ARL Electro-Optics Laboratory Lidar Applications

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Over the past five years ARL has established a capability for optical and spectroscopic research, and the development, design, prototyping, and testing of electro-optical instruments and systems. The Laboratory is in a position to exploit the rapidly developing technology of lasers and electro-optical devices for basic research and advanced system development. Familiarity with diverse sensors and the electronics for mating them with digital signal processing systems is leading to improvements in techniques for the acquisition of atmospheric and oceanographic data.

Laser experiments in light propagation through air and water are underway. The present emphasis is on lidar systems that transmit pulsed laser light and measure the intensity of backscattered light in a manner analogous to radar. Lidar, operating in the infrared, visible, and ultraviolet spectral regions, is a unique tool for monitoring the atmosphere. It can provide data on meteorological phenomena, and can measure atmospheric properties of interest for the development of future optical communication and tracking systems. There will be similar opportunities in the next decade for the development of underwater electro-optical systems.

The ARL Electro-Optics Laboratory is a center for a wide range of research and development activities, applying state-of-the-art optical techniques and devices to scientific investigations and advances in technology. Current efforts are in the application of lidar systems for remote sensing of atmospheric properties, and studies of underwater propagation of light in the blue-green spectral region. Experiments with ARL's Lidar Atmospheric Measurements Profiler (LAMP) provide data on meteorological phenomena, atmospheric chemistry and dynamics, and microwave refractivity. Investigations of underwater propagation will produce data to support the development of underwater lidar, imaging, and communication systems. The laboratory has several special instruments and facilities, backed up by a wide variety of test equipment and calibration systems.

A major effort is on the development of a Lidar Atmospheric Profile Sensor (LAPS), the prototype of an operational meteorological instrument. The LAPS will become a key component of the Navy's Shipboard Meteorological and Oceanographic Observing System (SMOOS) to provide data inputs to Tactical Environmental Support System 3 (TESS3). The LAPS program is sponsored by the Environmental Program Office of SPAWAR (PMW165). Navy plans call for LAPS sea tests in 1995, a step in the transition from basic research (6.1) to hardware demonstration (6.4) within a five-year time frame.

Another system scheduled for completion in 1993 is the Water Aerosol/Vapor Environment-Lidar And Radar Sounder (WAVE-LARS) to investigate aerosols and clouds, sponsored by the Department of Energy. The goal is a better understanding of environmental effects of the national fuel policy. The WAVE-LARS uses a volume-scanning lidar to investigate microphysical processes such as cloud formation. Data on aerosol scattering at multiple wavelengths will provide critical information on radiative transport of energy in the atmosphere. Programmed simultaneous scans by lidar and 94-GHz radar will provide repeated mapping of a selected volume of the atmosphere. The lidar and radar returns are processed in real time to produce a common database. The instruments are housed in shipping containers, and can be set up to operate as a remote field laboratory.

A Giant Atmospheric Lidar (GAL) is being assembled from residual property from major programs of the Navy and the Penn State Astronomy Department. Its transmitter is a large injection-seeded excimer laser with an output of more than 250 watts. The receiver uses seven mirrors of one-meter diameter in a close-packed hexagonal array. With a signal intensity three orders of magnitude higher than that of the best current lidar sounders, the GAL will make measurements to the heights of low-orbit satellites. It will measure minor atmospheric species in regions previously inaccessible to remote sensing. The Electro-Optics Laboratory is also equipped to investigate underwater light propagation with several lasers at different wavelengths. Measurements of depolarization, attenuation, time-domain pulse spreading, and spatial beam spreading produce information on the basic physical properties of the waters of different oceanic regions.

LAMP LIDAR

ARL's Lidar Atmospheric Measurements Profiler (LAMP) is the primary instrument for several ongoing efforts, including investigations of middle-atmosphere dynamics and chemistry under NSF sponsorship, and studies of particle distributions and optical scattering by aerosols and particles in the troposphere for the Navy's NRAD office. Figure 1 shows the LAMP system mounted on a laboratory cart. The transmitter includes a laser and energy monitor on the bottom shelf; the laser beam goes up through a beam expander to beam-steering mirrors coaxial with the receiver optical system. The receiver on the top shelf is a modified Cassegrain telescope that focuses output light on the entrance aperture of a detector box on the middle shelf. Received light can also be transferred to the detector box with an optical fiber. One detector subsystem measures atmospheric properties from the surface to an altitude of 20 km and another covers altitudes from 2 to 80 km. They measure backscatter intensity, extinction, visibility, temperature, gas densities, aerosol distributions, water vapor concentration, and cloud properties. The system is housed in a standard 8- × 8- × 20-foot shipping container; it can be transported to remote locations to operate as a field laboratory.

The LAMP development began with experience gained in the development, design, and operation of two earlier experimental Air Force lidar systems.[1, 2] Building on the results of these efforts, the LAMP extends the previous work of many investigators. Melfi[3] showed the power of techniques based on Raman scattering for water-vapor measurements. Chanin and Hauchecorne[4] have shown the usefulness of high-altitude lidar

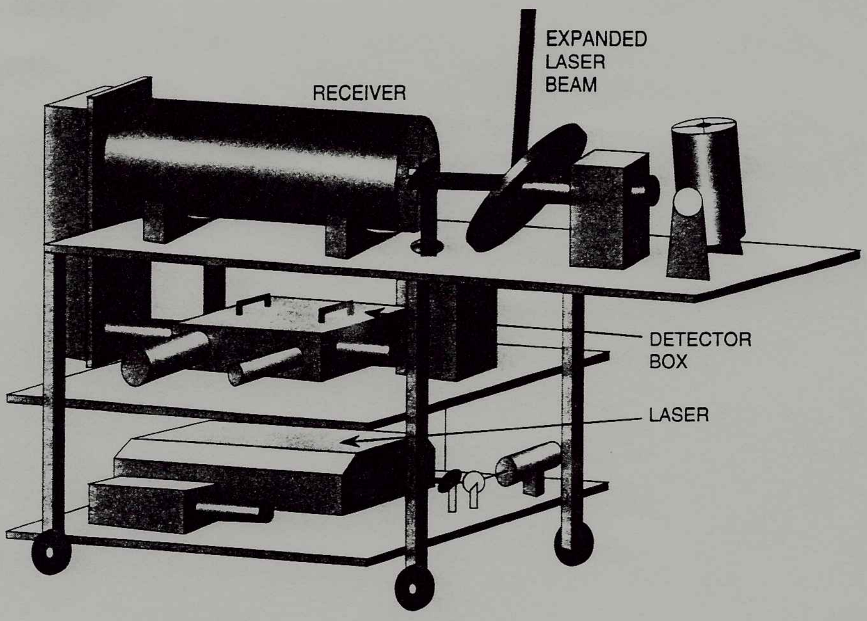

FIGURE 1. LAMP LIDAR MOUNTED ON LABORATORY CART.

profiles. Aerosol measurements by McCormick et al.[5], and Carswell[6] have established the capability of lidar to measure several atmospheric optical scattering properties. The LAMP was built and tested in 1990 and 1991 by faculty, staff, and graduate students of the Applied Research Laboratory and the Penn State Electrical Engineering Department. It exploits recent advances in laser technology, extending the operational altitude and incorporating multiple detector subsystems to make simultaneous measurements at different wavelengths.

The transmitter is a Nd:YAG laser with 30-watt average power and 200-megawatt peak output. Its fundamental wavelength is 1064 nanometers; frequency doubling and mixing can generate wavelengths of 532, 355, and 266 nm. Because of the low intensity of the sky background at the shortest ultraviolet wavelength, it is of interest for daytime operations. Measurements of Rayleigh and Raman scattering at diverse wavelengths produce information on atmospheric dynamics and profiles of atmospheric species. The LAMP transmits visible 532 nm light and 355 nm ultraviolet, and processes the returns with as many as eight detectors. The monostatic optical configuration enables the detectors to receive near-field light, so the output signal spans a wide dynamic range. To cover the full dynamic range, the signal is separated into low- and high-altitude channels. A mechanical shutter blocks high-intensity low-altitude returns from all high-altitude detectors, which only receive returns from altitudes above 2 km. High-intensity returns produce analog signals that are digitized at 10 MSps to give 15-meter altitude resolution from the surface to 25 km. Photons are counted in weak Raman signals and high-altitude signals; 500-nanosecond bins provide 75-meter range resolution from 2 to 80 km. The detector box includes channels for the first Stokes vibrational N_2 Raman signals at 607 nm and the H_2O signal at 660 nm. Measurements of rotational Raman backscatter at 528 and 530 nm are the basis for temperature profiles of the lower atmosphere in the presence of clouds and boundary-layer aerosols.

Figure 2 shows examples of LAMP outputs corrected for the decrease in intensity with the square of the altitude. Rayleigh scattering signals from low- and high-altitude channels are merged to give continuous gas-density profiles over the full range of the 532- and 355-nm signals. Their ceiling varies from 60 to 80 km with changes in atmospheric transmission. Returns from Pinatubo aerosols are seen between 20 and 30 km. Backscatter from aerosols also adds significantly to the signal at lower altitudes. The 355-nm returns from cirrus cloud strata in the vicinity of 10 km are obscured by molecular backscatter. The 532-nm light, not as strongly scattered by molecules, shows more distinct returns from these clouds. At lower altitudes the 607-nm Raman channel produces an N_2 density profile and the 660-nm channel produces a water-vapor profile.

Profiles taken on different days show that cloud layers do not cause significant changes in the background profile of small aerosols throughout the troposphere. There are long-term spatial and temporal changes in these aerosols, but they change surprisingly little as clouds come and go. The tropospheric aerosols are obviously composed of particles much smaller than the lidar wavelengths. The strength of their returns indicates that these aerosols have high densities. Their global distribution plays an important role in the radiation budget of the Earth's atmosphere. They may raise the albedo enough to

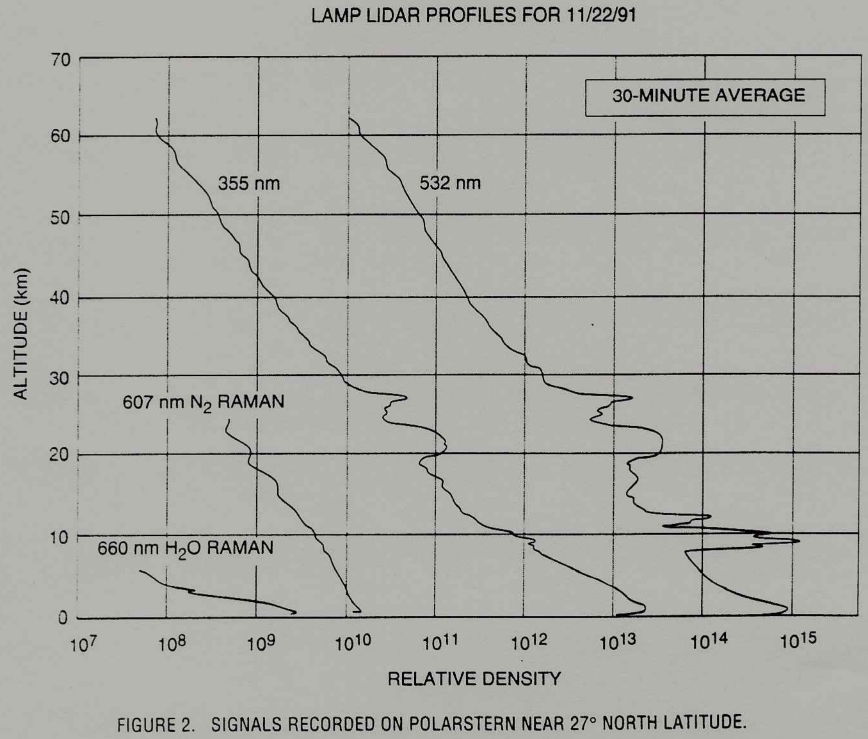

FIGURE 2. SIGNALS RECORDED ON POLARSTERN NEAR 27° NORTH LATITUDE.

counterbalance the greenhouse effect, explaining the failure of meteorological observations to show the magnitude of the predicted global warming from "greenhouse" gases.

At tropospheric altitudes the Raman N_2 profile and the 532- and 355-nm Rayleigh returns make it possible to distinguish extinction, molecular scattering, and backscatter due to particles. Vibrational Raman scattering peaks can be obtained for any molecular species of interest (such as O_2, N_2, or H_2O). The intensities of the Raman returns are typically three orders of magnitude lower than that of the 532-nm Rayleigh return. For each molecule, shifts to longer wavelengths (the first Stokes transitions) can be separated from the background by filters. For example, N_2 vibrational Raman scattering of the 532-nm wavelength produces a return at 607 nm; Figure 2 shows a useful return to an altitude of 25 km. For H_2O, the wavelength is 660 nm and the return extends up to 7 km. Each vibrational Raman spectral line is broadened by the rotational lines around the vibrational states. The ratio of the H_2O signal to the N_2 signal is a measure of the water vapor concentration. The system sensitivity and uncertainty factors are the same for each channel, and tend to cancel out in the ratio. Figure 3 compares water vapor profiles measured by the LAMP lidar and standard balloon-borne meteorological instruments. The lidar profile includes statistical error bars of one standard deviation.

Rotational Raman measurements are compared to the thermal distribution of molecular energy states to determine the temperature. The rotational states correspond to many spectral lines forming an envelope on both sides of the excitation wavelength. These are the Stokes (longer wavelength) and anti-Stokes (shorter wavelength) regions. The population distribution in the rotational states is a function of temperature, so the temperature can be deduced from the ratio of signals at the 530- and 528-nm wavelengths scattered from the laser wavelength of 532 nm. Figure 4 shows altitude profiles of the individual signals (on the right) and their ratio (on the left) with error bars of one standard deviation.

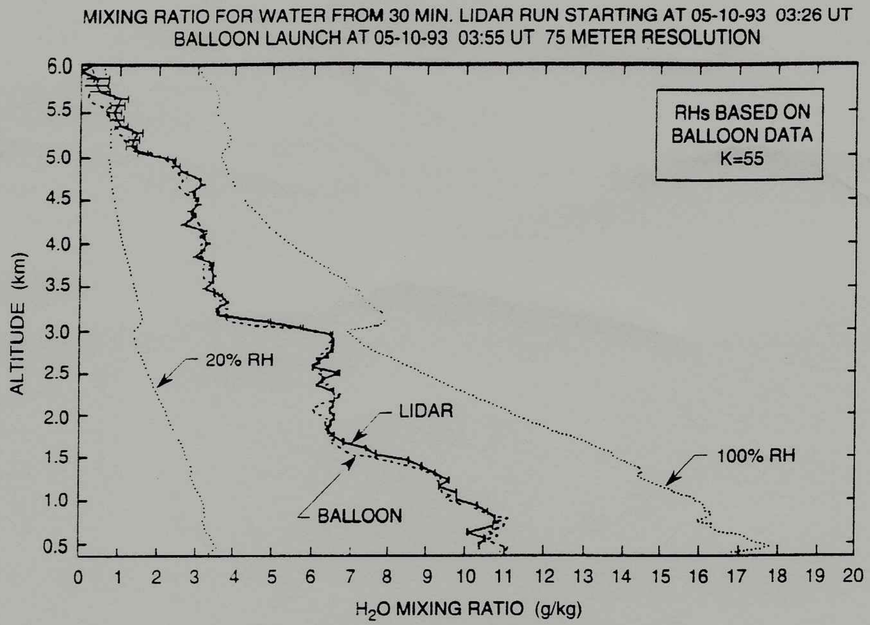

FIGURE 3. VIBRATIONAL RAMAN WATER VAPOR MEASUREMENT COMPARED WITH DATA TAKEN AT THE SAME TIME FROM BALLOON-BORNE INSTRUMENTS.

THE LADIMAS CAMPAIGN

In 1991 the container-housed LAMP field laboratory was transported to Norway to participate in an international effort to study the LAtitudinal DIstribution of Middle Atmospheric Structure (LADIMAS). Researchers from Penn State, the University of Massachusetts (Lowell), Saskatchewan University, Bonn University, and Wuppertal University cooperated in a voyage from Arctic to Antarctic waters. The project included measurements by lidar, rocket instrument packages, and balloon-borne instruments between 70 degrees North and 65 degrees South latitude. Results from lidar, digisonde, microwave radiometer, and infrared spectrometer measurements include information on atmospheric structure, chemistry, gravity waves, and tides, as well as the formation of layers of meteoric iron.

For the first data-gathering session in September 1991, the mobile LAMP was set up at the Andoya Rocket Range in northern Norway. Lidar data and data from rocket-borne instruments were compared. Then the LAMP was moved to the POLARSTERN helicopter deck for operational testing between Tromso, Norway, and Bermerhaven, Germany. Measurements were made on each clear night, and on some cloudy nights measurements were made below and into the clouds. After a pause at the Alfred-Wegener-Institut in Bremerhaven for loading more equipment and supplies, the POLARSTERN proceeded to Antarctic waters. The LAMP produced a massive body of data on atmospheric properties over a wide range of latitudes and altitudes. This unique data set is under continuing investigation to study atmospheric properties on a global scale, to examine environmental changes, and to test current models of the atmosphere. The voyage of the POLARSTERN demonstrated lidar capabilities: lessons learned in operations under adverse environmental conditions are valuable for the practical design of an advanced meteorological instrument.

Strong stratospheric scattering layers were observed in the LADIMAS campaign. Analysis of the signals produced temperature and density profiles above 30 km.[7] Measurements at two wavelengths make it possible to distinguish molecular and particle scattering components.[1, 2] The molecular scattering cross section is much larger for 355-nm radiation than for 532 nm, but the particle scattering cross sections for the two wavelengths may not differ significantly. Figure 5 is a latitudinal plot of the backscatter intensity of 532-nm light. The strong variation with latitude is the result of the Pinatubo eruption, which transported dust to stratospheric heights and resulted in aerosol scattering from stratospheric layers lasting many months.

Nichols[8] recognized the importance of turbidity in describing the color of the sky after Rayleigh[9] showed that the blue color was due to molecular scattering. Turbidity is defined as the ratio of the total attenuation to that due to molecules alone (see van de Hulst[10]). Typical turbidity values vary from about 1.5 to 6 on clear days. The total lidar backscatter signal divided by the signal that would be generated by molecular backscatter alone is a ratio similar to the turbidity definition. It is not exactly the same because the attenuation is not directly related to the backscatter intensity. Interesting results have come from

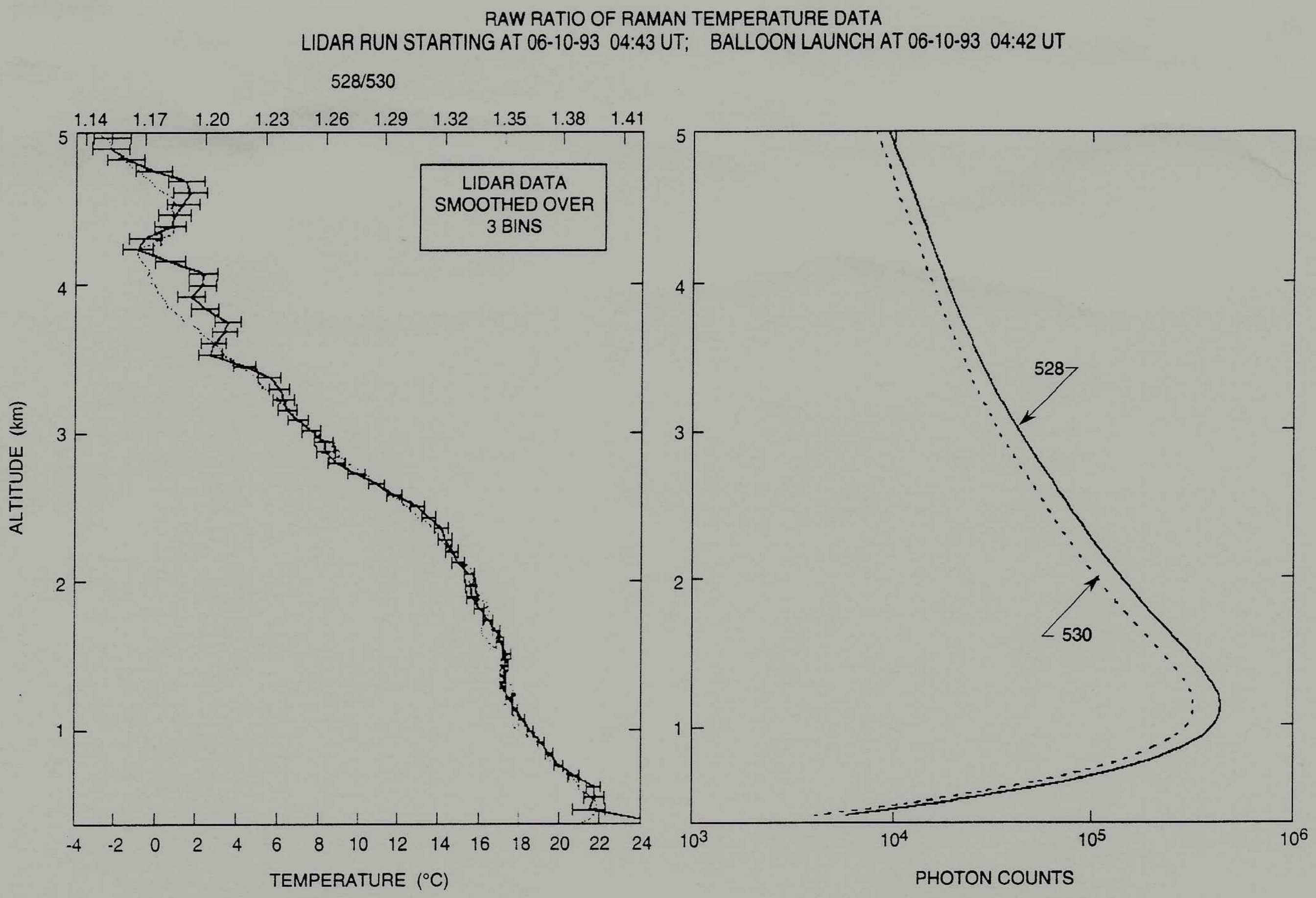
RAW RATIO OF RAMAN TEMPERATURE DATA
LIDAR RUN STARTING AT 06-10-93 04:43 UT; BALLOON LAUNCH AT 06-10-93 04:42 UT

FIGURE 4. TEMPERATURE PROFILE FROM 528 AND 530 NM ROTATIONAL RAMAN SIGNALS COMPARED WITH TEMPERATURE PROFILE MEASURED BY BALLOON-BORNE INSTRUMENTS

a study of the backscatter intensity and extinction of the Raman N_2 signal at 607 nm. The particle diameters of small aerosols distributed through the troposphere are comparable to this wavelength, and in the vicinity of 5 km they produce a 532-nm signal stronger by a factor of 2 than that predicted for molecular scattering. The 355-nm signal is 10 times stronger than that due to molecular scattering alone. The small-aerosol component of the tropospheric backscatter was relatively uniform over the ocean from Arctic (70°N) to Antarctic latitudes (65°S). In the presence of clouds, the background from small-aerosol scattering varies remarkably little. Clouds do not change the slope or magnitude of the aerosol component significantly, except for the expected attenuation by the cloud itself. The magnitude of the small-aerosol scattering is quite significant. The influence of the turbidity due to small-aerosol scattering will be important in a study of the turbidity contribution to radiative energy transfer in the atmosphere.

The global distribution of atmospheric turbidity due to small aerosols is less obvious than the distribution of clouds, but it can be a significant factor in the Earth's radiation budget. Global warming estimates must be revised downward if less solar energy enters the lower atmosphere to participate in the "greenhouse" effect. Both cloud formation and small-aerosol turbidity are nonlinear processes, and their coupling is uncertain, but it is important to gain a better understanding of changes in the global distribution of aerosols.

SUMMARY

ARL's LAMP system has shown that lidar is a unique tool for improving our understanding of the atmosphere. The LADIMAS campaign demonstrated that lidar measurements agree consistently with data from rocket- and balloon-borne instruments over a wide range of latitude and altitude. Lidar is a cost-effective means for studying the structure, dynamics, and chemistry of the atmosphere. Measurements of the continuous presence of relatively small aerosol particles throughout the troposphere have provided significant findings applicable to ongoing studies of the Earth's energy budget and climate changes.

Research instrument demonstrations at ARL and other laboratories around the world have established lidar as a viable technique for measuring diverse atmospheric parameters. Results are being applied to develop prototypes of operational lidar systems. Current ARL efforts for the Navy are focused on the development of a prototype lidar for ship and shore installation for real-time measurements of meteorological and microwave-refractivity parameters. Advanced remote-sensing systems of this type will eventually provide most of the data now gathered by meteorological balloons. The first-generation Lidar Atmospheric Profile Sounder (LAPS) is under development for the SPAWAR Advanced Meteorological Program Office (PMW165). It will apply Raman lidar principles to produce profiles of atmospheric temperature and water-vapor concentration. These two properties can be combined to provide radar operators with microwave refractivity information in real time. In addition to the Navy program, several ARL efforts are sponsored by NSF and DOE. These investigations are carried out by a team of eight faculty members, staff engineers, and technicians, who guide the efforts of about a dozen graduate students. Related research activities are joint efforts with the Penn State Electrical Engineering Department. ARL benefits from the energy and enthusiasm of graduate students working on the projects, and the Electrical Engineering Department gains access to state-of-the-art electro-optical hardware to give the students hands-on experience.

ACKNOWLEDGMENTS

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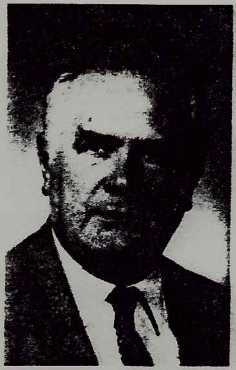

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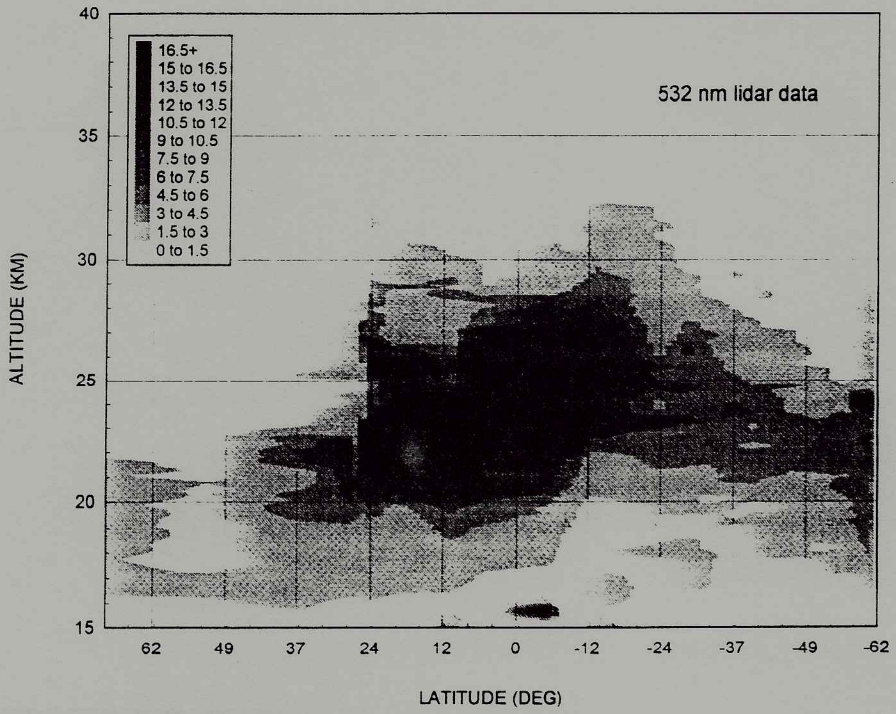

FIGURE 5. LATITUDINAL DISTRIBUTION OF 532-NM RAYLEIGH SCATTERING PROFILES, SHOWING STRATOSPHERIC LAYERS OF PINATUBO AEROSOLS.