

A New Raman Water Vapor Lidar Calibration Technique and Measurements in the Vicinity of Hurricane Bonnie

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The NASA/Goddard Space Flight Center Scanning Raman Lidar has made measurements of water vapor and aerosols for almost ten years. Calibration of the water vapor data has typically been performed by comparison with another water vapor sensor such as radiosondes. We present a new method for water vapor calibration that only requires low clouds, and surface pressure and temperature measurements. A sensitivity study was performed and the cloud base algorithm agrees with the radiosonde calibration to within 10-15%. Knowledge of the true atmospheric lapse rate is required to obtain more accurate cloud base temperatures. Analysis of water vapor and aerosol measurements made in the vicinity of Hurricane Bonnie are discussed.

1. Introduction

Water vapor is the most important greenhouse gas in the Earth's atmosphere. Accurate long-term measurements of water vapor are desired to understand the feedback processes of global warming. The NASA/Goddard Space Flight Center Scanning Raman Lidar (SRL) has been measuring profiles of water vapor for nearly a decade.

Calibrating the SRL water vapor data has frequently been done using an ensemble of radiosonde data (Ferrare *et al.*, 1995). Raman lidars have also been calibrated based on total precipitable water vapor measurements made by a microwave radiometer (Turner *et al.*, 2000). As an alternative to the technique of calibrating a Raman water vapor lidar with respect to other water vapor instrumentation, we present a new method for calibrating the Raman water vapor data, which uses cloud base as determined by the SRL and surface based measurements. Other than the lidar data, only surface based measurements are used as input to the algorithm. Measurements of water vapor and aerosols in the vicinity of hurricane Bonnie will be presented using the new calibration.

2. System Description

Since only nighttime data are presented here, a brief description of the nighttime system follows. Complete system details have recently been published (Whiteman and Melfi, 1999).

The nighttime measurement system uses a XeF excimer laser to transmit light at 351 nm. The system operates at 400 Hz with 30-60 mJ per pulse for average output of 12-24 W in the far field. A 0.76 m, f/5.2, variable field-of-view Dall-Kirkham telescope gathers backscattering from the laser return and the vibrational Raman-shifted returns from O₂ (371.5 nm), N₂ (382.5 nm), and water vapor (402.8 nm). The telescope is aligned with an elliptical flat mirror (1.2 m x 0.8 m) to enable horizon-to-horizon scanning. Beam splitters separate the return beam into low- and high-sensitivity channels for each wavelength to extend the range of the measurements. The data are typically saved in the form of 1-minute contiguous files with an altitude resolution of 75 m.

The low- and high-sensitivity channels for each wavelength are merged over a range where both channels are giving good data. To obtain the aerosol scattering ratio, the ratio of the merged aerosol (elastic return) and nitrogen profiles is first

corrected for spectral differential transmission through the atmosphere (Whiteman *et al.*, 1992). Following this, the ratio is normalized to unity in a cloud-free region of the atmosphere between 6-10 km. The ratio of the water vapor and nitrogen signals must also be corrected for differential transmission before obtaining the water vapor mixing ratio calibration constant. That procedure will now be considered.

3. Calibration During CAMEX-3

In August and September 1998, the SRL was on site at Andros Island, Bahamas, as part of the validation/calibration ground-site for the third Convention and Moisture Experiment (CAMEX-3). The intent of CAMEX-3 was to acquire an extensive data set in and around hurricanes to improve hurricane tracking and intensification modeling. While at Andros Island, several hurricanes passed nearby influencing the SRL measurements of water vapor.

Several methods have been used to calibrate the SRL water vapor profiles, such as from first principles (Sherlock *et al.*, 1999) and by comparison with the water vapor mixing ratio or precipitable water vapor measurements from other instruments (Turner *et al.*, 2000).

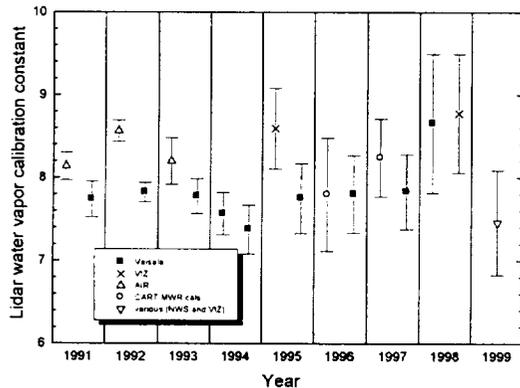


Figure 1 The SRL calibration constant using various radiosondes from 1991-1999.

Because of wide availability and relative ease of use, radiosondes are often used to provide this calibration (Ferrare *et al.*, 1995). To avoid errors from day-to-day variability, faulty data, etc., an ensemble of coincident lidar-radiosonde comparisons are used to obtain the calibration constant. The SRL calibration constant with respect to radiosondes has been tracked over the years and, as can be seen in figure 1, this constant has been relatively stable over the past nine years. Note that the calibration due to Vaisala radiosondes has changed by only 6% peak-to-peak from 1991-1997. Thus, despite the variations that can exist from batch to batch among radiosondes, it seems

apparent from this figure that with a sufficiently large number of radiosondes, a stable constant can be obtained. There were several system modifications between 1997 and 1998 (see Cadrola *et al.*, 1999) which could account for the approximately 15% increase in calibration constant in 1998.

Nonetheless, a technique for calibrating the water vapor Raman lidar which does not rely on the measurements of another sensor is an attractive objective. We present below a technique that uses only surface based measurements of pressure and temperature.

4. Calibration Using Clouds

Computing a lidar calibration with clouds, requires a measure of the water vapor mixing ratio at the base of the cloud. This can be obtained if one knows the pressure and temperature at cloud base. The pressure at cloud base can be derived from ground measurements using the hypsometric equation. Likewise, the cloud base temperature can be derived from ground measurements using a dry adiabatic lapse rate (9.8° C/km). Since cloud base is defined as the point where the air is saturated, the derived cloud base temperature is converted into water vapor mixing ratio using the Clausius-Clapeyron equation.

For a sensitivity analysis, a range of temperatures was used for the Clausius-Clapeyron equation since it is nonlinear. At 16° C, $\pm 1^{\circ}$ resulted in ± 1.2 hPa vapor pressure, which amounts to about ± 0.9 g/kg over the pressures used (850-930 hPa). At 23° C, $\pm 1^{\circ}$ resulted in ± 1.7 hPa vapor pressure, which amounts to ± 1.2 g/kg over the same pressures. The sensitivity of converting the vapor pressures to g/kg was 0.2 g/kg for pressure changes of ± 10 hPa. These results indicate that the technique is more sensitive to errors in temperature than in pressure.

Cloud base was obtained from the peak in the low aerosol data in the first two kilometers (Eberhard, 1986). In cases where a double peak was found, then the lower peak was taken as cloud base. Data were screened for rain or virga occurrences, for the technique is not applicable in such conditions.

The 10 m radiosonde data were used to test the sensitivity of this method. Only radiosondes through or near clouds and lidar data within ± 10 minutes of radiosonde launch time were used for this study. To maintain the validity of the well mixed boundary layer assumption, only data with cloud base at or below 1.05 km were utilized. The difference between the derived and radiosonde pressures at cloud base was 9.43 ± 0.87 hPa and the difference in the temperatures at cloud base was $-2.05 \pm 1.33^{\circ}$ C. This led to a difference in the water vapor mixing ratios of -1.49 ± 1.00 g/kg.

The true value of this algorithm is that one only needs surface measurements of pressure and temperature to utilize it. Using this new cloud-base calibration technique, we obtain calibration values within 10-15% of the calibration value using radiosonde comparisons. This large difference in calibrations is due to the difference in cloud base temperatures. As mentioned above, using the dry adiabatic lapse rate gave a cloud base temperature difference of 2° C, which could lead to a difference in the mixing ratios of 2 g/kg. For water vapor mixing ratios at cloud base in a subtropical air mass (approx. 13-20 g/kg), 2 g/kg amounts to a 10-15% difference.

Knowledge of the true atmospheric lapse rate is required to utilize this cloud calibration algorithm. The radiosonde data show a lapse rate of 7-7.5° C/km, significantly different from dry adiabatic. The difference in lapse rates could be due to the high relative humidities in the subtropical air at Andros. Lapse rates in warm humid air masses could be as low as 4° C/km (Holton 1992, p. 290).

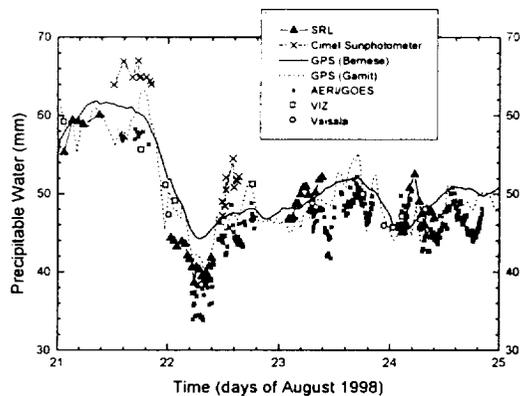


Figure 2. A comparison of precipitable water vapor for the period of Aug. 21-24, 1998, before and during the passage of Hurricane Bonnie.

Upon derivation of the lidar calibration constant, the data are calibrated and can then be analyzed meteorologically. A sample analysis is presented in the next section.

5. Hurricane Bonnie Passage

While the SRL was deployed at Andros Island, Bahamas during CAMEX-3, several hurricanes, including Bonnie, influenced the weather on Andros. Hurricane Bonnie's closest approach to Andros Island occurred on August 24, 1998 at 2300 UTC. Fig. 2 is a precipitable water vapor (PWV) comparison for Aug 21-24 for various instruments at Andros Island, including Vaisala and VIZ radiosondes, two methods of PWV computation from GPS (Bernese and Gamit), Cimel sunphotometer, AERI/GOES (Atmospheric

Emitted Radiance Instrument, combined with GOES profiles), and the SRL. By computing the SRL PWV in layers (0-1, 1-2, 2-3, 3-4, 4-5 and 5-8 km), it can be shown that the PWV in the lower 2 kms did not change much. Most of the drying occurred in the 3-5 km region of the middle troposphere. This drying would be due to hurricane outflow and subsequent subsidence.

Another feature of hurricanes that was measured by the SRL was cirrus cloud outflow. The thin dark band starting at 0500 above the thick dark band in figure 3, is cirrus cloud outflow from Hurricane Bonnie. These cirrus outflow clouds were at altitudes as high as 16-17 km. This altitude was higher than non-hurricane cirrus clouds that were measured before and after hurricane passage. Radiosonde temperatures show the height of the tropopause increasing as the hurricane approaches, probably due to the deep convection near the eye. Closer to the eye, the clouds would probably be higher leading to troposphere-stratosphere exchange.

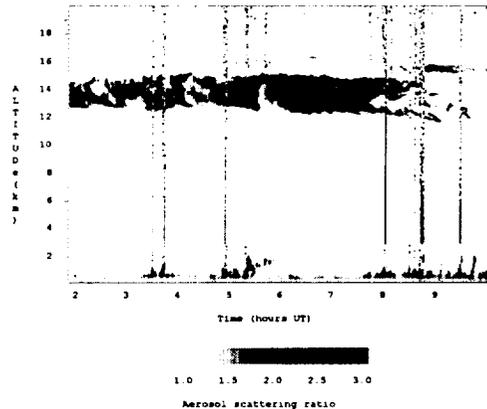


Figure 3. Image of aerosol scattering ratio from 8/23/98 at Andros Island. The thin band of cirrus above the dark band, starting at 0500 UTC is hurricane outflow.

6. Conclusions

We have presented here a method for lidar water vapor calibration that uses only ground temperature and pressure as an alternative to calibration with respect to other water vapor sensors. This method is more sensitive to a proper derivation of cloud base temperature than to cloud base pressure. The SRL calibration obtained using the cloud base algorithm was within 10-15% of the calibration obtained from radiosondes. Knowledge of the true atmospheric lapse rate would improve the cloud base temperature derivation.

We also discussed measurements in the vicinity of Hurricane Bonnie. These measurements show mid-tropospheric drying due to outflow subsidence and cirrus clouds that are at the level of

the tropopause due to the deep convection of the hurricane.

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