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LIDAR MEASUREMENTS OF ATMOSPHERIC PROPERTIES

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Capability of laser remote sensing for measurement of atmospheric properties has expanded during the past few years. It is possible to provide real time measurements of the profiles of most properties of the structure, dynamics and primary chemical constituents of the atmosphere. The temperature and density profiles can be obtained using the rotational Raman signals from the molecular profiles of the neutral constituents. The dynamical properties can be examined using a tracer, such as water vapor or particulate scattering, or from Doppler velocity measurements. The major species of the atmosphere are obtained from vibrational Raman scattered measurements or DIfferential Absorption Lidar (DIAL) techniques, the profiles of nitrogen, oxygen, water vapor and ozone can be routinely measured. The profiles of the primary molecular species can be used to measure the optical extinction. Meteorological profiles can be used to provide the real time measurements of several other useful parameters, such as the RF refractivity. The refractivity of the lower atmosphere effects the propagation paths of radars, radio communications and navigational systems. Variations in refractivity, thus local propagation conditions, can be fully described if the profiles of the molecular density and water vapor profiles are known. Laser remote sensing techniques can now provide these measurements with high spatial and temporal resolution of many useful parameters, under most environmental conditions. A semi-automated operational prototype instrument has been prepared, Lidar Atmospheric Profile Sensor (LAPS), which provides the meteorological properties and refractivity as real time data products. Examples of the measurement capability for atmospheric properties obtained with the new operational prototype (LAPS) instrument are presented. The LAPS lidar was tested onboard the USNS Sumner during September and October 1996 and successfully demonstrated that high quality meteorological profiles can be obtained.

INTRODUCTION

The Lidar Atmospheric Profile Sensor (LAPS) was developed as a prototype for an operational instrument which can be deployed on aircraft carriers, or other large ships, and at shore facilities to meet requirements for atmospheric and meteorological data. The LAPS instrument provides profiles of the water vapor and temperature through the lower troposphere. These profiles are used to calculate profiles of RF refractivity. The LAPS instrument uses vibrational Raman scatter to measure the water vapor and rotational Raman scatter to measure temperature. Daytime measurements of water vapor are obtained by using the "solar blind" portion of the ultraviolet spectrum. Ultraviolet measurements also provide the capability for measuring the tropospheric ozone profiles from a DIAL (DIfferential Absorption Lidar) measurements of the Raman shifted N_2 and O_2 signals. The fabrication of the LAPS instrument was completed in April 1996 and performance tests were conducted during the rest of the year. During September and October 1996, the LAPS instrument was deployed onboard the USNS Sumner for performance testing. The instrument has successfully demonstrated capability to provide the meteorological profiles as real time data products. We plan make use of the instrument to assess the optimum utilization of this new capability and determine the limits of the instrument to operate in a wide range of meteorological conditions. The LAPS instrument can provide important new results for research investigations for the understanding of problems in atmospheric physics and chemistry.

LAPS Prototype Instrument Development

Objective of LAPS Instrument (Lidar Atmospheric Profile Sensor)

The objective of the LAPS Program was to develop a lidar profiler capable of providing real time measurements of atmospheric and meteorological properties, particularly those profiles which directly determine the RF refractivity in an operational environment.

Background of the LAPS Program

The LAPS Program was begun in 1991 with the goal of using laser remote sensing techniques to provide an operational lidar sensor prototype instrument for at sea demonstration within 5 years. The instrument was designed to be rugged, provide automated operation, and be field serviceable such that it can be operated by Navy personnel on Navy ships with a reasonable amount of training. Measurements of water vapor and temperature profiles provide RF refractivity profiles covering altitudes from the surface to 5 km with emphasis on the region up to 3 km. The instrument has been prepared to become a SMOOS sensor and provide data through an interface with the TESS(3) system. Future developments include upgrades which add capabilities to measure the wind velocity and describe the electro-optical environment. A successful demonstration, with sea tests of performance, was completed in October 1996 on the USNS Sumner. The demonstration and tests were completed within the originally planned demonstration period. The LAPS instrument was prepared as an operational prototype for use on aircraft carriers and at shore based sites. Many factors, such as measurement costs, personnel requirements, volume (for storing expendable instruments helium and preparation of the instrumented balloons), pollution from battery acid, radio signal give-away of ship location, and others, make it important to implement this new technology. The LAPS instrument can replace most of the requirements for radiosonde balloons, particularly with the addition of the wind measurement. Since the formulation of the original requirements for use on aircraft carriers and shore sites, the need to employ such an instrument on small surface combatants has arisen. The lessons learned in the development of the LAPS instrument have provided a basis for the design of an advanced compact diode pumped lidar which will be able to provide the data required for smaller surface ships, where instrument size and weight are more critical factors. The ALAPS (Advanced Lidar Atmospheric Profile Sensor) will also use eye safe ultraviolet wavelengths which remove the requirements for radar and allows measurement of the evaporative duct.

Raman Measurement Techniques

The ratio of vibrational Raman back scatter signals from the molecules of the water vapor (660 nm and 295 nm from the 2nd and 4th harmonics of Nd:YAG laser) and molecular nitrogen (607 nm and 284 nm) are at wavelengths widely separated from the exciting laser radiation and can be easily measured using modern filter technology and sensitive detectors. We have built upon the past twenty years of lidar technique development. The ratio of rotational Raman signals at 528 nm and 530 nm provides a measurement which is sensitive to atmospheric temperature. Based upon research of several other investigators and our efforts at PSU, we now have the capability for reliably profiling several properties (Ref 1 - 15). In order to push the lidar measurement capability into the daylight conditions, we have used the "solar blind" region of the spectrum between 260 and 300 nm. Night time measurements are made using the 660nm/607nm (H_2O/N_2) signal ratio from the doubled Nd:YAG laser radiation at 532 nm. Daylight measurements are obtained using the 294.6nm/283.6nm (H_2O/N_2) ratio from the quadruple Nd:YAG laser radiation at 266 nm. 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 from 277.5nm/283.6nm, and the lower troposphere ozone profile is obtained.

The molecular density effect on the refraction can be determined from the temperature profile and a surface pressure measurement. We have been able to demonstrate that the rotational Raman signal provides a useful temperature profile. The design and construction of the narrow band filters to eliminate the large back scatter signal from the nearby fundamental laser line presents the primary challenge. The ratios of the measured signals at 530nm/528nm from the doubled Nd:YAG at 532 nm have been used to provide a robust technique to obtain the temperature profile.

The RF-refractivity, N, represents the significant figures of the refractive index, n, and is based upon the following empirically derived relationship,

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

$$= 77.6\ P/T + 3.73 \times 10^5\ e/T^2 , \qquad (2)$$

where the water vapor partial pressure, e (mbar), is related to the specific humidity, r (gm/kg), by the relation,

$$e\ (\text{mbar}) = (r\ P)/(r + 621.97). \qquad (3)$$

The errors associated with the measurement may be considered based upon analysis of the propagation of errors. The errors have the approximate values given by,

$$\Delta N = (\delta N/\delta r)\ \Delta r + (\delta N/\delta T)\ \Delta T + (\delta N/\delta P)\ \Delta P , \quad (4)$$

$$\delta N/\delta r \sim 6.7 \qquad \delta N/\delta T \sim -1.35 \qquad \delta N/\delta P \sim 0.35$$

$$dN/dz = 6.7\ dr/dz - 1.35\ dT/dz + 0.35\ dP/dz . \qquad (5)$$

The values used in these relationships, which are typical of the lower atmosphere, show that it is the gradients in water vapor are most important in determining RF ducting conditions.

The Raman techniques, which use of ratios of the signals for measurements of water vapor and temperature, remove essentially all of uncertainties, such as any requirement for knowledge of the absolute sensitivity and non-linear factors caused by aerosol and cloud scattering.

Lidar Atmospheric Profile Sensor (LAPS)

The LAPS lidar instrument has been developed from lessons learned in preparing and using prior research instruments. The LAPS unit was designed to include many automated features which make the instrument "user friendly" for operators who are not specialists in lasers or electro-optics. The instrument was fabricated during FY95/96 and has been deployed onboard the USNS Sumner, a Navy survey ship, in the Gulf of Mexico and along the Atlantic coast of Florida during September-October 1996, to perform tests and validate its performance. It has performed well and provided excellent data products. The LAPS instrument was designed to provide the real-time data product of RF-refractive conditions with automated control of most operating features. More than twenty features have been designed into the instrument to control and simplify the instrument operation. It is intended that a weather officer could obtain the data on demand or acquire data according to some planned schedule. Advanced versions of the instrument are planned to include capability to measure the wind field, the electro-optical environment and other parameters. The long term plan for the instrument is to replace most of the current balloon sonde profiling and thus enable data collection at more frequent intervals to support radar operations or weather affected missions.

The shipboard testing periods for the Lidar Atmospheric Profile Sensor (LAPS) instrument were intended to demonstrate its ability to measure the RF refractivity and demonstrate the capability for automated operation 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, and these measurements provide real-time profiles of RF refractivity. Profiles are currently obtained at each minute, with a vertical resolution of 75 meters from the surface to 7 km. The vertical resolution will be improved to the range of 3 to 15 meters, in the near future, using a new fast electronics package, which has recently been demonstrated as a single channel prototype in our laboratory. The LAPS instrument includes several sub-systems to automate the operation and provide the real-time profiles. Also, the instrument includes an X-band radar which detects aircraft as they approach the beam and automatically protects a 6 degree cone angle around the beam. The instrument also includes self calibration and built-in-tests to check many functions. Table 1 lists the primary characteristics of the LAPS lidar.

In addition to the water vapor and temperature profiles, the true extinction and ozone profiles are also measured. By comparing the molecular profiles, from the N_2 Raman and rotational Raman, with the neutral atmosphere density gradient, the extinction profile can be obtained. The ratio of the ultraviolet N_2 and O_2 vibrational Raman measurements, which are on the slope of the Hartley band of ozone, provides a DIAL measurement of the ozone profile in the lower atmosphere, surface up to 3 km.

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 285 nm -- Daytime Water Vapor 276 and 285 nm -- Raman/DIAL Ozone
Data System	DSP 100 MHZ	75 meter range bins
Safety Radar	Marine R-70 X-Band	protects 6° cone angle around beam

Examples of LAPS Measurements

The LAPS development has been directed toward the measurement of the refractivity of the atmosphere for determination of electromagnetic ducting conditions. The equations which are usually adopted for calculations of the refractive index are based upon temperature, pressure and water vapor partial pressure. Figure 1 shows an example of the comparison of the LAPS lidar water vapor profile (data points with $\pm 1\sigma$ statistical error of the photon count) with a radiosonde balloon released at the same time period (solid line). The lidar measurement points represent individual measurements at 75 meter range bins integrated over 15 minutes, no smoothing of the lidar vertical profile has been applied. The gradual departure between the mean value of the two profiles at high altitude is attributed to the spatial homogeneity of the atmosphere as the balloon drifts away from the release site, often by several 10's of kilometers during the time while it rises to 5 km altitude. The profile in Figure 1 was obtained from the integration of 15 minutes of data collected at 23:20 EDT on 23 June 1996. Figure 2 shows the profile of the same period measured by the "solar blind" ultraviolet detectors and compared to the same radiosonde profile. We use time sequences of the one minute profiles as false color images to observe the trends and dynamical changes in the lower atmosphere. Time sequences are very useful in observing the changes in meteorological conditions. Figure 3 shows two examples of the temperature profiles determined from the LAPS lidar compared to the rawinsonde balloon corresponding results, the measurements were made at 21:34 EDT on 30 May 1996 and 23:27 on 20 July 1996. These measurements also show the $\pm 1\sigma$ error which would be larger at the upper altitudes if there had not been a three point smoothing filter applied at middle altitudes and a five point smooth applied at upper altitudes. Below 2 km, the statistical error is small, a fraction of a degree, but the errors grow rapidly at higher altitude. The temperature measurements are not optimized and approximately ten times improvement in signal is expected from two changes. The detector currently uses neutral density filters to maintain the signal in a liner operating region, which will be extended by a factor of five using the newer high speed electronics. The current limit is set by the saturation of the photon count rate due to the electronics limitations. A second area of improvement is in the selection of the wavelength and bandwidth for the temperature measurement filters. The tradeoff study to optimize this selection was recently completed [20]. The LAPS program has been focused on preparation of an operational prototype for measurements of atmospheric RF refraction. The development has been very successful and provided an operational prototype instrument which can provide the real time profiles of the atmospheric and meteorological properties required for mission support on Navy ships. The prototype testing has included a successful demonstration on a Navy ship.

Summary of Shipboard Testing during 1996

The installation of the LAPS instrument on the USNS Sumner was accomplished on 30 August at Pascagoula MS. During the weekend, 31 August - 2 September, the instrument was tested and prepared for shipboard operation. Testing of the LAPS instrument was carried out during the period while the USNS Sumner carried out survey operations in the areas near the Florida Keys and near the Bahama Islands during the periods 3 - 21 September and 27 September - 15 October. Between 21 and 27 September, the USNS Sumner was in Port Everglades at Fort Lauderdale, FL, where tours were given for scientists attending the OCEANS 96 Conference.

During the period while the USNS Sumner was at sea, the LAPS lidar was used to gather data in 352 hourly subdirectories. Thus measurements were obtained during an average of 10 hours each day during the sea trials. Measurements were obtained during both day and night time conditions. On several occasions, the LAPS lidar instrument was run continuously for extended periods, including one period of 24 hours and one of 36 hours. Measurements were made in all weather conditions and the instrument was available 99 % of the time. It was only down during one period of 10 hours for scheduled routine maintenance and alignment. The operations during cloudy periods where generally successful in providing sufficient data between clouds and through light clouds to provide useful profiles. Approximately 5 to 10 % of the time period (the detail survey has not been completed at this time), we experienced clouds with optical thickness such that limited operations provided profiles only below their base.

The LAPS lidar can be used to characterize the marine boundary layer. The results show unprecedented ability to characterize the variations that occur in the marine boundary layer which causes important effects upon Navy missions. The measured properties provide the capability to generate the real time profiles of RF refractivity, visibility and the meteorological profiles which are needed to forecast the weather conditions. Examples of the shipboard real time data display of the water vapor profiles and the temperature profiles measured are shown in Figures 4 - 7. Figure 4 shows the raw ratio of the measured Raman signals on 17 September 1996 at 0200, and the right hand panel shows the measurement compared to a radiosonde profile at the same time. Figures 5 and 6 show the real time display for water vapor and temperature profiles at 0200 GMT on 17 September 1996 from the shipboard data records. Figures 5 and 6 show the same graphical display that is available to the operator. The $\pm 1\sigma$ statistical count error is shown for every second data point on the real time plots, so the significance of the variations can be observed. Figure 4 also shows the post mission analysis which compares the lidar and balloon profiles. The operator also has a real time display which updates the one minute time sequence of the water vapor profiles as a false color display (the color represents the specific humidity in gm/kg). The time sequence display is convenient for detecting changes in the local meteorology that indicate the approach of a weather front or a change in the weather conditions. Figure 7 shows a display of the refractive conditions. In the lower panels of Figure 7, the temperature and water vapor components are shown that were used to calculate the RF refractivity, N (light line), and modified refractivity, M (dark line), in the upper panel of Figure 7. The modified refractivity shows the adjustment which accounts for the earth curvature and permits an easy interpretation of the location of RF refracting ducts.

Figure 8 shows an example of the daytime measurements and displays the raw Raman signal ratio in the left hand panel on 10 September 1996 at 1923 GMT (1523 local). The corrected signal profile as been corrected for tropospheric ozone absorption. The right hand panel shows the comparison between the measurement and the radiosonde balloon. Figure 9 shows an example of an ozone profile measured with the instrument, this result was during a period of enhanced ozone pollution on 7 July 1996 at State College PA.

The optical extinction profile from the LAPS instrument is determined from the gradients in the profiles of 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, we have found that the optical extinction cannot be determined from the backscatter signal at the fundamental laser wavelengths [16]. However, the true extinction can be determined from the Raman shifted wavelengths from the profiles of primary molecular species [22,24,26,28]. Examples of the measurements of optical extinction which have been obtained from the 2nd harmonic of the Nd:YAG laser using the rotational Raman scatter at 530 nm and the nitrogen vibrational Raman scatter at 607 nm are shown in Figure 10. The results are shown on both linear and logarithmic scales in order to show both the major and minor contributions to the optical extinction. Use of Raman scatter signals at both the visible and ultraviolet wavelengths permits optical extinction measurements at several wavelengths and thus a size distribution can be estimated.

The LAPS instrument was operated and data obtained on every operation attempted or planned during the period of the sea trial. All of the indications and investigations of the data show that the instrument was fully successful in demonstrating the capability to obtain the meteorological data and RF refractivity conditions during day and night conditions and in all 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.

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 part of the critical parameters which weather balloons provide today and the lidar techniques will provide in the future. Basically, the tests and evaluation of the LAPS lidar has demonstrated the following data products:

(1) Real-time profiles of RF refractivity
(2) Nighttime measurements of water vapor, 0 - 10 km
(3) Daytime measurements of water vapor, 0 - 4 km
(4) Rotational Raman temperature profiles, 0 - 10 km
(5) Aerosol extinction profiles, 0 - 10 km
(6) Ozone measurements, 0 - 3 km.

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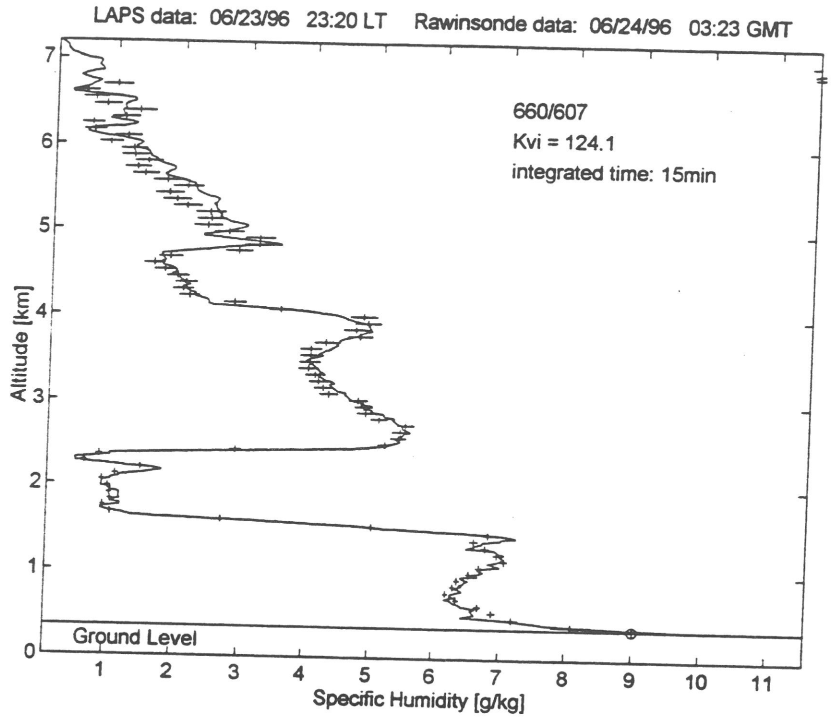

Figure 1. The Profile of specific humidity measured by the LAPS instrument on 23 June 1996. The lidar measurement points at 75 meter spacing are shown with their ±1σ statistical error (no smoothing between individual measurements). A radiosonde profile from a balloon package released at the same time is shown as a line for comparison. The symbol ⊕ indicates the surface measurement made by a point sensor in the LAPS instrument.

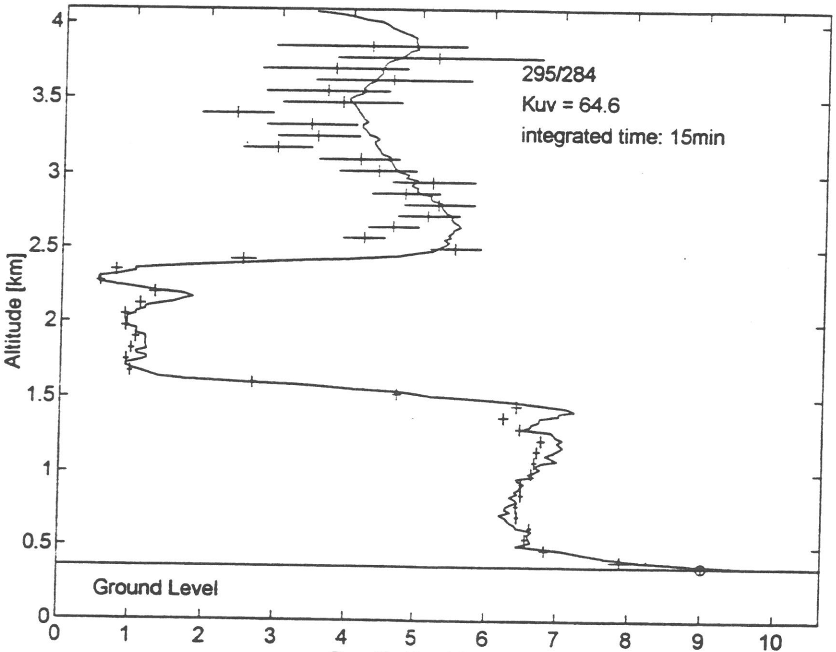

Figure 2. The measurement of water vapor from the ultraviolet channels at the same time as the data of Figure 1. The optical scattering due to the molecular and particulate components of the atmosphere reduces the useful range to altitudes less than 4 km.

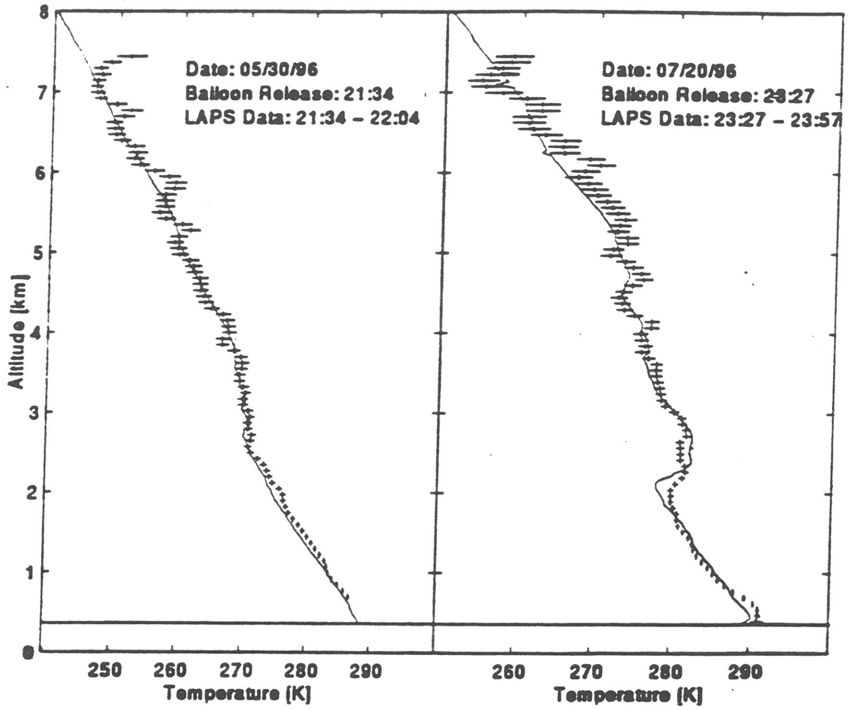

Figure 3. Temperature profiles are measured from the rotational Raman scatter signal from the LAPS lidar instrument. Examples of measurements obtained on 30 May 1996 at 21:34 EDT and 20 July 1996 at 23:27 are shown.

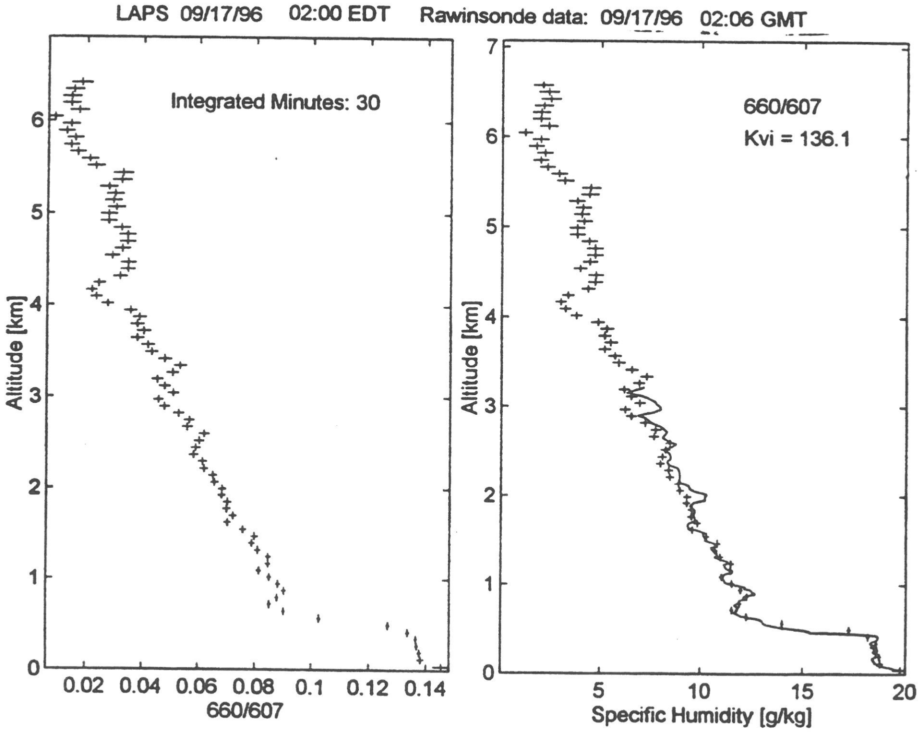

Figure 4. The water vapor measurements of the LAPS instrument obtained on the USNS Sumner on 17 September 1996 at 0200-0230 Z. The left panel shows the raw signal ratio and the right panel shows the reduced data compared to a radiosonde. The profile includes the statistical error bars (±1σ) on each data point.

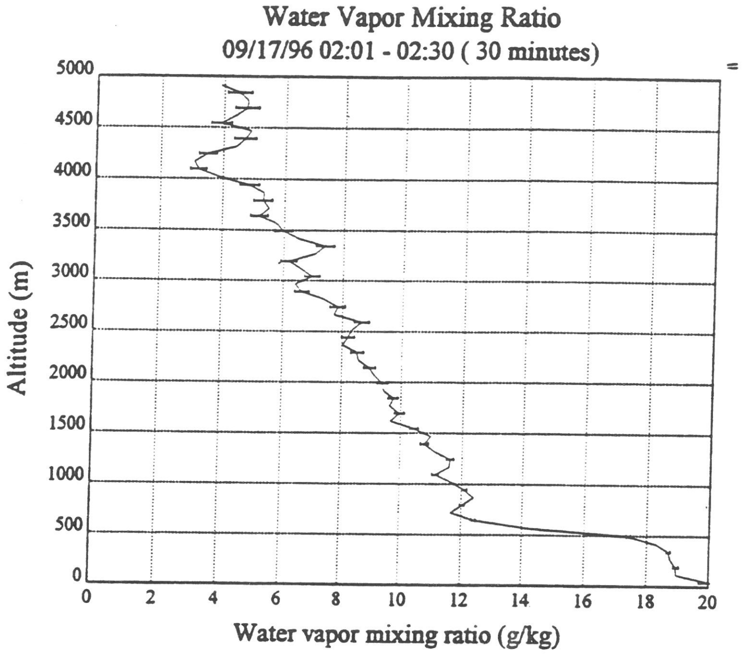

Figure 5. The water vapor measurements of the LAPS instrument from the real time data display obtained on the USNS Sumner on 17 September 1996 at 0200-0230 Z (same data as Figure 4). The statistical error bars (±1σ) are shown on every other data point.

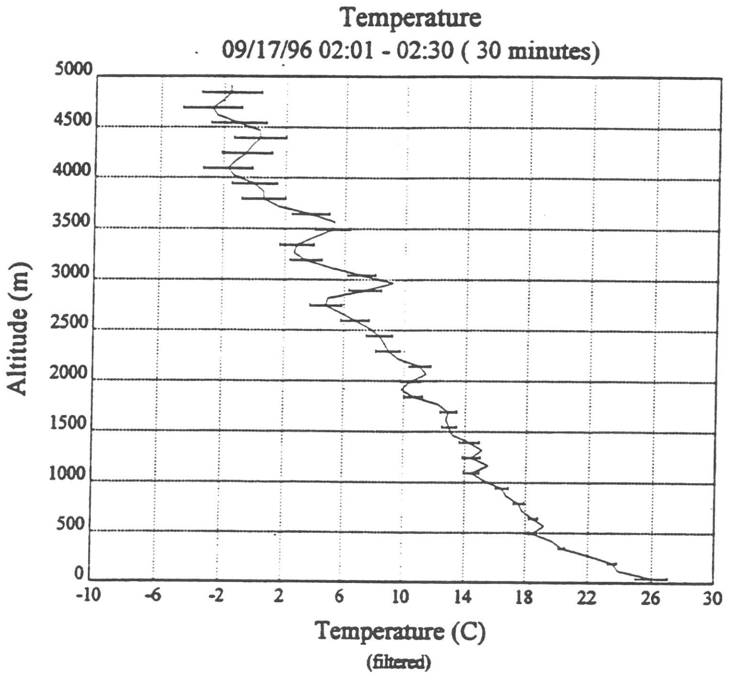

Figure 6. The temperature measurements as displayed by the real time display program of the LAPS instrument obtained on the USNS Sumner on 17 September 1996 at 0200-0230 Z. The profile includes the statistical error bars (±1σ) on every other data point. At upper altitudes the temperature data has been smoothed using a Hanning filter.

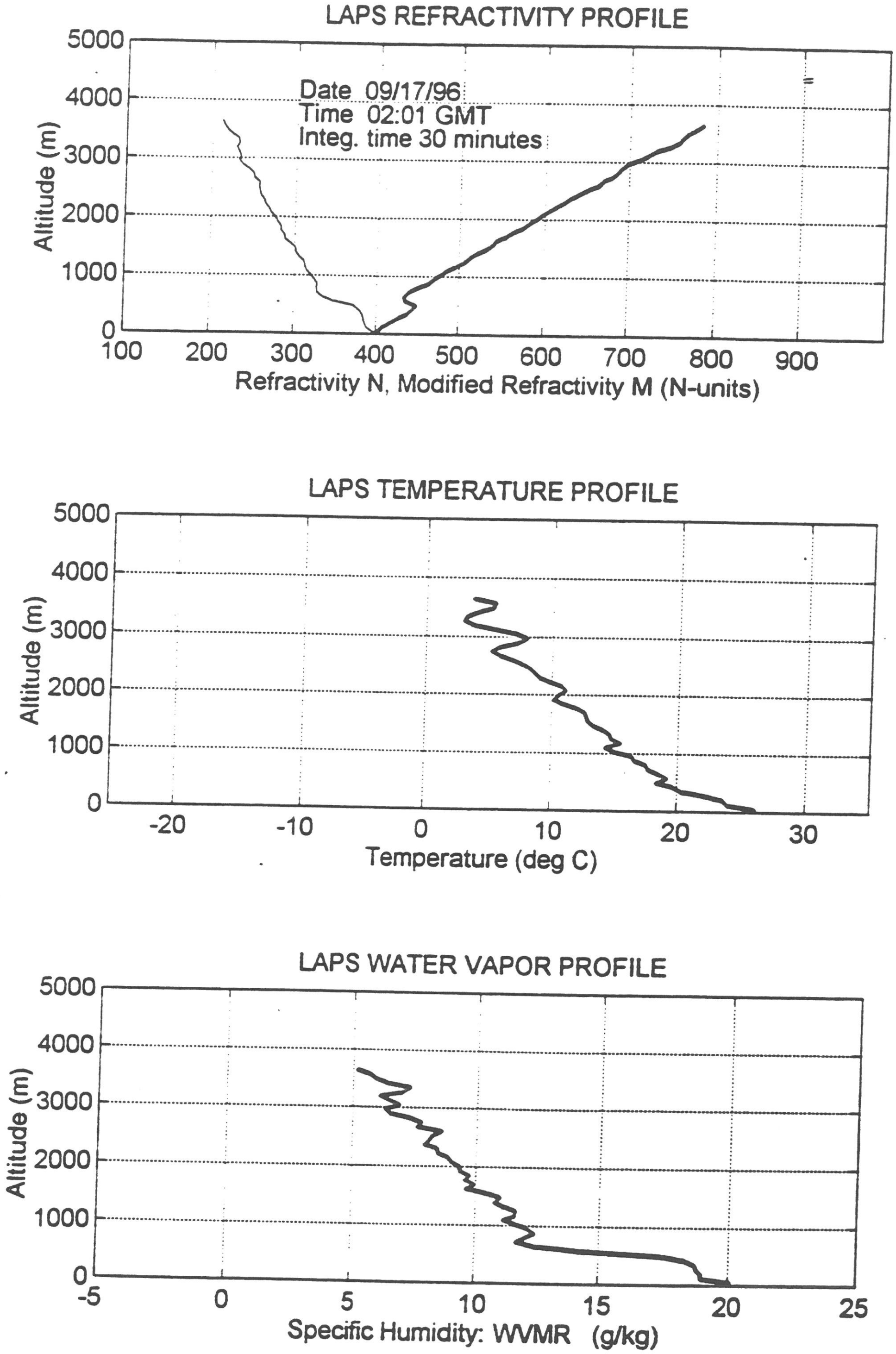

Figure 7. The lower panels show the water vapor (see Figure 4 and 5) and temperature (see Figure 6) measurements from the data gathered onboard the USNS Sumner on 17 September 1996. The upper panel shows the RF-refractivity (thin line) and modified refractivity (thick line) profiles calculated from the lidar measurements of water vapor and temperature.

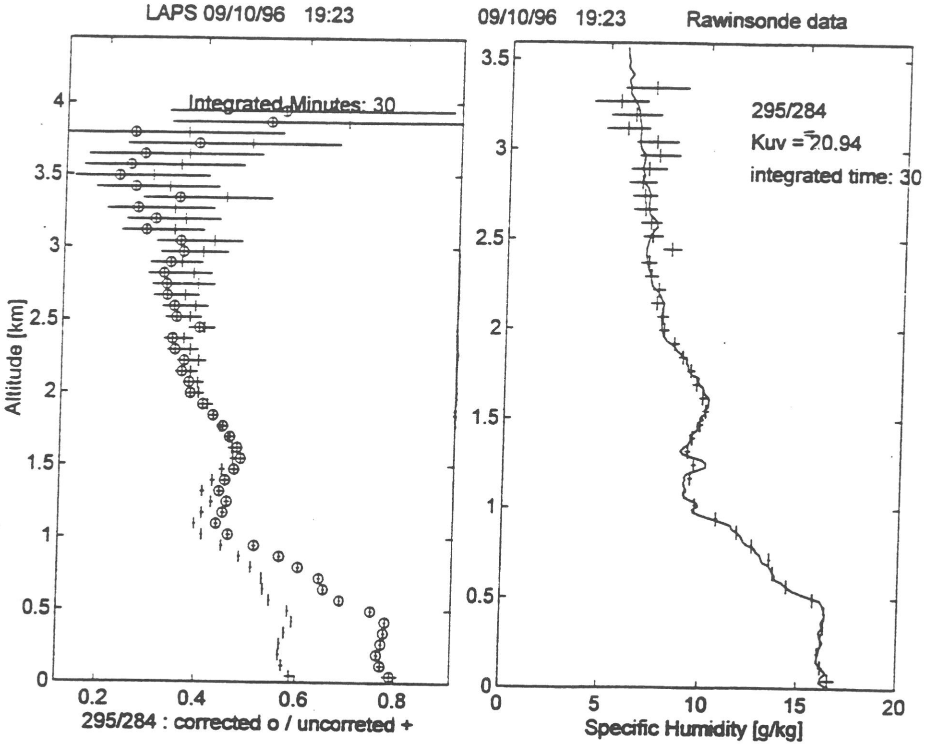

Figure 8. The raw signal ratio of the ultraviolet data channels is shown together with the comparison of the measurements with a radiosonde balloon profile. The measurement was made at 3:20 PM local time on 10 September while the USNS Sumner was off the Florida coast.

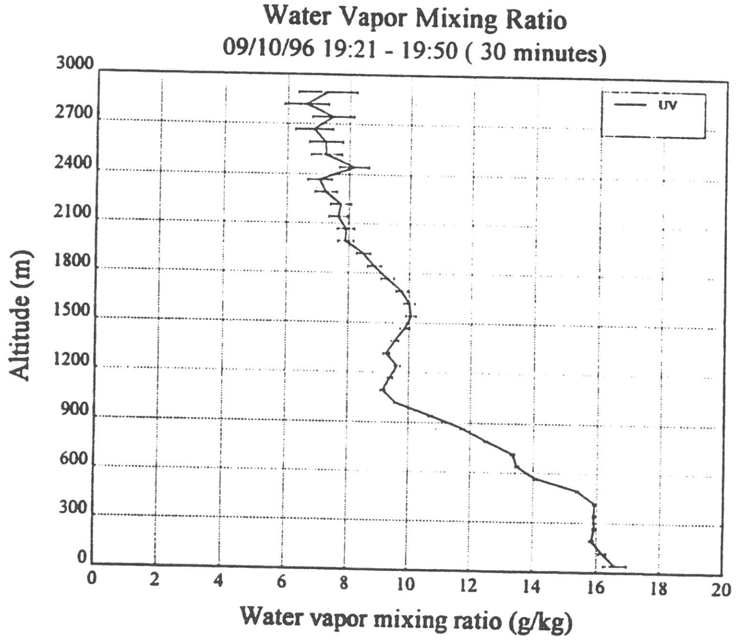

Figure 9. The real time display of the daytime ultraviolet data is shown for the same time period as the data of Figure 8.

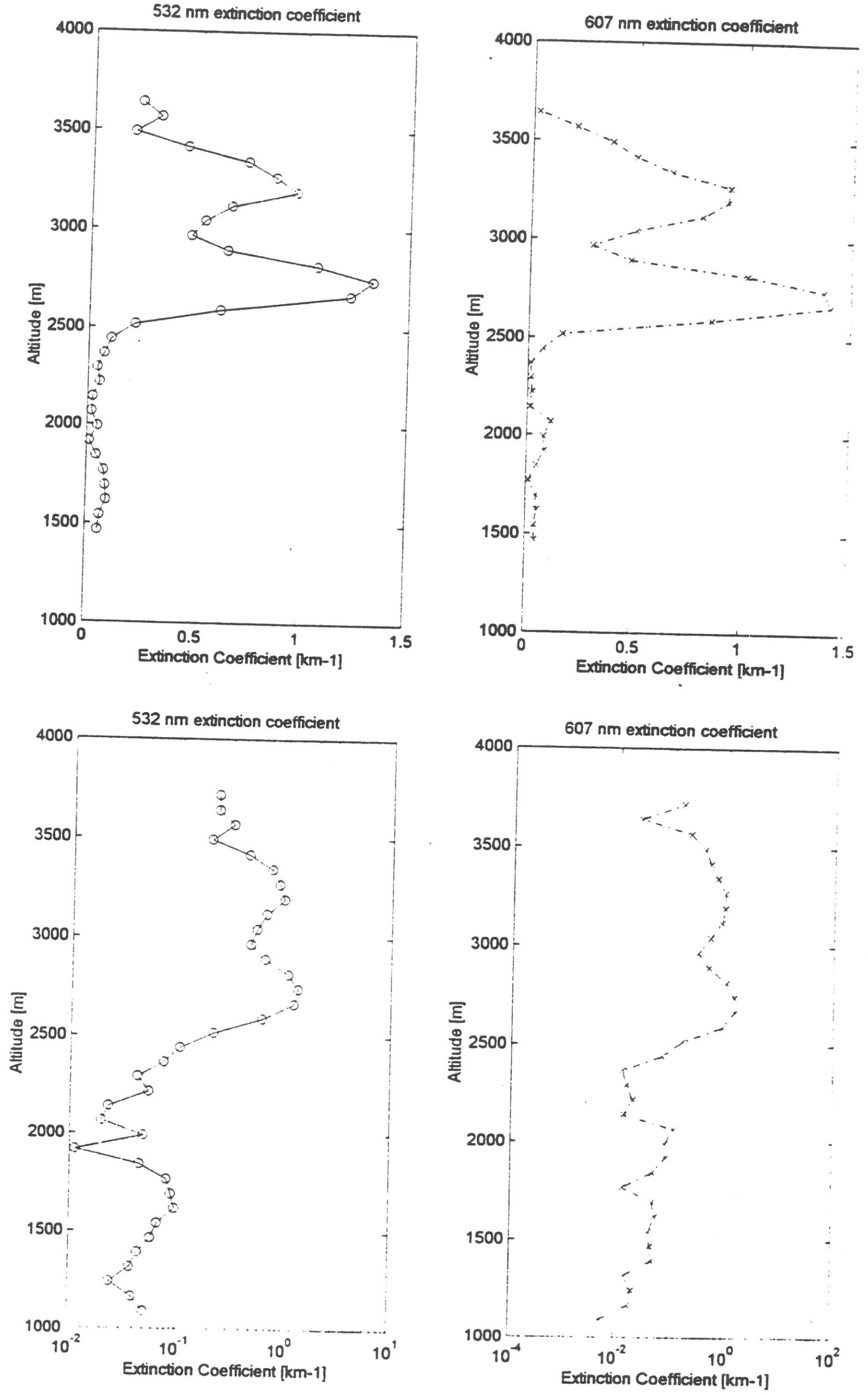

Figure 10. The measurements of the optical extinction through cloud layers is shown on 10 October 1996 during the shipboard tests of LAPS. The measurements show the true extinction calculated from the 607 nm molecular nitrogen and the 530 nm rotational Raman profiles. The 530 nm profile has been used to correct the 607 profile since it provides the extinction of the 532 nm laser transmitter.