Raman Lidar Capability to Measure Tropospheric Properties

C. Russell Philbrick
Penn State University
Department of Electrical Engineering and
Applied Research Laboratory
University Park PA 16802
crp3@psu.edu

ABSTRACT

The Lidar Atmospheric Profile Sensor (LAPS) instrument is the fifth in a series of lidar instruments leading to a first operational prototype for obtaining meteorological profiles in the lower atmosphere. It was prepared and tested to determine its capability to provide automated shipboard operation for atmospheric properties under a wide range of meteorological conditions. The instrument measures the water vapor profile based on the vibrational Raman scattering and the temperature profile based on the rotational Raman scattering. Profiles of the Raman signals are obtained each minute with a vertical resolution of 75 meters from the surface to a user selected altitude. The measured 1 minute profiles are integrated for user selected intervals to simultaneously determine the real time atmospheric profiles for specific humidity, temperature, optical extinction and ozone. Daytime measurements of water vapor, extinction and ozone are made using the "solar blind" ultraviolet signals. The instrument includes a safety radar which detects aircraft as they approach and automatically shuts down the beam. The weather sealed instrument has been designed to include features such as real time data display/transfer, environment control, and performance self-tests to control many functions. Tests have proven the qualities of ruggedness, reliability and general performance of the LAPS lidar system.

RAMAN LIDAR TECHNIQUES

Raman scattering provides an important signal because it is unique to specific molecules. It is most useful because the vibrational Raman scattering provides distinct wavelength shifts for vibrational energy states of the different molecules and the rotational Raman scattering provides a signal with a wavelength dependence corresponding to atmospheric temperature. The ratio of Raman back scatter signals from the molecules of the water vapor at 660 nm and 294 nm from the 2^{nd} (532 nm) and 4^{th} (266 nm) harmonics of Nd:YAG laser and molecular nitrogen (607 nm and 284 nm) are at wavelengths that are widely separated from the exciting laser radiation and can be easily isolated for measurement using modern filter technology. The measurements are made using sensitive photon counting detectors. The ratios of rotational Raman signals at 528 nm and 530 nm provide a measurement that is sensitive to atmospheric temperature. Based upon accomplishments by several groups, we now have the capability for reliably profiling most of the important properties of the atmosphere with lidar [Ref 1 - 17]. In order to push the lidar measurement capability into the daylight conditions, the "solar blind" region of the spectrum between 260 and 300 nm has been used. Night time measurements are made using the 660/607 (H_2O/N_2) signal ratio from the doubled Nd:YAG laser radiation at 532 nm. Daylight measurements are obtained using the 294/284 (H_2O/N_2) ratio from the quadruple Nd:YAG laser radiation at 266 nm, where a small correction for the tropospheric ozone must be applied. That correction can be obtained from the ratio of the O_2/N_2 signals 278/284 and the ozone profile is also obtained in the lower troposphere. The temperature measurement is obtained from the ratio of 528 to 530 nm signals as a measure of the rotational state population distribution [17,18,19].

The Raman techniques use ratios of signals to measure water vapor and temperature and thus have a major advantage in removing essentially all of uncertainties, such as any requirement for knowledge of the absolute sensitivity and non-linear factors caused by aerosol and cloud scattering.

The optical extinction profiles from the LAPS instrument are determined from the gradients in the molecular profiles of the atmosphere caused by clouds and aerosol scattering. The gradient of the neutral density profiles can be used to directly determine the optical extinction. In general, optical extinction cannot be determined from the backscatter signal at the fundamental laser wavelengths [20]. However, the extinction profiles can be determined from the Raman

Table 1. LAPS Lidar Characteristics

Transmitter	Continuum 9030 -- 30 Hz 5X Beam Expander	600 mj @ 532 nm 130 mj @ 266 nm
Receiver	61 cm Diameter Telescope	Fiber optic transfer
Detector	Seven PMT channels Photon Counting	528 and 530 nm -- Temperature 660 and 607 nm -- Water Vapor 294 and 284 nm -- Daytime Water Vapor 278 and 284 nm -- Raman/DIAL Ozone
Data System	DSP 100 MHZ	75 meter range bins
Safety Radar	Marine R-70 X-Band	protects 6^{o} cone angle around beam

shifted wavelengths of primary molecular species [21,22,23,24]. Measurements of optical extinction have been obtained from the 2^{nd} harmonic of the Nd:YAG laser using the rotational Raman signal at 530 nm and the nitrogen vibrational Raman signals at 607 and 284 nm. Raman scatter signals measured at several wavelengths provides optical extinction profiles which can be used to estimate the changes in size distribution.

LIDAR ATMOSPHERIC PROFILE SENSOR

The objective of the LAPS Program was to develop a lidar profiler capable of providing real time profiles of atmospheric and meteorological properties, with emphasis directly measuring the RF refractivity which is directly determined from measurements of water vapor and temperature profiles. The LAPS instrument hardware was completed in mid-1996 and it was tested onboard the USNS SUMNER in the period August to October 1996. The LAPS instrument can obtain most of the measurements which are currently provided by radiosonde balloons. LAPS was preceded by the LAMP (Lidar Atmospheric Measurements Profiler) research instrument which was developed in 1990 and has been used to test the various measurement techniques that have been employed in the LAPS. Table 1 lists the primary characteristics of the LAPS lidar.

LAPS PERFORMANCE

Examples of the LAPS water vapor profiles compared to individual balloon rawinsondes are shown in Figure 1. During shipboard tests, the lidar measurements were compared to 97 standard rawinsonde balloons. Several balloon instruments failed to provide results but the average value of a ratio of the lidar and balloon results for each available flight are summarized in Figure 2. The lidar data are taken from the 30 minute integration at the time of the balloon release. Error in the balloon measurement, differences in the atmosphere between the vertical lidar profile and the balloon location (up to 50 km away during assent), or differences due to changes in the height of sharp profile gradients are factors which cause variations to be observed. The dynamics of the atmosphere causes differences between the point samples of the balloon measurements and the lidar vertically integrated 30 minute profile (note the profile in right panel of Figure 1). The differences observed between the lidar and the sonde result in an average difference of ±4.6% for the visible channels and 8.9% for the ultraviolet channels. The ultraviolet signal variations are larger because the error in the ultraviolet signals grows rapidly above 3 km and intermittent drifting of SO_2 emission from the ship's diesel engines across the lidar beam caused noticeable absorption at 294 nm. The lessons learned from the test included the following items:

- Flash lamps can provide long operation ~10^8 shots
- Operation can be conducted in all weather, clouds, rain, snow
- Radar can provide safe operation - no interference
- LAPS is a robust instrument - continuous measurements can be made
- Realtime data product - 1 minute update provides useful trend data
- SO_2 from ship stack causes an error in UV water vapor (294 nm)
- Gain stability requires protection of visible detectors in daylight

The LAPS instrument tests have demonstrated the measurements of the real time profiles of the properties which determine the RF-refractivity. The temperature and water vapor measurements are the critical parameters which weather balloons provide today and the lidar techniques will provide in the future.

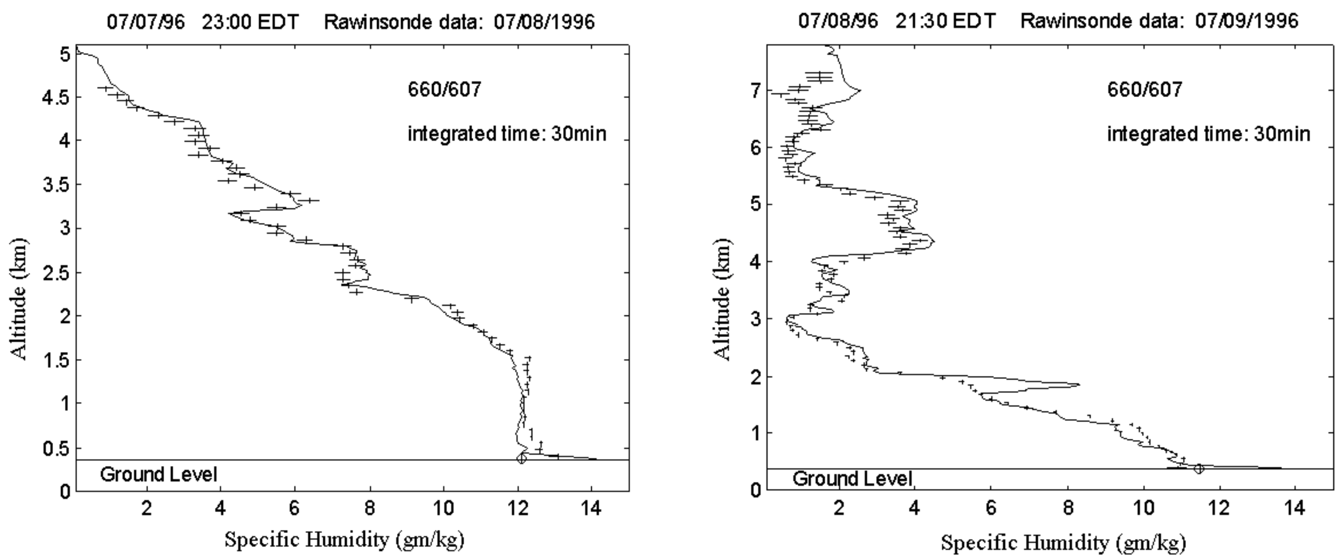
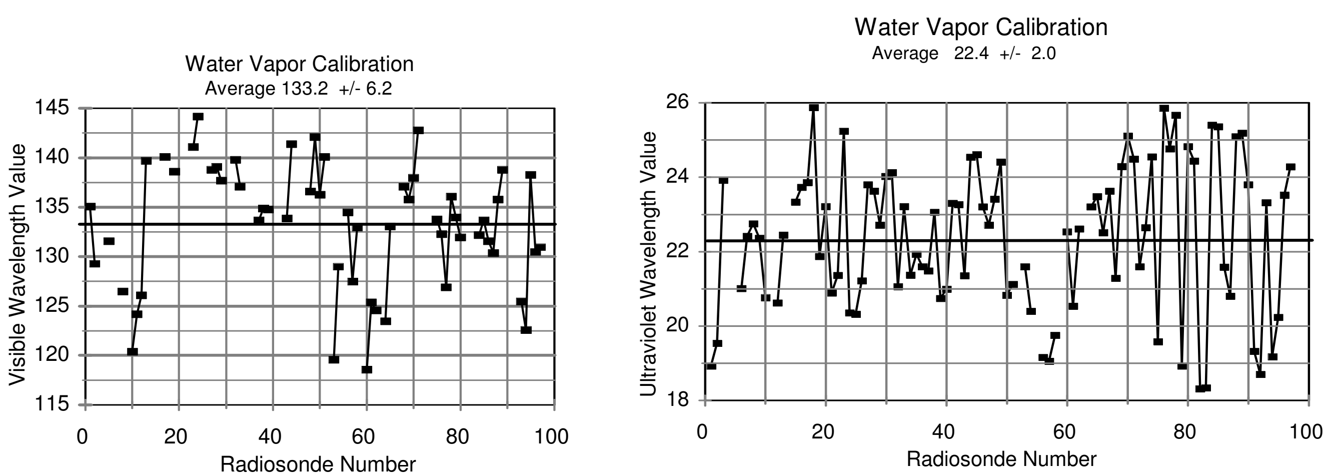


Figure 1. Two examples of LAP water vapor profiles are shown from measurements at State College PA on July 7 and 8 1996. The individual lidar points are shown with their ±1 σ error, the rawinsonde profiles are shown as a line



and a point measurement at the surface is indicated.

Figure 2. Summary of the comparison of ratio of the 30 minute lidar data to balloon data for each flight.

Thousands of profiles for water vapor, temperature, optical extinction and ozone have been measured and these are now being prepared in a data base to be used for investigations of atmospheric conditions.

SUMMARY

The LAPS instrument was operated and data were obtained on every operation attempted or planned during the period of the sea trial. Several scientific investigations have provided additional results during the past year. Investigations of the data show that the instrument was successful in demonstrating the capability to obtain the meteorological data and RF refractivity conditions during day and night conditions and in a wide range of weather conditions. The LIDAR system offers the capability to obtain high quality RF ducting prediction data with real time data products and routine update without the use of radiosonde expendables. We expect that the "operational environmental system" of the future will be based upon lidar profile data combined into a mesoscale grid model which is run to provide the spatial continuity, within constraints imposed by the measured profiles, and provide the predictive conditions with products tailored to system, mission and scientific investigation requirements.

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