelvin.

Differences in the refractivity of the troposphere are due primarily to changes in water vapor concentration with lesser contributions due to changes in density, which can alternatively described using the temperature and pressure measurements. When modifications are made to the instrument to allow observations down to ground level, refractivity measurements can be derived for the full profile.

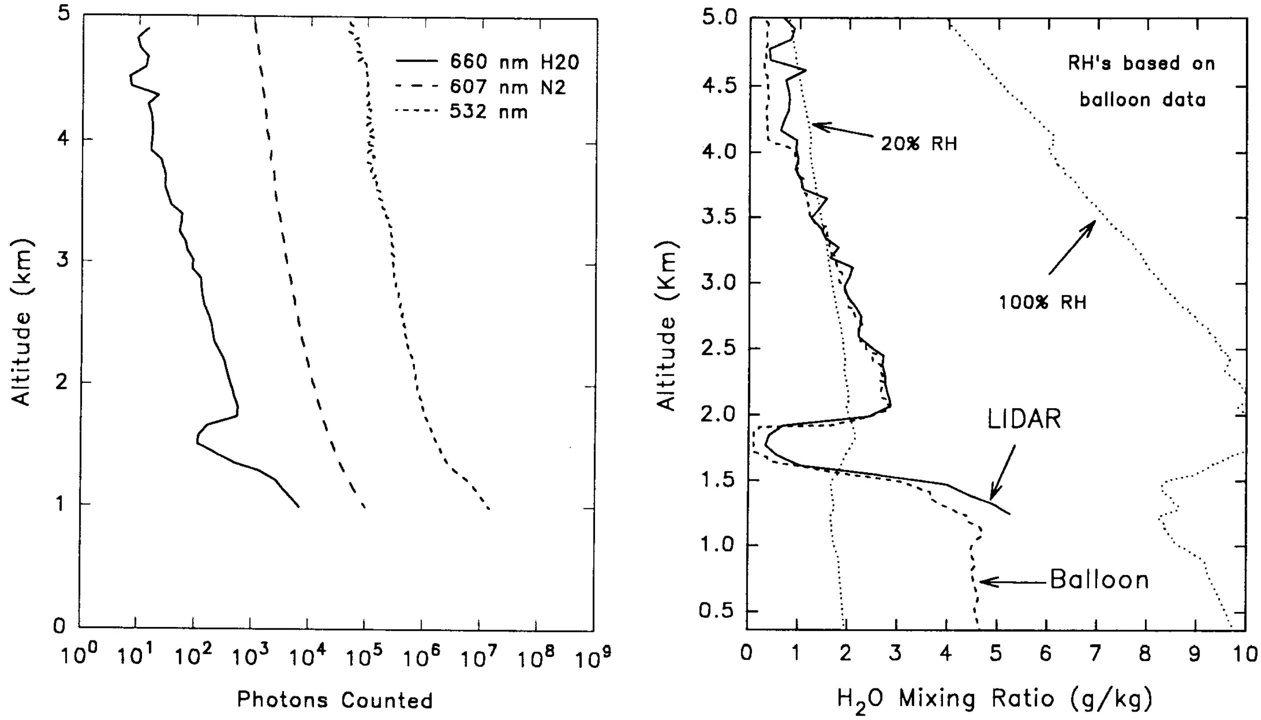

Figure 2 - Raw and processed data for 30 minute lidar run starting on 10-08-92 at 02:03 UT. Balloon launch was on 10-08-92 at 02:10 UT.

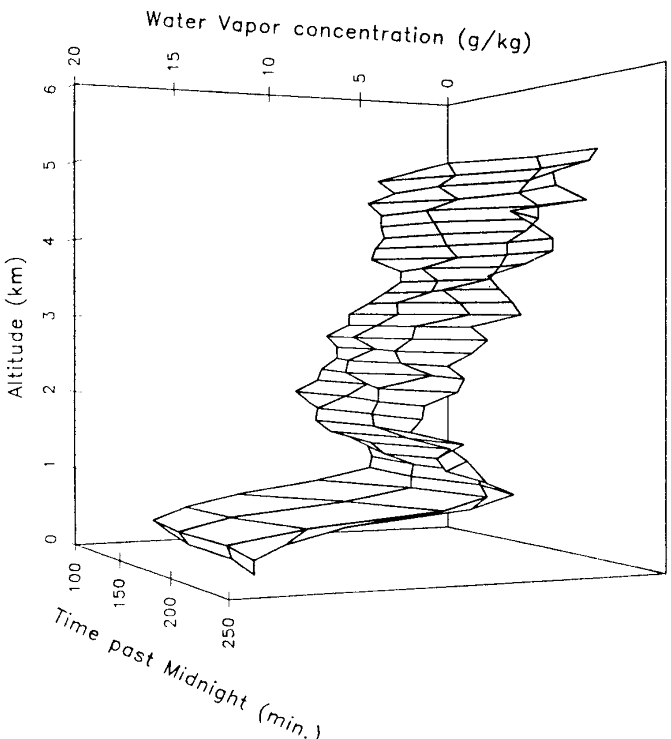

Figure 3 - A three-dimensional plot of 4 consecutive lidar runs taken shortly after midnight (UT) on 11-26-92 aboard the Polarstern near the equator.

Another interesting feature is evident in Figure 2. On October 10, 1992 both balloon and Lidar data were taken at roughly the same time. A very dry layer of air was observed at about 1.5 km. Both the balloon and the lidar were in very close agreement as evidenced by the graph. This gives an indication of the accuracy obtainable with lidar measurements having a resolution of 75 m.

Figure 3 gives a good indication of the gross features of change in water vapor concentrations over time. The data were taken during the LADIMAS campaign at night during the course of two hours while the Polarstern was near the equator. Temporal studies in the change in water vapor can easily be obtained with a lidar without the need for the launching of a sequence of balloons.

Water vapor measurement is but one use of lidar. Currently Penn State is developing temperature measurements, cloud mapping and minor species measurements based on lidar techniques to better study atmospheric and meteorological topics. The data results discussed in this paper show the high degree of correlation obtained between weather balloon and lidar which shows the practical benefits of using lidar for accurate water vapor measurements.

ACKNOWLEDGEMENTS

The authors would like to acknowledge ARL, NSF CEDAR Program, SPAWAR PMW-165 Navy Environmental Systems Program Office, PSU College of Engineering and the Alfred Wegener Institute for Polar and Marine Research for their sponsorship and support for the LADIMAS program from which the data for this paper was obtained.

REFERENCES

Cooney, J.A., "Comparisons of Water Vapor Profiles Obtained by Radiosonde and Laser Backscatter," *J. Appl. Meteor.*, **9**, 182-184, 1970

Measures, R. M., *Laser Remote Sensing Fundamentals and Applications*, Krieger, Malabar Florida, 1992.

Melfi, S.H., J.D. Lawerence Jr., and M.P. McCormick, "Observation of Raman Scattering by Water Vapor in the Atmosphere", *Appl. Phys. Lett.* **15**, 295-297, 1969.

Melfi, S.H., D. Whiteman, and R. Ferrarre, "Observations of Atmospheric Fronts Using Ramam LIDAR Moisture Measurements," *J. Appl. Met.* **28**, 789-806, 1989.