AFRL-VS-HA-TR-98-0103
Environmental Research Papers, No. 1217

PROCEEDINGS OF THE BATTLESPACE ATMOSPHERIC AND CLOUD IMPACTS ON MILITARY OPERATIONS (BACIMO) CONFERENCE, 1-3 DECEMBER 1998

Editor:
Paul Tattelman

6 November 1998

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AIR FORCE RESEARCH LABORATORY
Space Vehicles Directorate
29 Randolph Road
AIR FORCE MATERIEL COMMAND
HANSCOM AIR FORCE BASE, MA 01731-3010

OPTICAL REMOTE SENSING OF ATMOSPHERIC PROPERTIES

C. Russell Philbrick* and Daniel B. Lysak, Jr.
The Pennsylvania State University
Applied Research Laboratory and
Department of Electrical Engineering
PO Box 30, State College PA 16804
814-865-2975, (fax) 863-8457, crp3@psu.edu

ABSTRACT

Techniques have been demonstrated which show the capabilities of lidar to measure the profiles of many meteorological and optical properties in the troposphere. The Lidar Atmospheric Profile Sounder (LAPS) instrument was prepared by the Applied Research Laboratory of Penn State University for the US Navy as an operational prototype that provides the profiles of water vapor and temperature as real time data products to support requirements for RF-refraction and meteorological data. The capability to measure the optical extinction at three wavelengths has been added to the instrument. The sounder was successfully demonstrated on the *USNS SUMNER* in Fall 1996 and has been used to gather data during several scientific research programs since that time. The data have provided an opportunity to investigate the variations of atmospheric properties with much finer resolution of the temporal variations than has been possible previously. Examples of some interesting variations in the properties of the lower atmosphere, including weather front passage and convective events, are used to show the importance of lidar measurements. The future directions for advancing our technical capabilities are apparent from the advances that have been made with the LAPS instrument. Future instruments will enhance the capabilities demonstrated here by further automation of lidar systems which use these Raman measurement techniques.

INTRODUCTION

The Lidar Atmospheric Profile Sensor (LAPS) instrument was prepared and tested to determine the capability of laser remote sensing to provide profiles of atmospheric properties during semi-automated shipboard operation over a wide range of meteorological conditions. Tests were conducted onboard the *USNS SUMNER* during September and October 1996 near the Florida coast. The instrument measures the water vapor profile based on the vibrational Raman scattering and the temperature profile based on the rotational Raman scattering. These measurements are used to calculate profiles of RF refractivity. Profiles of the Raman signals were stored each minute with a vertical resolution of 75 meters from the surface to a user selected altitude, typically between 5 and 15 km. The measured profiles are integrated, for selected intervals, typically 1, 5 or 30 minutes, to calculate the real time atmospheric profiles with their associated $\pm 1\sigma$ standard deviation for specific humidity, temperature, optical extinction and ozone. Daytime measurements of water vapor, extinction and ozone are made using the "solar blind" ultraviolet signals to obtain useful measurements without the intense daytime background. The LAPS prototype instrument includes several sub-systems to automate and monitor its operation. and it provides real-time display/transfer of the profiles. The instrument includes an X-band radar to detect aircraft as they approach the beam and automatically shuts down the laser to protect a 6 degree cone angle around the beam. The weather sealed instrument has been designed to include environment control, calibration, and performance self-tests to check many functions. The testing program has proven the qualities of ruggedness, reliability and general performance of the LAPS lidar system.

LAPS Instrument Development

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. 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. Lidar is a radar at optical wavelengths, where the laser transmitter sends a pulsed beam to scatter from the molecules and particles of the atmosphere. The arrival time of the backscattered light pulse provides a precise altitude for the scattering volume, and the intensity at the transmitted wavelength, as well as at several frequency shifted wavelengths (Raman scattering), provides a wealth of information on the atmospheric properties. Using the ratios of Raman shifted scattered radiation removes most of the uncertainties in deriving accurate data and provides a robust measurement of atmospheric properties. The primary sub-systems making up the LAPS lidar system are listed in Table 1.

Table 1. LAPS Lidar instrument sub-systems

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^{o} cone angle around beam

The LAPS lidar instrument has been developed from lessons learned during the development and testing of five prior lidar research instruments. The LAPS lidar has been specifically designed to be a rugged instrument, to provide automated operation, and to be field serviceable, so that it can be operated by technicians on Navy ships with a reasonable amount of training. More than twenty sub-systems 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 a planned schedule. The LAPS lidar has many advantages over current balloon techniques for atmospheric properties, it is capable of providing the RF refractivity profiles directly into radar propagation models for a continuously updated description of the local RF-propagation conditions, also the electro-optical propagation conditions can also be described. The LAPS instrument hardware was completed in mid-1996 and it was successfully tested onboard the *USNS SUMNER* in September/October 1996. The long term plan for the instrument is to replace most of the current balloon sonde profiling and enable continuous data collection to support radar operations or weather affected missions.

Raman Lidar Measurement Techniques

Raman scattering is one of the processes that occurs when optical radiation is scattered from the atmospheric molecules. Even though the intensity of Raman scattered radiation is much less than that scattered at the transmitted fundamental laser wavelength, it is most useful because the vibrational Raman scattering occurs at distinct wavelength shifts for each species and correspond to specific vibrational energy states of the molecules. The rotational Raman scattering provides a signal where the relative intensity of the shifted wavelengths depends directly upon the atmospheric temperature. The ratio of vibrational 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 285 nm) are at wavelengths widely separated from the exciting laser radiation and can be easily isolated for measurement using modern filter technology and sensitive photon counting detectors. The ratio of rotational Raman signals at 528 nm and 530 nm provides measurements which are sensitive to atmospheric temperature [Nedeljkovic 1993, Philbrick 1994, Haris 1995, and Balsiger 1996b]. Table 2 lists the measured signals acquired by the LAPS lidar. The altitude range of the measurements is extended at night using visible data channels, however the primary range of interest for RF-refractivity is between the surface and 3 km.

Based upon developments by other groups and in our laboratory, we now have the capability for reliably profiling most of the important properties of the atmosphere with lidar [Philbrick 1991, Whiteman 1992, Hauchecorne 1992]. 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. Nighttime 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 295nm/284nm (H_2O/N_2) ratio from the quadruple Nd:YAG laser radiation at 266 nm. A correction for the tropospheric ozone must be applied, it can be obtained from the ratio of the O_2/N_2 signals 278nm/284nm, thus the troposphere ozone profile is also obtained.

Table 2. The LAPS measurements from Raman scatter signals are summarized.

Property	Measurement	Altitude	Time Resolution
Water Vapor	660/607 Raman 294/285 Raman	Surface to 5 km Surface to 3 km	Night - 1 min. Day/Night - 1 min.
Temperature	528/530 Rotational Raman	Surface to 5 km	Night 30 min.
Optical Extinction 530 nm	530 nm Rotational Raman	Surface to 5 km	Night 10 to 30 min.
Optical Extinction 607 nm	607 N_2 - 1^{st} Stokes	Surface to 5 km	Night - 10 to 30 min.
Optical Extinction 285 nm	285 N_2 - 1^{st} Stokes	Surface to 3 km	Day and Night 30 min.
Ozone	276/285 Raman/DIAL	Surface to between 2 and 3 km	Day and Night 30 min.

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 technique to obtain the temperature profile. The Raman techniques, which use ratios of the signals for measurements of water vapor and temperature, have the major advantage of 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.

RF-Refractivity Measurements

Over a wide range of radar wavelengths, the refractive effects of the atmosphere can be simply described based upon the profiles of water vapor and temperature, because these describe the distribution of the molecular scatterers. It's larger scattering cross-section and extremely irregular spatial distribution cause water vapor profiles to be most significant for describing refractivity. The RF-refractivity, N, represents the significant figures of the refractive index, n,

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

and is based upon the following empirically derived relationship,

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

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,

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

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

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

The values used in these relationships, which are typical of the lower atmosphere, show that it is the gradients in water vapor that are most important in determining RF ducting conditions. The Raman lidar technique provides the water vapor and temperature profiles which can be used in these equations to directly determine the refractivity profile for input to propagation models [Philbrick 1995, Philbrick 1996b].

RESEARCH ACCOMPLISHED

The LAPS instrument was installed on the *USNS SUMNER* on 30 August at Pascagoula MS. Testing of the LAPS instrument was carried out during the period 1 September - 15 October 1996 in the Gulf of Mexico and along the Atlantic coast. The LAPS instrument has also participated in several scientific research projects, NARSTO-Northeast (Gettysburg PA, August 1996), SCOS (Hesperia CA, August-September 1997), ARM-Northslope (Barrow AK, March 1998), FIRE (Barrow AK, May 1998), NEC-OPS (Philadelphia PA, August 1998).

LAPS Measurements Onboard the *USNS SUMNER*

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 below and between clouds and through light clouds to provide useful profiles. During approximately 5 to 10 % of the time period, clouds with high optical thickness limited the operations and profiles are only provided below the cloud base at those times.

The LAPS development has been directed toward the measurement of the refractivity of the atmosphere for determination of electromagnetic ducting conditions. Figure 1 shows an example of time sequences of the LAPS lidar data for water vapor and temperature profiles during a 6 hour period on 11 October 1996 during the shipboard tests. Figure 1 (c) shows the time sequence of the RF-Refractivity profiles obtained from the water vapor and temperature shown in the accompanying plots. The lidar derived time sequence provides continuous updates of the radar refractivity and meteorological profiles for operational use, the sequence plots are useful because they show trends and immediately detect any changes in conditions.

The optical extinction profile from the LAPS instrument is determined from the signal loss in the molecular profiles caused by scattering by clouds and aerosol particles. The gradient observed in the major molecular species profiles can be compared with the neutral density scale height 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 [Rau 1994]. However, the extinction can be determined from the profiles of primary molecular species at the Raman shifted wavelengths [Philbrick 1996a, Stevens 1996a, O'Brien 1996, Stevens 1996b, Philbrick 1997a]. The optical extinction profiles can be determined from the gradients in each of the measured molecular profiles, at 607 (N_2), 530 (rotational Raman) and 284 (N_2) nm. Figure 2 shows a example of extinction measurements obtained directly from the Raman signals of the LAPS lidar during the *USNS SUMNER* tests. The wavelength dependent optical extinction can be used to describe changes in the particle size distribution as a function of altitude for the important small particles. These measurements can then be interpreted to determine the air mass parameter and atmospheric optical density.

We have also demonstrated that a new bi-static technique can be used to estimate particle density, size and distribution widths (of spherical scatters) by using the unique information contained in the polarization ratio of the scattering phase function versus angle. A bistatic receiver has been developed to provide data on the scattering phase function of the aerosols [Stevens 1996a,b, Philbrick 1998]. This technique can be implemented to utilize the same transmitter beam of the lidar to provide additional information on particle size and density.

LAPS Performance Summary

Examples of the LAPS profiles compared to individual balloon rawinsondes have been shown in several reports [Balsiger 1996a, Philbrick 1996b, Philbrick 1997b]. The important result for this investigation is that many comparisons were made to examine how well the instrument performed on the ship when a single calibration constant is applied and the measurements are compared to the reference of standard rawinsonde balloons. Here the LAPS

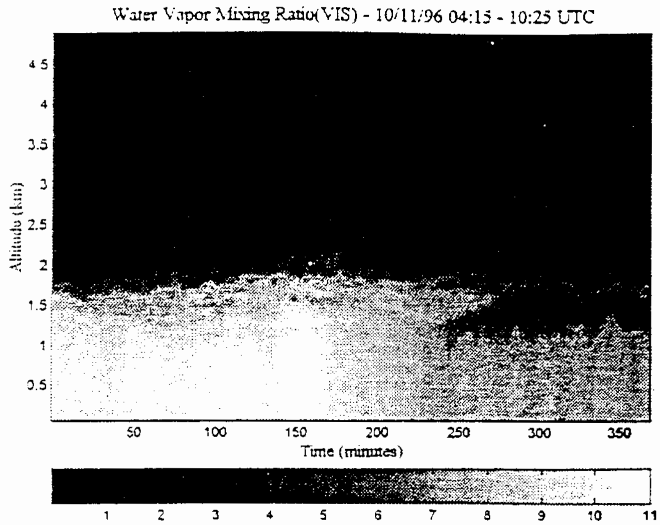

Figure 1 (a). A time sequence shows 6 hours of the water vapor profiles (specific humidity in gm/kg) measured onboard the *USNS Sumner* on 11 October 1996. The top of the boundary layer is clearly shown. Notice the dry layer at 1.5 km after 08:00 UTC and the upper moist layer between 3.5 and 4 km.

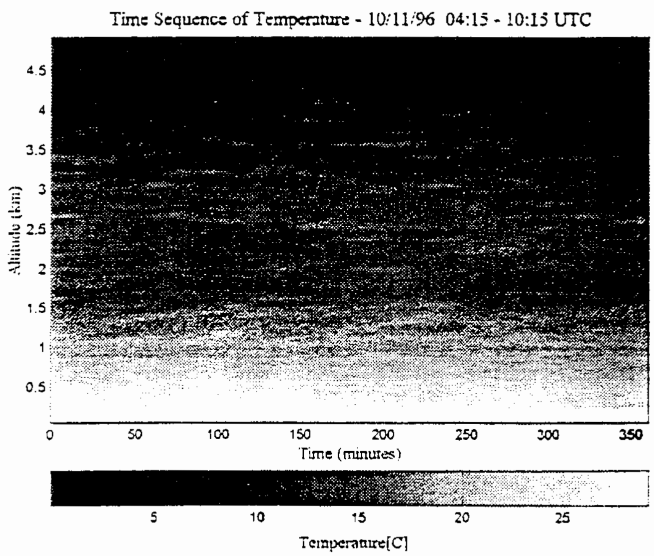

Figure 1 (b). Temperature profiles (C) measured during the same 6 hour period as the water vapor shown above. The temperature profiles show an inversion near 150 meters.

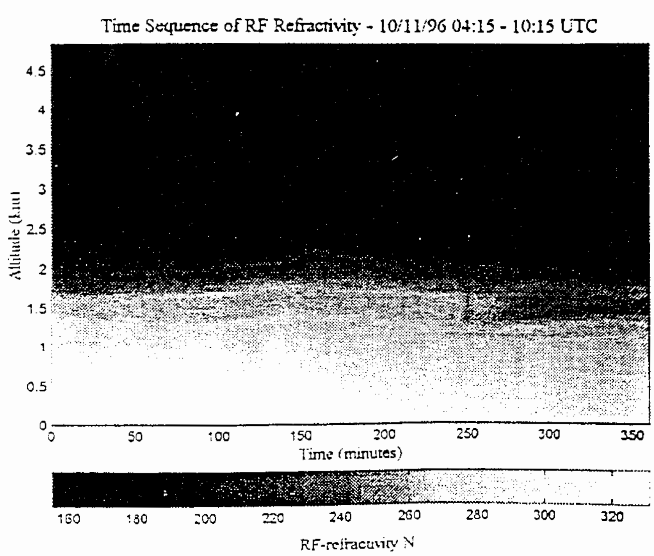

Figure 1 (c). The time sequence of the RF-refractivity profiles calculated directly from the water vapor and temperature profiles measured by the LAPS lidar. The time sequence gives an impression for the changes in refraction. Notice that the dry layer at 1.5 km and the water vapor gradient on the top of the boundary layer cause significant gradients in RF-refraction.

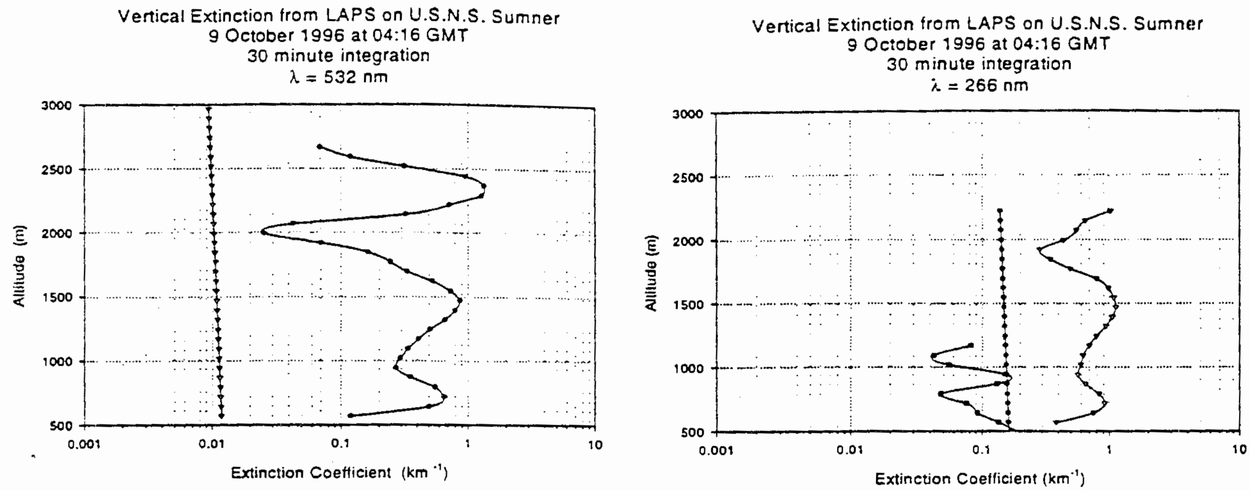

Figure 2. The extinction profiles measured by the LAPS instrument on the *USNS SUMNER* at visible (530 nm) and ultraviolet (285 nm) wavelengths. The profiles show the molecular, aerosol and ozone extinction components.

lidar results have been compared to the results for 97 rawinsonde flights. Several balloon instruments failed to give results, all of those which are available are summarized in Figure 3. The results here are based upon the average value of a ratio of the lidar and balloon data for each flight. The lidar data are taken from the 30 minute integration at the time of the balloon release. Any error in the balloon measurement, difference in the atmosphere between the vertical lidar profile and the balloon location (at times 50 km away by 5 km), or differences due to a changes in the height of a profile sharp gradient have been ignored. The last factor has been found to yield significant differences at times because the balloon data are point measurements during assent while the lidar integrates any effect due to a gradient that moves. The differences observed between the lidar and the sonde result in an average difference of ±4%, which is quite good considering the different measuring conditions. The major differences correspond to a few sondes at times when the visible channels have been effected by exposure to high solar intensity which temporarily shifts the detector gain due to saturation.

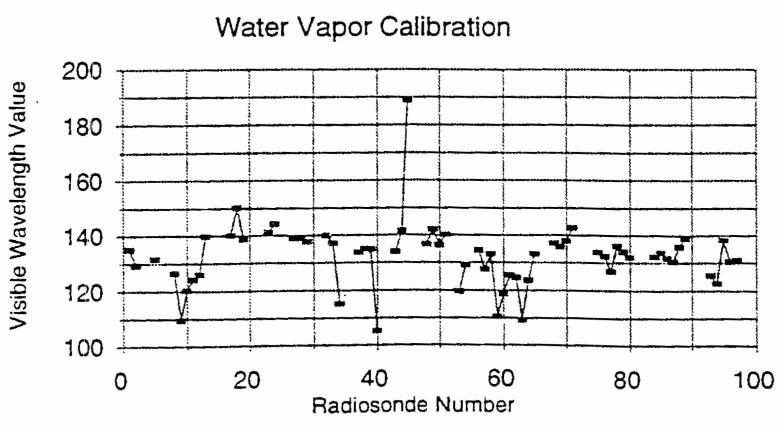

Figure 3. The average ratio of all data points of the lidar and balloons results for water vapor using the visible channels. Each point represents the average for the flight and corresponding lidar profile. A few of the points (for example #45) show the saturation effect from exposure to intense daytime radiation.

CONCLUSIONS AND RECOMMENDATIONS

The LAPS instrument was originally prepared for the Navy as an operational prototype for use on large ships and at shore sites. Many factors make it important to implement this new technology, these include items such as the limited temporal and spatial resolution of sonde measurements, balloon instrument expense and support costs, personnel support requirements, shipboard volume (for storing expendable instruments/helium and preparation of the balloons), pollution from battery acid, radio signal announces ship location, and other factors. The LAPS instrument approach can replace most of the requirements for radiosonde balloons. The lessons learned in the development of the LAPS instrument have provided the basis for an advanced design which will result in a smaller instrument. Planned upgrades should: (1) improve the vertical resolution and dynamic range using new higher speed electronics, (2) improve the detector design to allow automated self calibration, (3) provide capability to measure the wind velocity, and (4) add ability to describe the electro-optical environment.

The frequently large temperature gradients between the surface and the overlying air mass, particularly due to the warmer water surface and cooler overlying air mass lead to development of turbulent convective cells over the water surface. The aerosols generated by the surf, by choppy conditions over the open sea, and the churning propellor during the passage of a ship (IR ship tracks) are entrained in the convective cells. Several investigators in the EOPACE (Electro-Optical Propagation Assessment in the Coastal Environment) project have worked to characterize the physical properties of the aerosols with point measurements of the size, density, and composition [Gathman 1996, Lifkin 1997, Kiser 1996, Kiser 1997]. Understanding of the atmospheric optical properties is critical for use and interpretation of the many operational sensor systems. The lidar investigations are helping to provide the physical understanding of the atmospheric scattering properties which can form a basis for development of tactical decision aids for advanced optical sensor systems.

The LAPS instrument was operated and data obtained on every operation attempted or planned during the period of the sea trial. Investigations of the data show that the instrument was successful in demonstrating the capability to obtain the meteorological data 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 profiles combined with a mesoscale grid model, which provides the spatial continuity and provides a prediction of short-term and long-term conditions, within constraints imposed by the measured profiles.

ACKNOWLEDGMENTS

The development of the LAPS instrument was supported by the US Navy SPAWAR PMW-185 and ONR and testing was on the *USNS SUMNER* operated by NAVOCEANO. The METOC support for rawinsonde balloons was coordinated by Prof. K. Davidson and LCDR D. Harrison of the Naval Postgraduate School. The LAPS development was possible due to efforts of D.B. Lysak, Jr., T.M. Petach and the engineering staff of the PSU Applied Research Lab. Several graduate students of the PSU Department of Electrical Engineering have contributed much to the LAPS development, particularly P.A.T. Haris, T.D. Stevens and M.D. O'Brien.

REFERENCES

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

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

Gathman, S. G., and Jensen , D. R., "Maptip (Marine aerosol properties and thermal imager performance): Aerosol Characteristics in a Coastal Region", Naval Command, Control and Ocean Surveillance Center, San Diego, CA. RDT and E Div., NTIS ID No.: AD-A300 255, Aug 1995.

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

Hauchecorne, A., M. L. Chanin, P. Keckhut, and D. Nedeljkovic, "Lidar monitoring of the temperature in the middle and lower atmosphere," Appl. Phys. B55, 29-34, 1992.

Kiser, R. E., "The Generation and Characterization of Surf Zone Aerosols and Their Impact on Naval Electro-Optical Systems", MS Thesis, Naval Postgraduate School, Monterey, CA, December, 1996.

Kiser, R. E., K. L. Davidson ad C. R. Philbrick, "The Generation and Characterization of Surf Zone Aerosols and Their Impact on Naval Electro-Optical Systems," in **Proc. of the Electromagnetic/Electro-Optics Performance Prediction Sym.**, Naval Post Graduate School, Monterey CA, 355-375, June 1997.

Littfin, K. M., and D. R. Jensen, "An Overview of EOPACE (Electrooptical Propagation Assessment in Coastal Environments), Including In Situ and Remote Sensing Techniques", AGARD Conference Proceedings 582, Toulouse, France, pp. 10-1 to 10-8, October 1996.

Nedeljkovic, D., A. Hauchecorne and M. L. Chanin, "Rotational Raman lidar to measure the temperature from the ground to 30 km," IEEE Trans. Geos. Remote Sens. 31, 90-101, 1993.

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

Philbrick, C.R. "Lidar Profiles of Atmospheric Structure Properties," in **Earth and Atmospheric Remote Sensing**, SPIE Vol. 1492, 76-84, 1991.

Philbrick, C.R. "Raman Lidar Measurements of Atmospheric Properties," **Atmospheric Propagation and Remote Sensing III**, SPIE Volume 2222, 922-931, 1994.

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

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

Philbrick C. Russell, and Daniel B. Lysak, Jr., "LIDAR Measurements of Meteorological Properties and Profiles of RF Refractivity," 1996 Battlespace Atmospheric Conference, San Diego CA, December 1996b.

Philbrick, C. Russell, Michael D. O'Brien and Christophe Bas, "Optical Properties of the Lower Atmosphere," 1997 Battlespace Atmospheric Conference, San Diego CA, December 1997a.

Philbrick C. Russell, and Daniel B. Lysak, Jr., "Measurement Capability of the LAPS Lidar," 1997 Battlespace Atmospheric Conference, San Diego CA, December 1997b.

Philbrick, C.R., and D.B. Lysak, Jr., "Atmospheric Optical Extinction Measured by Lidar," in **E-O Propagation, Signature and System Performance Under Adverse Meteorological Conditions**, NATO Sensors & Electronics Technology Panel (SET), Naples, Italy, March 1998.

Rau, Y.-C., "Multi-Wavelength Raman-Rayleigh Lidar for Atmospheric Remote Sensing," PhD Thesis for Penn State University, Department of Electrical Engineering, May 1994.

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

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

Whiteman, D.N., S. H. Melfi and R. A. Ferrare, "Raman lidar system for the measurement of water vapor and aerosols in the Earth's atmosphere," Appl. Optics 31, 3068-3082, 1992.