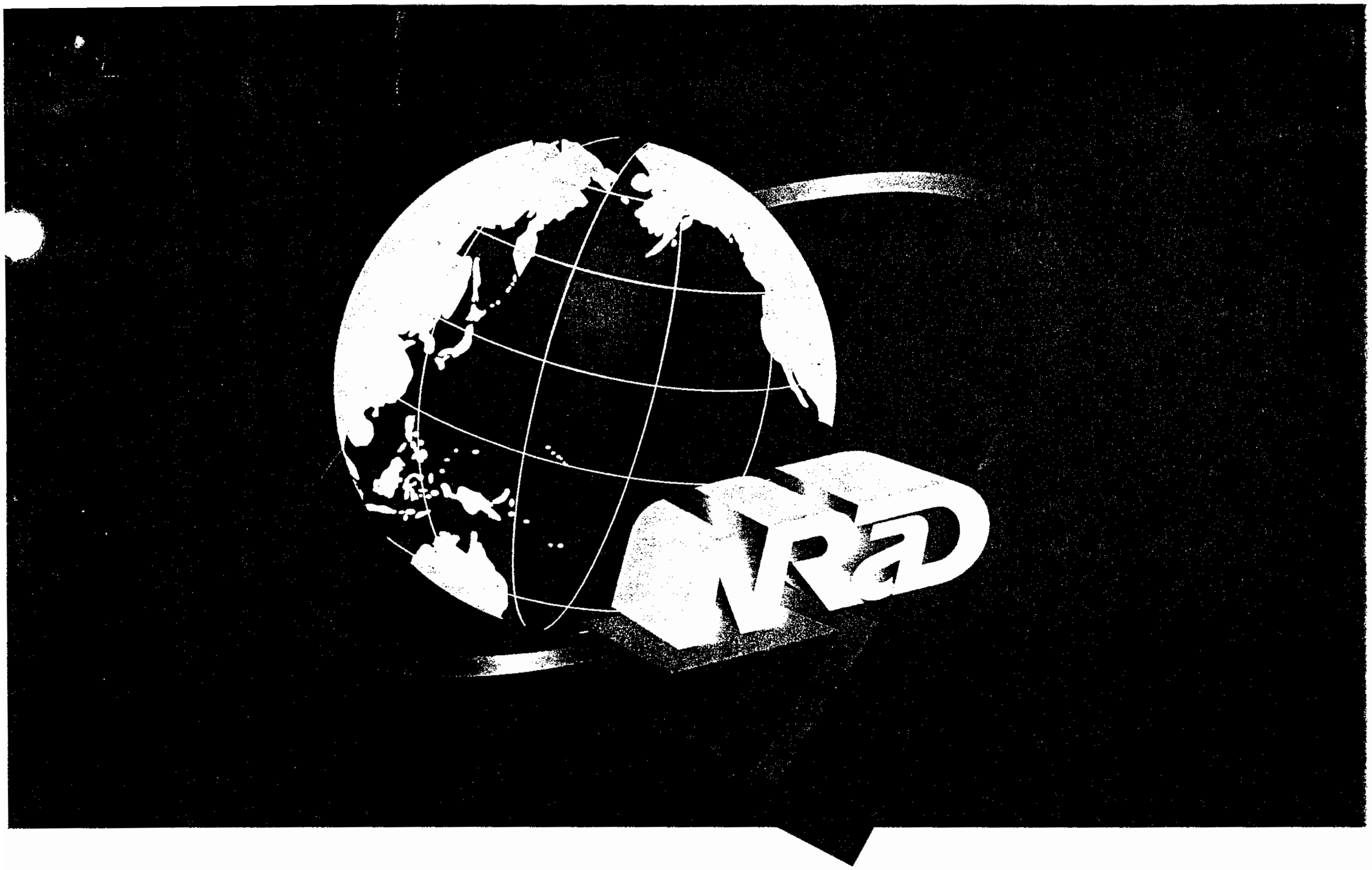

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LIDAR MEASUREMENTS OF METEOROLOGICAL PROPERTIES AND PROFILES OF RF REFRACTIVITY

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ABSTRACT

The refractivity of the lower atmosphere effects the propagation paths of radars, radio communications and navigational systems. Variations in RF propagation conditions are of concern in many civilian and military operational systems. The refractivity, thus local propagation conditions, can be fully described if the profiles of the molecular scatters, i.e. molecular density and particularly water vapor profiles, are known. The traditional techniques used to measure these atmospheric properties are based upon balloon sonde point sensor measurement of temperature and water vapor. Laser remote sensing techniques can now provide these measurements with high spatial and temporal resolution, under most conditions. Thus, lidar measurements can directly provide RF refractivity profiles. 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 which indicate the capability of Raman lidar techniques to provide the real time profiles of atmospheric properties and RF refraction. 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 from Raman lidar. Results from the real time measurements of the atmospheric profiles will be presented.

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 ship and at shore facilities to meet atmospheric and meteorological data requirements. The LAPS instrument can provide profiles of the water vapor and temperature through the lower troposphere. These measurements provide the profiles of RF refractivity. The LAPS instrument uses vibrational Raman scatter to measure the water vapor profiles and rotational Raman scatter to measure the temperature. The daytime measurements of water vapor are obtained by using the "solar blind" portion of the ultraviolet spectrum. The ultraviolet measurements also provide the capability for measuring the tropospheric ozone profiles from a DIAL (DIfferential Absorption Lidar) measurement 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. This report summarizes the significant results obtained during the shipboard tests and describes the instrument performance. Though not covered in this report, several significant scientific findings will be addressed in future scientific publications.

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

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 should 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 will include upgrades which add a capability to measure the wind velocity and describe the electro-optical environment. A most successful demonstration with sea tests of performance was completed in October 1996 on the USNS Sumner. 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 rawinsonde balloons, particularly with the addition of the wind sensing capability which has been temporally delayed. 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 also provide a basis for the preparation of an advanced compact diode pumped lidar which will be able to provide the data required for smaller surface ships and on aircraft, where instrument size and weight are more critical factors.

RAMAN MEASUREMENT TECHNIQUES

The vibrational Raman back scatter signals from the molecules of the water vapor and molecular nitrogen are at wavelengths widely separated from the exciting laser radiation and can be easily measured using modern filter technology and sensitive detectors [Ref 1-4]. The atmospheric temperature measurements have been made using the rotational Raman scattering of the molecular nitrogen and molecular oxygen, which together with the water vapor measurements permits determination of the RF-refractivity [Ref 5-9]. In order to push the lidar measurement capability into the daylight conditions, we have used the "solar blind" region of the spectrum between 270 and 300 nm [Ref 8,10]. 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.

RF-REFRACTIVITY

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,

$$e\ (mb) = (r\ P)/(r + 621.97). \qquad (3)$$

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 the gradients in water vapor are most important in determining RF ducting conditions.

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

MEASUREMENT CAPABILITY

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 [Ref 10-13]. 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. The characteristics of the primary sub-systems of the LAPS instrument are listed in Table 1. 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 15 meters, in the near future, using a new fast electronics package, which has recently been tested in our laboratory. The prototype 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, performance testing and built-in-tests to check many functions.

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 (upgrade to 15 m)
Safety Radar	Marine R-70 X-Band	protects 6° cone angle around beam

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

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 rawinsonde 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. The time sequence of the data is very useful in observing the changes in meteorological conditions. Figure 2 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 but there has 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.

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.

SHIPBOARD TESTING

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 3 - 6.

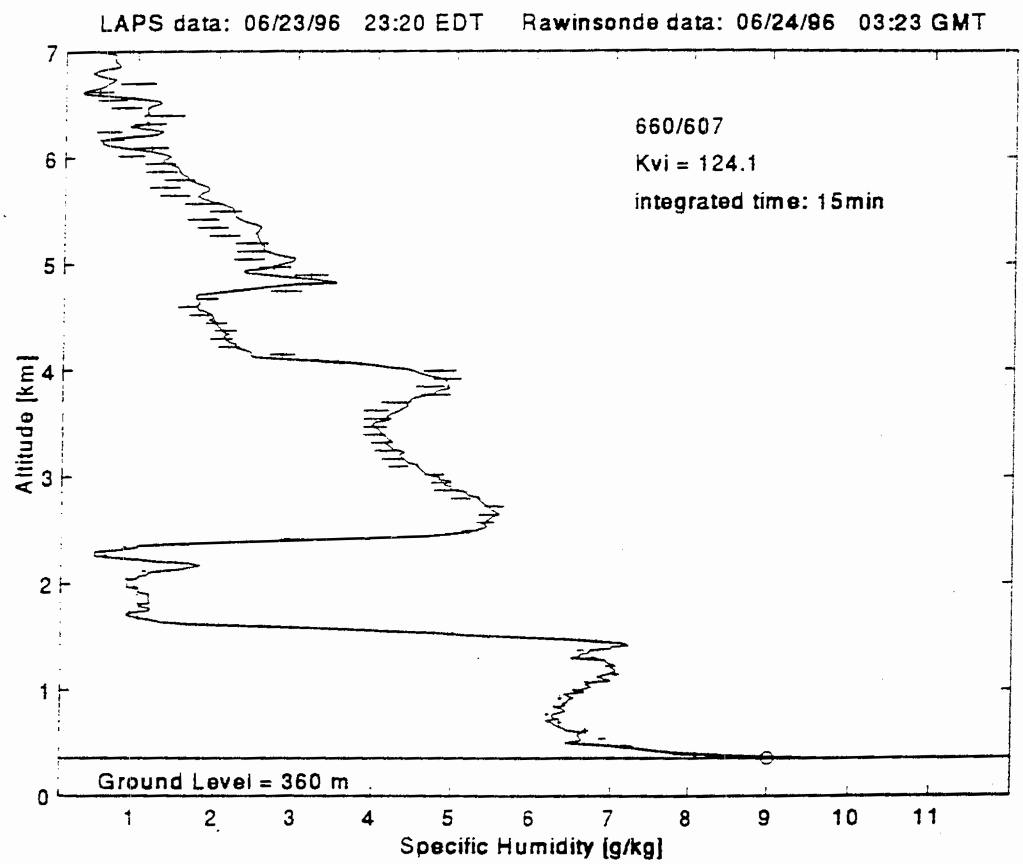

Figure 1. The profile of specific humidity measured by the LAPS instrument on 23 June 1996. The lidar measurement points at 75 meter spacing are shown with their $\pm 1\sigma$ statistical error (no smoothing between individual measurements). A rawinsonde profile from a balloon package released at the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

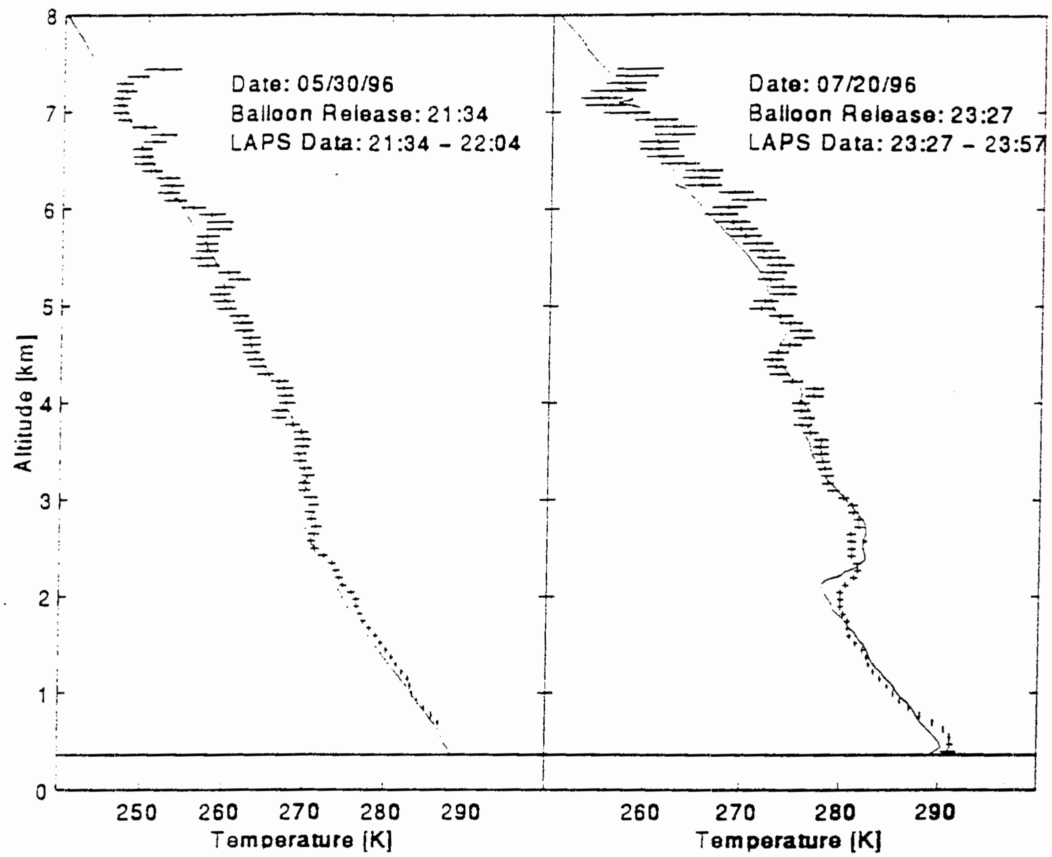

Figure 2. Temperature profiles are measured from the rotational Raman scatter signal from the LAPS lidar instrument. Examples of measurements obtained on 30 May 1996 at 21:34 EDT and 20 July 1996 at 23:27 are shown.

Figure 3 and 4 show the real time display for water vapor and temperature profiles at 0200 GMT on 17 September 1996 from the shipboard data records. These figures show the same graphical display that is available to the operator in Figures 3a and 4a. 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. Figures 3b. 3c, 3d and 4b also show the post mission analysis which compares the lidar and balloon profiles. Figure 3e shows the grey scale representation of the operator's real time display of the water vapor time sequence. The time sequence display is convenient for detecting changes in the local meteorology that indicates the approach of a weather front or a change in the weather conditions. Figure 5 shows the one minute time sequence of the water vapor profiles as a false color display (the scale represents the specific humidity in gm/kg), this display is a grey scale representation of the false color display in the real time display package. Figure 6 shows a display of the refractive conditions. In the lower panels of Figure 6, 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 6. The modified refractivity shows the adjustment which accounts for the earth curvature and permits an easy interpretation of the location of RF refracting ducts.

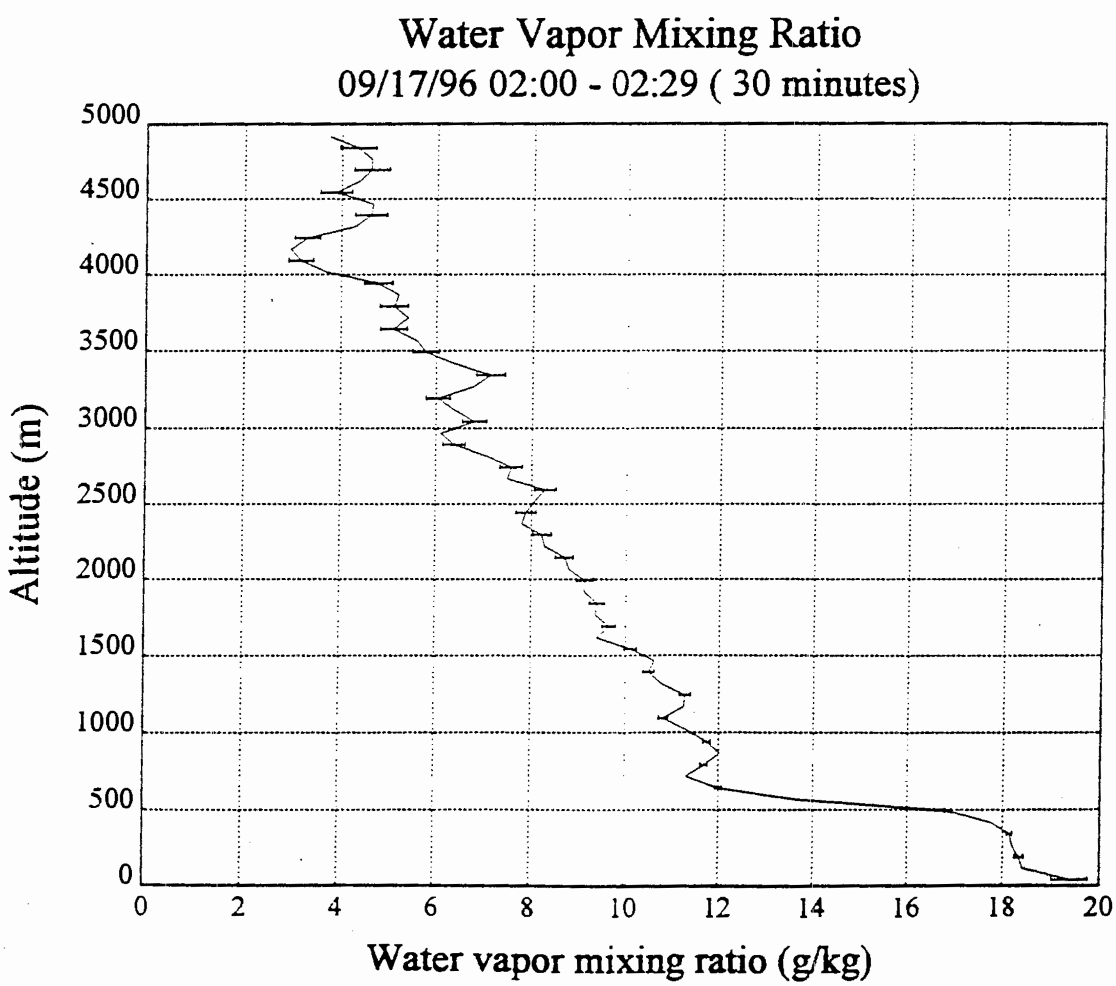

Figure 3 (a). The water vapor measurements as displayed by the real time display program of the LAPS instrument obtained on the USNS Sumner on 17 September 1996 at 0200-0230 Z. The profile includes the statistical error bars ($\pm 1\sigma$) on every other data point.

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.

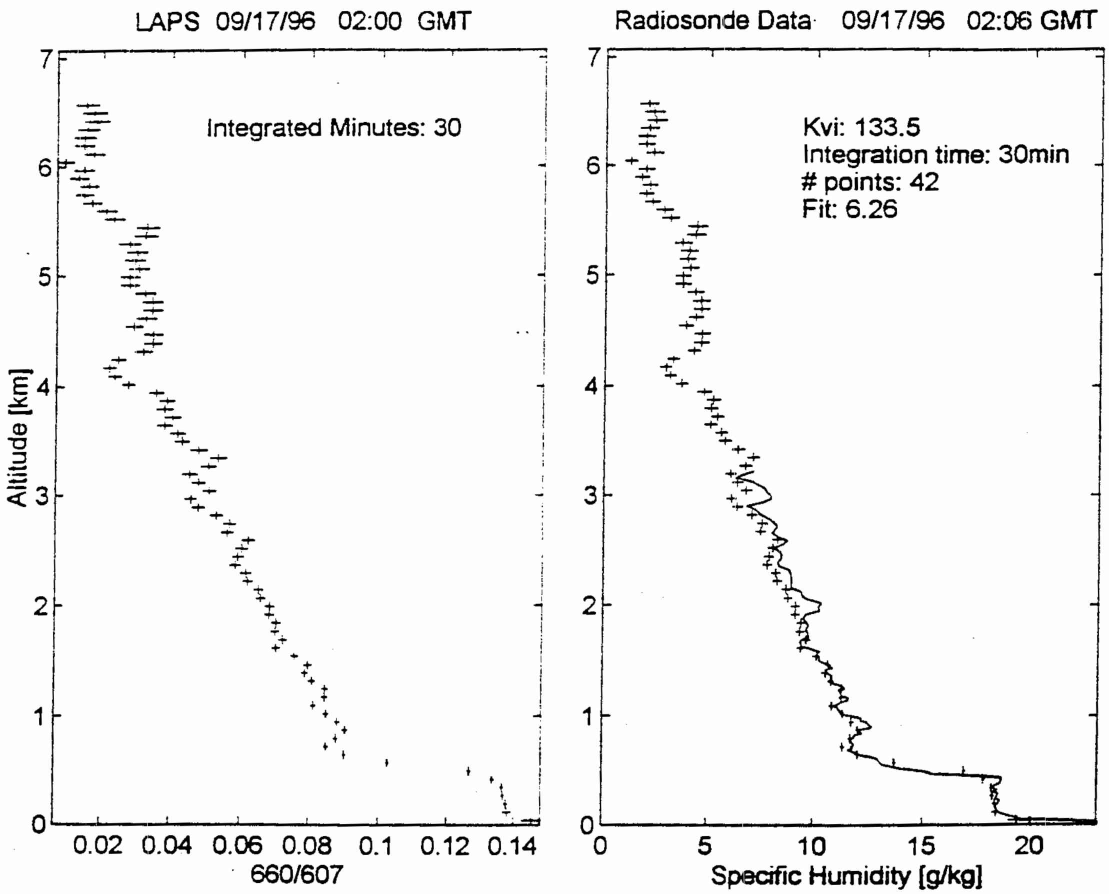

Figure 3 (b). The water vapor measurements of the LAPS instrument obtained on the USNS Sumner on 17 September 1996 at 0200-0230 Z (same data as Figure 3a). The profiles show the raw 660/607 wavelength ratio and the fit to the balloon sonde (solid line) at the same time period, both profiles show the statistical error bars ($\pm 1\sigma$) on each data point.

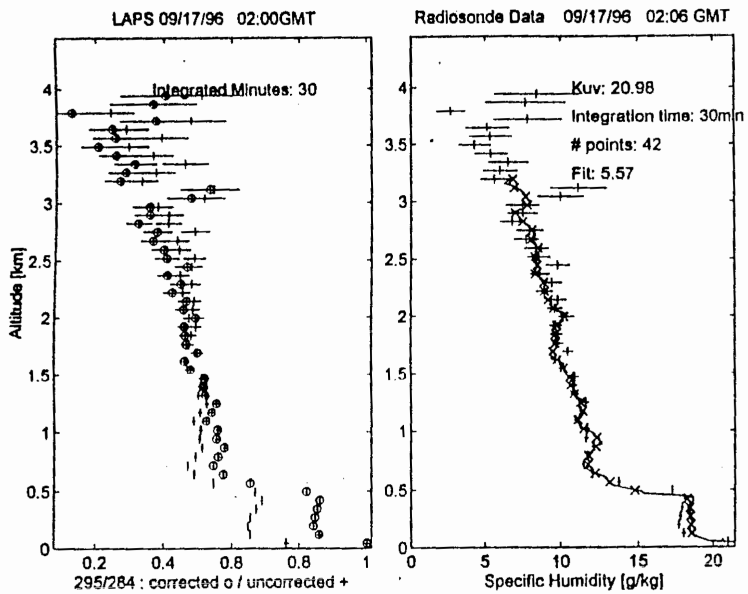

Figure 3(c). The ultraviolet water vapor measurements of the LAPS instrument obtained on the USNS Sumner on 17 September 1996 at 0200-0230 Z (same data as Figure 3a). The profiles show the raw 295/284 wavelength ratio and the fit to the balloon sonde (solid line) at the same time period, both profiles show the statistical error bars (±1σ) on each data point. The difference between the corrected (⊕) and uncorrected (+) signals is due to the ozone absorption.

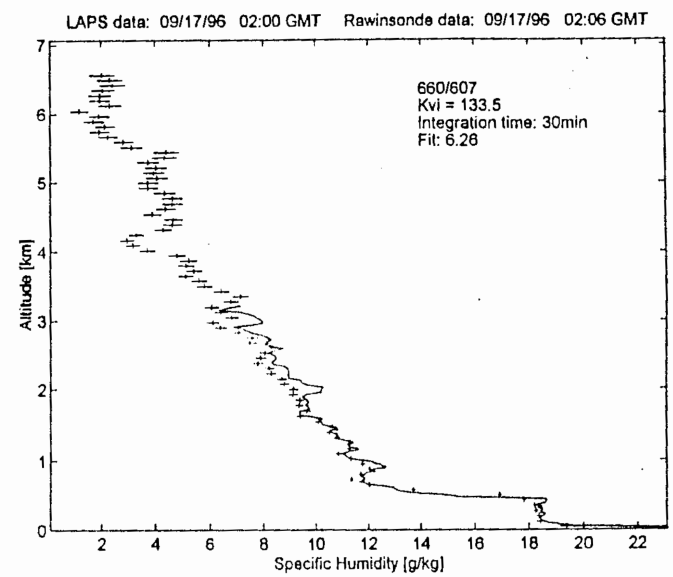

Figure 3(d). The water vapor measurements of the LAPS instrument and rawinsonde balloon obtained on the USNS Sumner on 17 September 1996 at 0200-0230 Z (same data as Figure 3a). The profiles show the water vapor measurements from the lidar and from the balloon sonde (solid line) at the same time period, the lidar profile shows the statistical error bars (±1σ) on each data point.

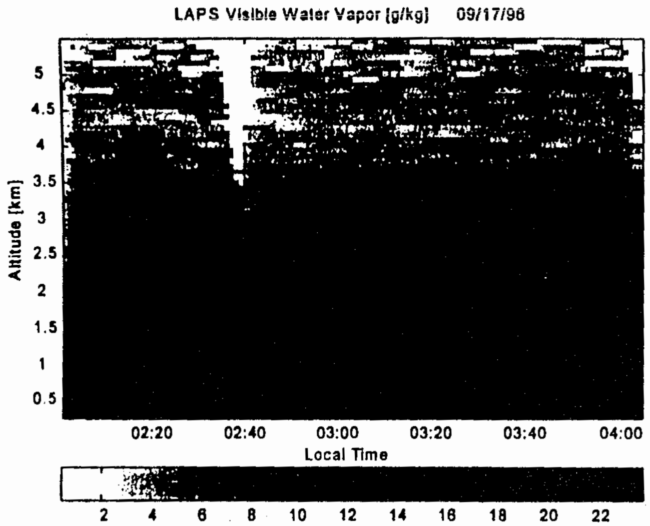

Figure 3(c). The trend of the 1 minute water vapor data is displayed for the period between 0200 and 0400 on 17 September 1996. The black and white display shown here does not give a good indication of the data quality observed by the operator in real time from the false color display. The scale gives the specific humidity in gm/kg. These measurements were obtained during a cloudy period and at 0238 a small cloud is observed to drift through the lidar beam.

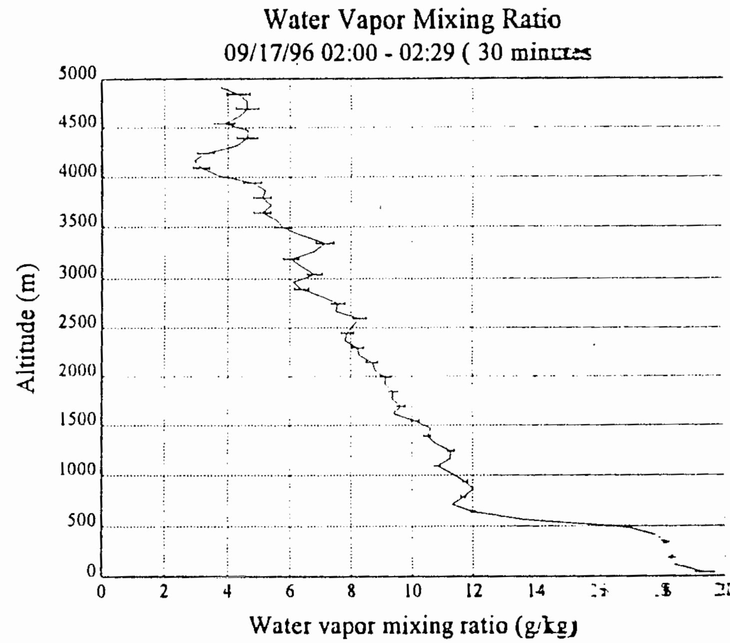

Figure 4(a). The temperature measurements as displayed by the real time display program of the LAPS instrument obtained on the USNS Sumner on 17 September 1996 at [illegible] Z. The profile includes the statistical error bars (±1σ) on every other data point. At upper altitudes the temperature data has been smoothed using a Hanning filter.

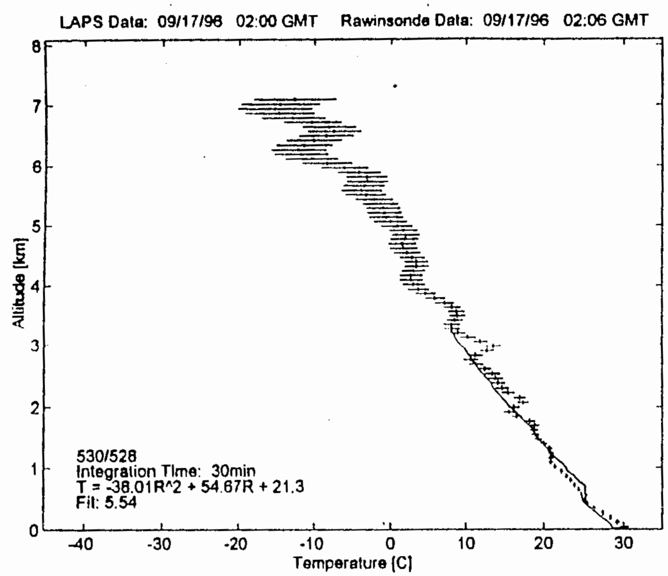

Figure 4(b). The temperature measurements from the LAPS instrument compared with a rawinsonde balloon release on the USNS Sumner on 17 September 1996 at 0200-0230 Z. The lidar profile includes the statistical error bars ($\pm 1\sigma$) on every other data point. At upper altitudes the temperature data has been smoothed using a Hanning filter. These are the same results as the lidar data as those displayed in the real time display shown in Figure 4a.

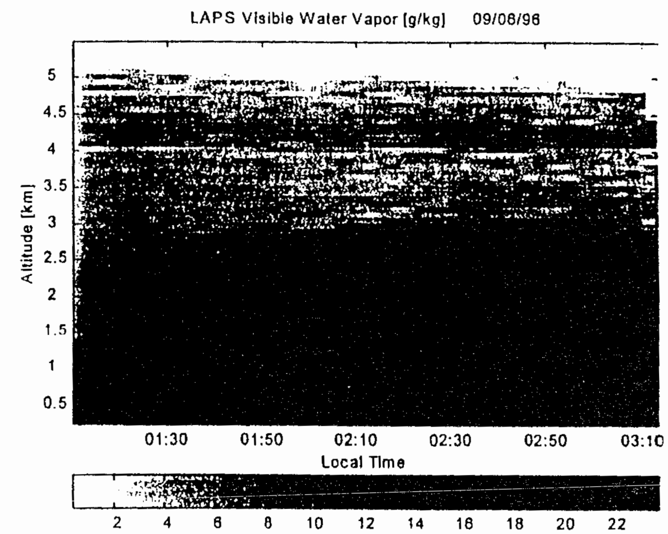

Figure 5. A time sequence of the 1 minute water vapor profiles show the variations that occur in the water vapor. The period of 0100 to 0300 on 6 September shows one of the typical unsettled periods where large variations occur in the boundary layer and elevated moist layers. This display is an attempt to show the variations observed by the operator in the false color display as a black and white figure.

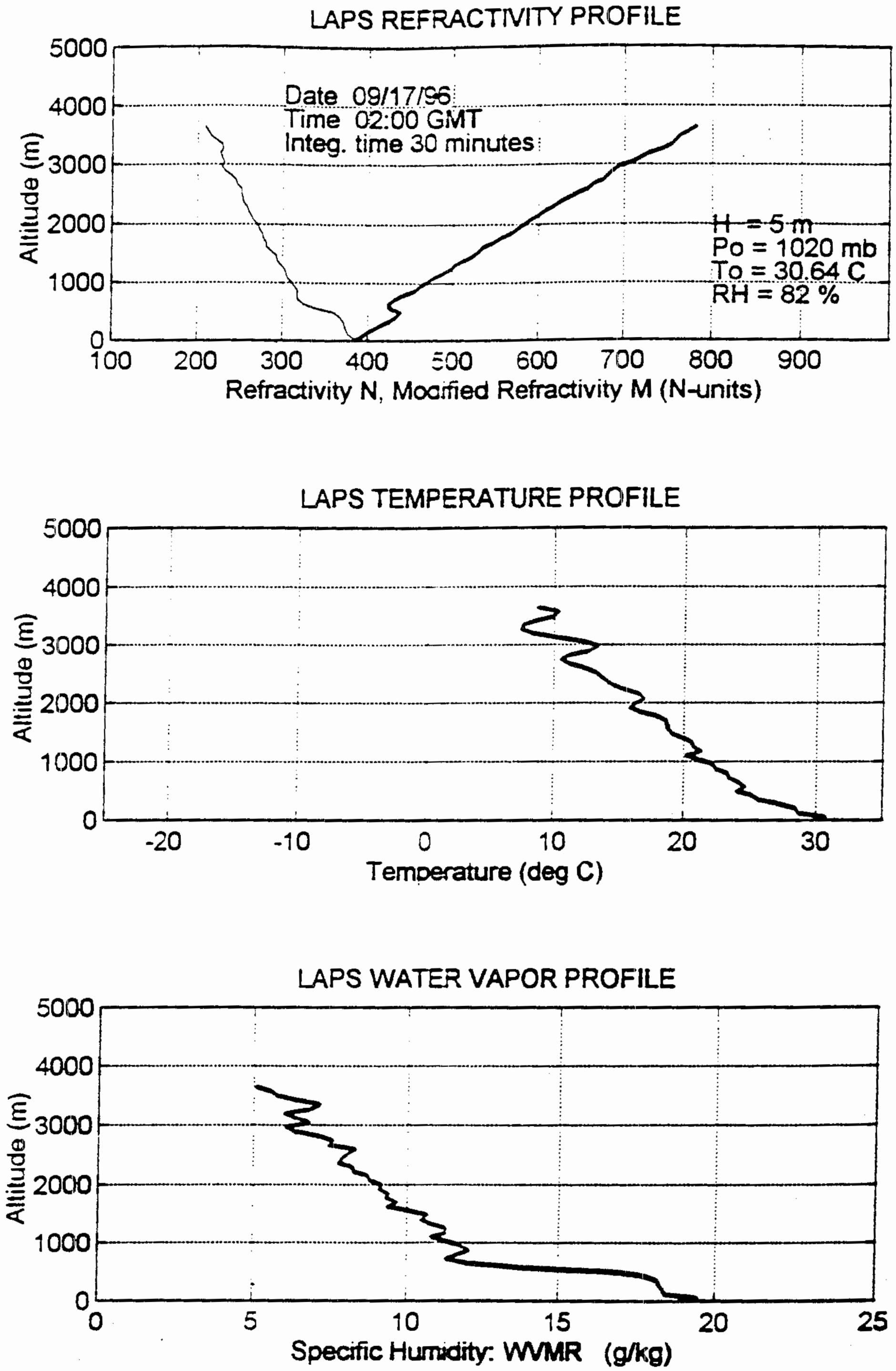

Figure 6. The lower panels show the water vapor (Figure 3a) and temperature (Figure 4a) measurements from the data gathered onboard the USNS Sumner on 17 September 1996. The upper panel shows the RF-refractivity (thin line) and modified refractivity (thick line) profiles calculated from the lidar measurements of water vapor and temperature.

SUMMARY

The completion of the fabrication and demonstration testing of the LAPS instrument during 1996 has shown that lidar can be developed to a level which permits routine measurements of atmospheric properties. The automated controls of many functions, which have typically isolated lidar within research laboratories, are not a problem and should not continue to limit the useful applications of lidar techniques. The LAPS has demonstrated that a rugged, weather sealed, instrument can be operated routinely and provide real time data products. The measurements can be made 24 hours per day and though limited in height, the daytime measurements of the lower atmosphere can certainly be performed.

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 points:

(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

The measurements of the LAPS instrument have been limited to 75 meter range resolution, however, the bench testing on newly developed high speed electronics will allow us to measure the future profiles with 7 meter resolution. The LAPS instrument is ready to be commercialize for use as land-based and shipboard instrument.

REFERENCES

1. "LAMP Lidar Tests at Point Mugu" Report for METOC Systems Program Office PMW-175, **ARL Report No. 94-2084-LP029**, July 1994.

2. "Multiple-wavelength Raman Lidar Measurements of Atmospheric Water Vapor," S. Rajan, T. J. Kane and C. R. Philbrick, **Geophys. Res. Let.** 21, 2499-2502, 1994.

3. "Lidar Measured Refractive Effects in a Coastal Environment," D. W. Blood, S. McKinley, C. R. Philbrick, R. Paulus and T. Rodgers, **Proceedings of IGARSS'94** (International Geophysics and Remote Sensing Symposium) at UCLA in Pasadena CA, August 1994, Vol I, pg 394-396, 1994.

4. "Lidar Measurements of Water Vapor Concentrations in the Troposphere," C. R. Philbrick, **Proceedings of IGARSS'94** (International Geophysics and Remote Sensing Symposium) at UCLA in Pasadena CA, August 1994, Vol IV, pg 2043-2045, 1994 .

5. "Pure Rotational Raman Lidar for Temperature Measurements in the Lower Troposphere," Paul A. T. Haris, PhD Thesis for Penn State University, Department of Electrical Engineering, August 1995.

6. "Lidar Measurements of Refractive Propagation Effects," C. R. Philbrick and D. W. Blood, in **Propagation Assessment in Coastal Environments**, NATO-AGARD CP 567, Paper 3, 13 pg, 1995.

7. "Remote Sensing by Active and Passive Optical Techniques," C. R. Philbrick, M. D. O'Brien, D, B. Lysak, T. D. Stevens and F. Balsiger, **NATO/AGARD Proceedings on Remote Sensing**, AGARD-CP-582, 8.1-8.9, 1996.

8. "Comparison of Lidar Water Vapor Measurements Using Raman Scatter at 266 nm and 532 nm," R. Harris, F. Balsiger and C. R. Philbrick, **Proceeding of IGARSS96 Conference on Remote Sensing for a Sustainable Future**, (International Geophysics and Remote Sensing Symposium) at Lincoln NB, May 1996, Vol III pg 1826-1829, 1996.

9. "Lower-tropospheric Temperature Measurements Using a Rotational Raman Lidar," F. Balsiger, P. A. T. Haris and C. R. Philbrick, in **Optical Instruments for Weather Forecasting**, SPIE Proceedings Vol. 2832, 53-60, 1996.

10. "Comparison of Lidar Water Vapor Measurements Using Raman Scatter at 266nm and 532 nm," F. Balsiger and C. R. Philbrick, in **Applications of Lidar to Current Atmospheric Topics**, SPIE Proceedings Vol. 2833, 231-240 1996.

11. "Particle Size Distributions and Extinction Determined by a Unique Bistatic Lidar Technique," T. D. Stevens and C. R. Philbrick, **Proceeding of IGARSS96 Conference on Remote Sensing for a Sustainable Future** (International Geophysics and Remote Sensing Symposium) at Lincoln NB, May 1996, Vol II pg 1253-1256, 1996.

12. "Optical Extinction from Raman Lidar Measurements," M. D. O'Brien, T. D. Stevens and C. R. Philbrick, in **Optical Instruments for Weather Forecasting**, SPIE Proceedings Vol. 2832, 45-52, 1996.

13. "Bistatic Lidar Measurements of Lower Tropospheric Aerosols," Timothy D. Stevens, PhD Thesis for Penn State University, Department of Electrical Engineering, May 1996.