Lidar and radiosonde measurements of coastal atmospheric refraction

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ABSTRACT

During the period June-October 1993, a series of measurements were carried out during Project VOCAR to investigate the properties of the coastal atmosphere over the southern California coastal zone, including the offshore Sea Test Range operated by the Naval Air Warfare Center Weapons Division (NAWCWPNS), Point Mugu, California. During summer, this region is frequented by persistent and strong radio/radar ducting conditions, in a refractive environment similar to those which impact Fleet operations in certain weather regimes worldwide. Characterization of the variability of refractive conditions in the lower atmosphere is a key element of the VOCAR study. Measurements at Point Mugu (about 60 miles northwest of Los Angeles) were made with a number of remote and direct sensing techniques, providing an opportunity to examine their respective capabilities to determine atmospheric refraction and related properties for radar/radio performance assessment applications. Some early results are presented from comparisons of refractive profiles from radiosonde data and an atmospheric lidar, developed and operated by Pennsylvania State University Applied Research Laboratory personnel.

1. INTRODUCTION

Various civilian and military applications of radar/radio systems require measurement, analysis and prediction of refractive conditions to assess the propagation of electromagnetic energy in the lower atmosphere.[1,2] A principal concern is the variability of those conditions in space and time. Ordinarily, stratification and horizontal uniformity are assumed, and in particular, over the open ocean this is a normally acceptable representation for the typical domain of interest for radar and radio coverage. Nevertheless, it is recognized that significant lateral variability often exists near air mass boundaries such as frontal zones, and in coastal regions. The Navy, which operates in these regions, has a special interest in determining the magnitude and dimensions of this variability, and its relationship to geographic, oceanographic and meteorological factors which may permit anticipation of its behavior for given locations and times.

While investigating refractive variability, it is important to consider the effects of the scale of refractive structures on radar/radio propagation, with emphasis on features of greatest operational impact. An ultimate goal should be to classify the variability in terms of components related to predictable environmental features and thus amenable to deterministic modeling and representation, and to other phenomena whose features are not specifically predictable and thus must be treated statistically unless observed in process. For example, over long radio paths, the propagation will depend on a mix of relatively extensive and persistent patterns which will cause more or less orderly deviations in signal characteristics, and smaller refractive irregularities which are turbulent or otherwise complex and transient in nature, and thus inherently unpredictable.

To establish the significance of these atmospheric perturbations in a real world environment, simultaneous measurements of atmospheric conditions and radio signal behavior are needed. A concerted effort to do this in the coastal region of southern California was initiated in 1992 as a task entitled VOCAR (Variability of Coastal Atmospheric Refractivity). Under the direction of the Naval Command, Control and Ocean Surveillance Center (NCCOSC) RDT&E Division (NRaD) in San Diego, an effort was conducted to measure atmospheric and radio parameters for a prolonged period, with contributions from multiple participants, especially during an intensive observation period during August 1993. The radio data were obtained by NRaD, largely through monitoring of airfield Automatic Terminal Information Service (ATIS) transmissions at 120-140 MHz and 200-300 MHz, supplemented by additional transmitter equipment placed on San Clemente Island, offshore from San Diego. Many of the

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meteorological measurements were obtained by conventional techniques such as balloon-borne radiosonde ascents, aircraft measurements, and surface weather observations from local, State and Federal agencies in addition to Naval Air Warfare Center Weapons Division (NAWCWPNS) mainland and island sites. More developmental and novel approaches included weather satellite imagery, up-down radiosonde flights, and a variety of both active and passive remote sensing systems at several locations.

One of the remote sensing techniques employed during VOCAR was a Lidar Atmospheric Measurement Program (LAMP) instrument.[3,4] The LAMP instrument uses a high power Nd:YAG laser with an output of 1.5 J/pulse at 20 Hz. The fundamental wavelength is doubled to obtain 600 mJ pulses at 532 nm and mixed to obtain 225 mJ pulses at 355 nm, or doubled again to produce 80 mj pulses at 266 nm. The transmitter, receiver, detector, and data system combination have been integrated into a standard shipping container, which serves as a field laboratory. The primary receiver is a 42 cm diameter Cassegrainian telescope. Measurements of the back-scatter radiation are typically made simultaneously at the laser output wavelengths of 532 and 355 nm, or 266 nm, with several different detectors in order to cover the dynamic range and to obtain information at selected Raman shifted wavelengths. The water vapor measurements are obtained using Raman channels for N2, at 607, 387 or 283 nm, and for H2O, at 660, 407 or 295 nm. These channels use photon counting detectors, with range bins of 500 nanoseconds (75 meter altitude steps). The temperature measurements are made using the rotational Raman signals in the anti-Stokes envelope at 528 and 530 nm.[5]

The LAMP instrument is of particular interest because it can provide essentially real-time, successive measurements at relatively short time intervals of one to thirty minutes, and is capable of operation at various elevation angles, on selected azimuths to provide information on three-dimensional atmospheric structure for a distance around the site. In contrast, radiosondes require some time to acquire measurements during ascent (at around 200-300 meters per minute), and although usually considered to define conditions in the vertical, they actually travel over a Lagrangian path carried by the wind. Another potential advantage of the LAMP, or a newer version named LAPS (Lidar Atmospheric Profile Sensor) being engineered for shipboard use is the anticipated reduction in expendable hardware, and elimination of the need for balloon inflation and release procedures, which are sometimes quite difficult at sea.

Before a shipboard lidar version can be tested under realistically stressful operational conditions, it is first necessary to establish the feasibility of obtaining reliable vertical refractive data, or profiles, under routine day/night and clear/cloudy conditions. Two test periods were conducted with the LAMP at NAWCWPNS Point Mugu during 1993, one during the VOCAR intensive operating period. Work is underway to compare LAMP data with concurrent radiosonde measurements to investigate applicability of the lidar technique to Navy operations, and refractive assessment measurements in particular. A few of the first, preliminary results of these comparisons are presented herein.

2. ATMOSPHERIC REFRACTION PARAMETERS AND ELEVATED DUCTING

The propagation phenomenon being considered here is the bending of electromagnetic waves at radar/radio frequencies within the lower atmosphere, and consequent propagation effects on Navy communications, detection and tracking of targets, etc. For energy emitted at small elevation angles, this bending can be inferred from the sign and rate of vertical variation of refractive index (n), as described in various standard references on radio propagation.[6] Because refractive index near the Earth's surface usually ranges between 1.00025 to 1.0004, to eliminate the use of repetitious digits it is convenient to work instead with the refractivity (N), given as

$$N = (n-1) \times 10^{6}, \tag{1}$$

so that N at low altitudes normally lies between 250 to 400. For radio/radar frequencies, refractivity can be determined from measurements of temperature, pressure and humidity as

$$N = 77.6\, P/T + 373000\, e/T^{2}, \tag{2}$$

where P is the atmospheric pressure in hPa, T is the temperature in degrees Kelvin, and e is the water vapor pressure in hPa. In the "standard" refractive conditions found within well-mixed atmospheric regions, vertical gradients of approximately -39N per 1000 meters, or -12N per 1000 feet are typical, and atmospheric distortion of propagation patterns is minimal. When N decreases with altitude at a rate greater than about -157N per 1000 meters, or -48N per 1000 feet, trapping or ducting of electromagnetic energy may be expected, which can produce anomalous propagation of energy beyond the standard radio horizon. This value of critical gradient arises from geometric optics considerations, and is related to the radius of curvature of the earth. Another parameter, known as modified refractivity (M), is employed in which the curvature of the Earth is effectively incorporated, given as

$$M = N + 0.157\,h\,, \qquad (3)$$

where h is altitude in meters. Trapping is indicated where M decreases with altitude. This is useful for interpreting atmospheric profile plots, because trapping layers are immediately obvious in relation to the critical condition, which appears as a vertical line in such a diagram.

Figure 1 presents several idealized M profiles representing three versions of a type of duct commonly described as "elevated", since they typically form aloft (as opposed to another type, the "evaporation duct", which always forms as a relatively shallow layer in contact with a water surface). These variants differ according to the altitude of the duct base, which may be determined graphically by dropping a vertical line from the duct top, marked by the relative M-minimum (top of the trapping layer and duct) on the profile. The duct base lies at the altitude where this value intercepts the lower portion of the profile, or the surface. The duct strength, or potential effect on a given radiator, is related to the change in M-units across the trapping layer. An "optimum coupling height" is found within the duct, at the relative M-maximum and trapping layer base. Energy from an emitter placed at that height would be most effectively trapped, compared to other altitudes within the duct. At other altitudes the effect would vary in relation to the difference in M at that altitude, and the minimum M at the duct top. These interpretations are based on geometric optics, and although not always strictly correct are still useful in propagation assessment applications. In Figure 1a, the entire ducting region is elevated, and the performance of near-surface radar/radio systems would be essentially that expected for standard conditions. The duct is surface-based in Figure 1b, suggesting substantial impact on surface systems. For radar, this condition is sometimes evident as the "inversion ring" phenomenon, an annular zone of enhanced clutter some distance from the emitter. Figure 1c shows the trapping layer and optimum coupling height itself on the surface, indicating strong downward refractive bending, with considerably enhanced radar clutter from the emitter outward beyond the normal radio horizon.

Actual atmospheric refractive profiles often resemble the simple, tri-linear profiles described above. For Navy applications we are especially concerned with the possibility of the duct becoming surface-based, in which event propagation to and from ship systems may be significantly affected. Because the refractivity near sea level tends to be controlled by local sea surface temperature, which usually changes only slowly with time, the value and trend of the minimum M aloft is of great interest.

3. ELEVATED DUCT OCCURRENCE AND VARIABILITY

Weather conditions favoring the occurrence of an elevated duct are prevalent in temperate latitudes over the eastern portions of the world's oceans.[7] This condition is particularly evident over the area along and offshore coastal southern California. The main factors contributing to this situation are long periods of fair weather with subsiding, dry and relatively warm air aloft, over a moist and cooler marine atmosphere. Along the immediate coast local upwelling of cold water further increases the vertical contrast in air masses, and the associated gradient in refractivity. At locations from San Diego to Point Arguello (northwest of Santa Barbara), the incidence of trapping conditions aloft can occur over 80% of the time during summer months, the most affected season of the year. The Navy installation at Point Mugu is in the heart of this region, with typical marine layer depths and duct heights around 500 meters altitude, higher and more sporadic in winter, descending during late summer to become surface-based on many occasions. The facility frequently experiences anomalous propagation effects on radar and communication systems, which are located at various altitudes on the mainland and offshore islands. This has lead to an active interest in the development and application of techniques for analyzing and forecasting these conditions.[8]

Propagation assessment models have generally incorporated the assumption that refractive layers are horizontal over the region of interest. This is believed to be an acceptable representation most of the time, away from significant weather disturbances, and especially over the open ocean. But near coastal regions, the assumption is more questionable because of a number of terrain-induced atmospheric phenomena found there, classified as "mesoscale" in meteorological terminology. This is meant to signify features with dimensions roughly from tens to hundreds of kilometers, with lifetimes between about one hour and one day. Studies by the University of California at Los Angeles(UCLA)[9,10] offshore southern California have revealed systematic deformations in the marine layer/elevated duct topography on the order of 100 meters or more in the vertical, with spatial scales around 100 km horizontally. The depth of the marine layer and altitude of the accompanying elevated duct is affected by the diurnal sea/land breeze cycle, and by atmospheric internal wave motions caused by airflow around and over island and coastal terrain. Horizontal shear and eddying in the wind field are also accompanied by perturbations of the interface at the top of the marine layer. Much of this activity is qualitatively detectable in weather satellite imagery, as the distortions of the marine layer depth modulate imbedded stratocumulus cloud fields in visually distinctive patterns. There is a problem, however, in obtaining sufficiently dense quantitative measurements to adequately diagnose refractive conditions required for application of range-dependent propagation models. During the VOCAR 10-day intensive observation period in August 1993, a special effort was made to obtain data from a variety of methods to provide the basis for study of mesoscale refractive variability and evaluate the importance of this information to assist in the explanation of concurrently observed propagation conditions.

4. ELEVATED DUCTS IN RADIOSONDE AND LIDAR DATA

Measurement techniques used to discern mesoscale atmospheric refractive structures for VOCAR included aircraft, radiosondes, tethered sonde, surface observations, and a number of remote sensing systems. Most of the data gathered is still being processed by the several groups participating, so a total synthesis for the study period has not yet been carried out. At NAWCWPNS we are particularly interested in analysis of the radiosonde information, since that method has been our primary basis for routine determination of refractive and other conditions for direct support of Range operations. At any given site, the assessment of variability from radiosondes is limited basically to temporal changes in a limited volume above and around that location. These temporal changes are, however, in part related to the spatial domain because of translation of features by the wind or propagating as gravity waves on the upper boundary of the marine layer. A rough calculation indicates that for typical wind speeds, features with dimensions of 1 to 400 km could appear locally as variations with periods between about 15 minutes to 12 hours, if carried with the flow. To some extent, conversion of such features to the spatial domain can supplement the other fairly sparse spatial observations. Construction of height-range cross sections of refractivity along various radio paths is a major goal of our effort, to provide range-dependent input for testing modeled versus observed propagation. In addition, a statistical analysis of the persistence of the elevated duct characteristics will be performed to help develop guidance for setting a maximum interval between profile measurements. It is not generally practicable to obtain radiosonde profiles at time intervals less than a few hours, so the remote sensing techniques, capable of more continuous operation, offer a potentially valuable alternative or supplement to this conventional approach.

Many comparisons of LAMP lidar and radiosonde profiles have been made previously, and generally good agreement is found; an evaluation study is currently being prepared. An example of lidar and radiosonde measurement of water vapor is shown in Figure 2. The lidar plot is from the near real time analysis program of the LAMP system and illustrates the data product that can be provided for quick field evaluation. The Raman lidar profile is plotted as a solid line, with bars representing one standard deviation of error in the signal. The radiosonde data are shown as a dotted line. Figure 3a repeats the same data as Figure 2, but for an altitude range of surface to 1500 meters for comparison with the temperature results given in Figure 3b. The same plotting conventions are used in the latter, which represents measurements of temperature from the rotational Raman lidar, and from the meteorological sounding. The lidar temperature measurements are a more recent capability and the performance is still to be assessed; the spectral stability of the beam splitting optics has been found to require special care.

For the VOCAR intensive operation period, two sets of data consisting of 19 individual profiles from the LAMP instrument have been examined for indications of elevated ducts. These were obtained during early morning hours, mostly before sunrise, on 26 and 27 August 1993. Temperature, humidity and pressure were derived by PSU/ARL from the raw lidar measurements, and converted into refractivity using a relationship similar to that given in equation (2). The data shown are layer averages, for 75 meters in altitude and 1/2 hour in time, although the profiles were taken and stored at one minute intervals. Data editing was performed where the humidity measurements were not reliable. The first layer above the surface was eliminated because of questions of interference from dust and fluorescence in the near field; these questions are under study. Additional upper level points were eliminated where the signal to noise ratio would cause errors larger than 20%. Of these profiles, five were nearly coincident in time with the release of a radiosonde. The radiosondes were of the Vaisala type, and are used regularly by the Navy and many other groups around the world for determination of meteorological conditions aloft, including refraction. The sonde data were obtained at two-second intervals, corresponding to about six to ten meters vertical resolution, but the individual releases were usually separated by about four hours.

As has been discussed earlier, the presence of an elevated duct is quickly revealed by inspection of M-profiles. For the five concurrent lidar/radiosonde sounding events, pairs of M-profiles up to 1500 meters altitude were plotted from the two sounding sources, and are shown in Figures 4-8. The times are Greenwich meridian, designated by the letter Z in meteorological convention. In these graphs the LAMP lidar profiles are dashed, the radiosonde solid lines. The overall shape of the profiles is similar, but some significant differences are apparent. The lower portion of the lidar profiles is roughly 10 M-units less than values in the radiosonde profiles in Figures 4 and 5. The match is very close in Figures 6 and 7, except that the lidar exceeds radiosonde M-values by as much as 20 units in the uppermost levels. In Figure 8 the match aloft is very good, but the lidar exceeds radiosonde values in the 300-600 meter altitude region. In terms of likelihood of ducting, the most important consideration is the amplitude of the relative minimum in M-value within the first few hundred meters altitude. The lidar favors surface-based ducting more than the radiosonde in Figures 4 and 5, but is comparable to the radiosonde in Figures 6 and 7. In Figure 8, both methods suggest the duct base does not reach down to the surface, and the lidar indicates weaker ducting aloft than the radiosonde.

Additional radiosonde and lidar profiles were available which, although at different times, are interesting to compare in terms of the minimum M-values aloft. Figure 9 shows how this parameter varied based on all lidar and radiosonde profiles at Point Mugu for the 48-hour period beginning at 0000Z 26 August (1600 PST 25 August). Lidar-derived data are marked by diamonds, and radiosonde by asterisk. Both techniques agree with respect to the direction of change from the 26th to the 27th, but differences up to 30 M-units were apparent between the two profile sources.

The causes of the disagreements have not yet been determined. It is reasonable to expect some differences because the two sets of profiles were not precisely coincident in space and time, and rapid horizontal changes in air-mass conditions can occur within the land-sea boundary region where the profiles were obtained. Further analysis of these and additional profiles will be needed to determine if systematic biases exist relatable to balloon trajectories. The lidar measurements are at substantially coarser resolution in the vertical, and so could not detect all of the features which might appear in the radiosonde data, but this is not a great disadvantage as long as the minimum M aloft is noted properly. At times the dry layer aloft which is responsible for this minimum can become rather thin, in which event the intensity or even presence of trapping conditions requires the higher resolution measurements. The trade off is, as has been noted, in the better time resolution feasible with the remote sensing approach. Presuming that the relative accuracy and reliability of the two methods can be determined to be comparable for refractive purposes, the best situation would be a complementary application carried out to utilize the strengths of each.

5. ACKNOWLEDGMENTS

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6. REFERENCES

1. Hitney, H. V., J. H. Richter, R. A. Pappert, K. D. Anderson and G. B. Baumgartner, Jr., "Tropospheric Radio Propagation Assessment," Proc. IEEE, **73**, 265-283, 1985

2. Richter, J. H., Editor, Radio Wave Propagation Modeling Prediction and Assessment, AGARD-AG-326, 1985

3. Philbrick, C. R., D. B. Lysak, T. D. Stevens, P. A. T. Haris and Y.-C. Rau, "Atmospheric Measurements Using the LAMP Lidar during the LADIMAS Campaign," *16th International Laser Radar Conference*, NASA Publication 3158, 651-654, 1992.

4. McKinley, S. C., and C. R. Philbrick, "Tropospheric Water Vapor Concentrations Measured by a Penn State/ARL Lidar," *Proceedings of the IEEE Topical Symposium on Combined Optical-Microwave Earth and Atmosphere Sensing*, 185-188, 1993.

5. Philbrick, C. R., "Raman Lidar Measurements of Atmospheric Properties," *Atmospheric Propagation and Remote Sensing III*, SPIE **2222**, these proceedings 1994.

6. Jursa, A. S., Editor, *Handbook Of Geophysics And The Space Environment*, AFSC, U.S. Air Force, 1985

7. Bean, B. R., and E. J. Dutton, *Radio Meteorology*, Dover, Mineola, New York, 1968

8. Rosenthal, J. S., R. A. Helvey, S. W. Lyons, A. D. Fox, R. Szymber and L. Eddington, "Weather Satellite and Computer Modeling Approaches to Assessing Propagation over Marine Environments," AGARD Conf. Proc. **453**, 47-1 to 47-15, 1989

9. Neiburger, M., G. Beer and L. Leopold, "The California Stratus Investigation of 1944," U. S. Dept. of Commerce, Washington, D. C., 1945

10. Edinger, J. G. and M. G. Wurtele, "Interpretation of Some Phenomena Observed in Southern California Stratus," *Mon. Wea. Rev.*,**100**, No. 5, 389-398, 1972

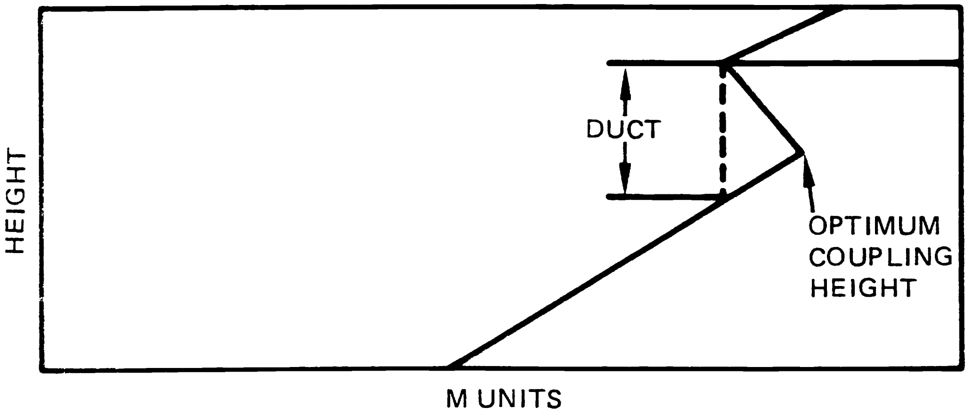

Fig. 1a. M-profile: Elevated Duct (trapping layer elevated).
Minimum M aloft > surface M.

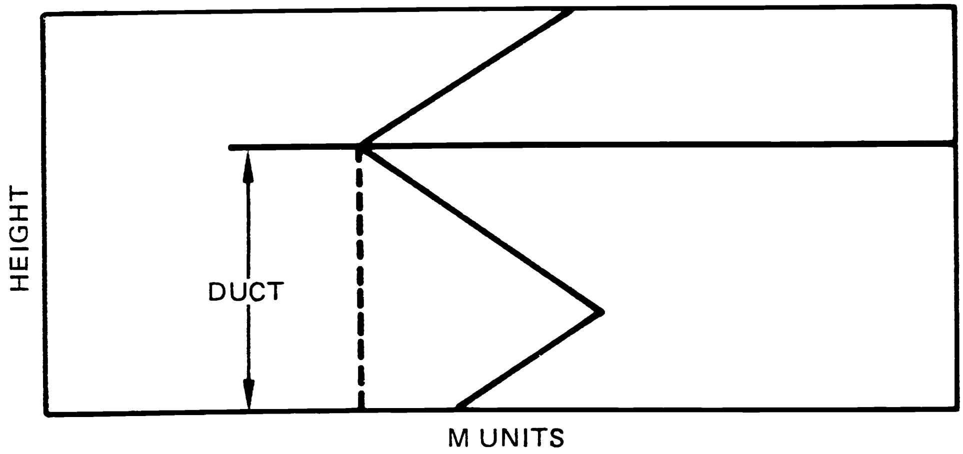

Fig. 1b. M-profile: Surface-based Elevated Duct (trapping layer elevated).
Minimum M aloft < surface M.

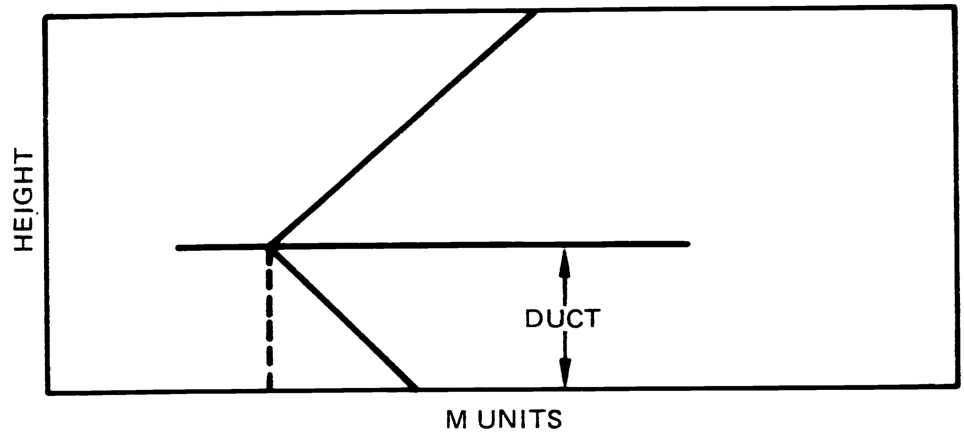

Fig. 1c. M-profile: Surface Duct (trapping layer on surface).
Minimum M aloft < surface M.

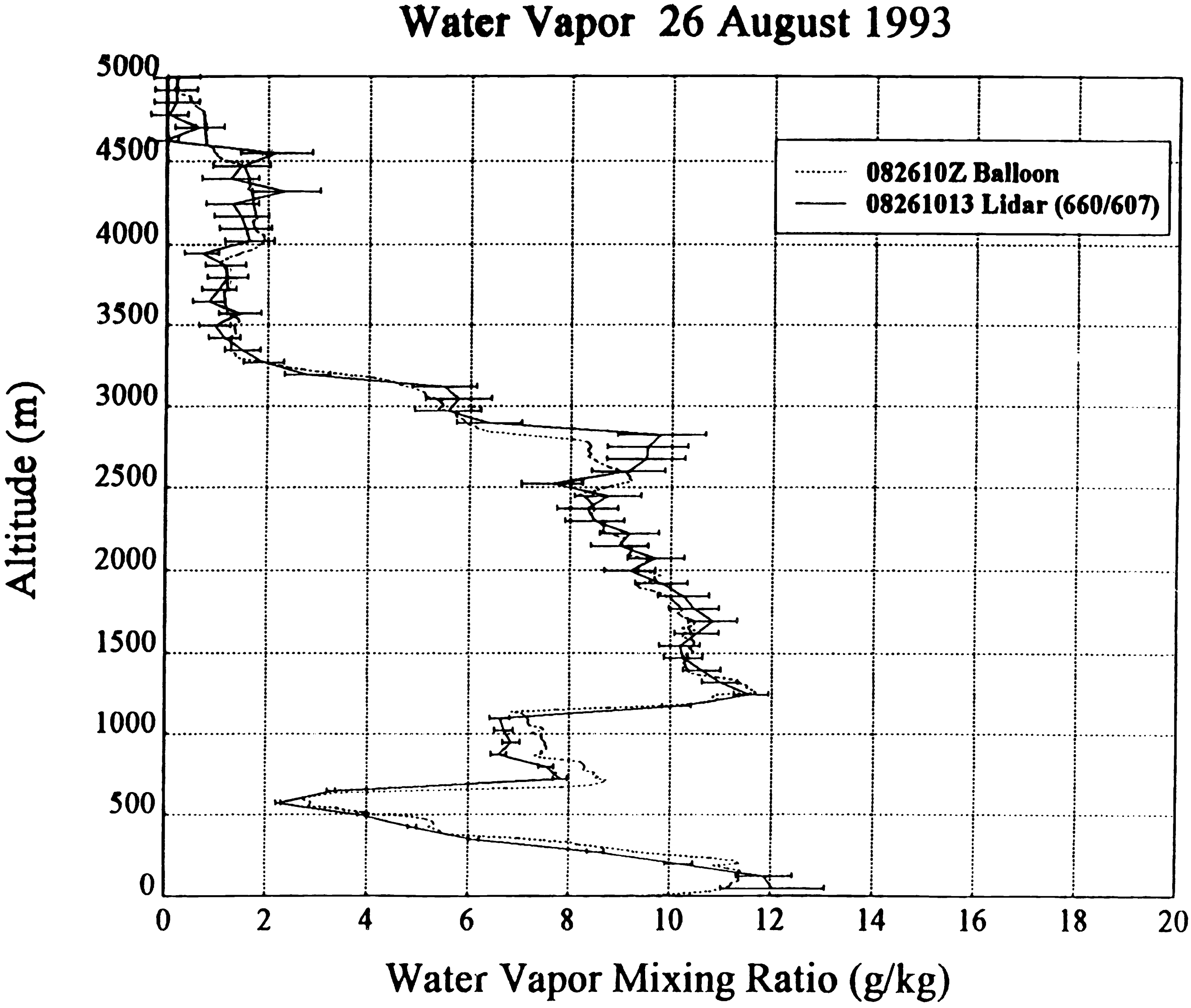

Fig. 2. Raman lidar and meteorological balloon (radiosonde) measurements of water vapor profiles on 26 Aug 93. The lidar profile is the solid line with error bars (one standard deviation). The radiosonde profile is a dotted line. The steep decrease in humidity between about 100 to 600 meters altitude indicates the presence of a strong trapping layer.

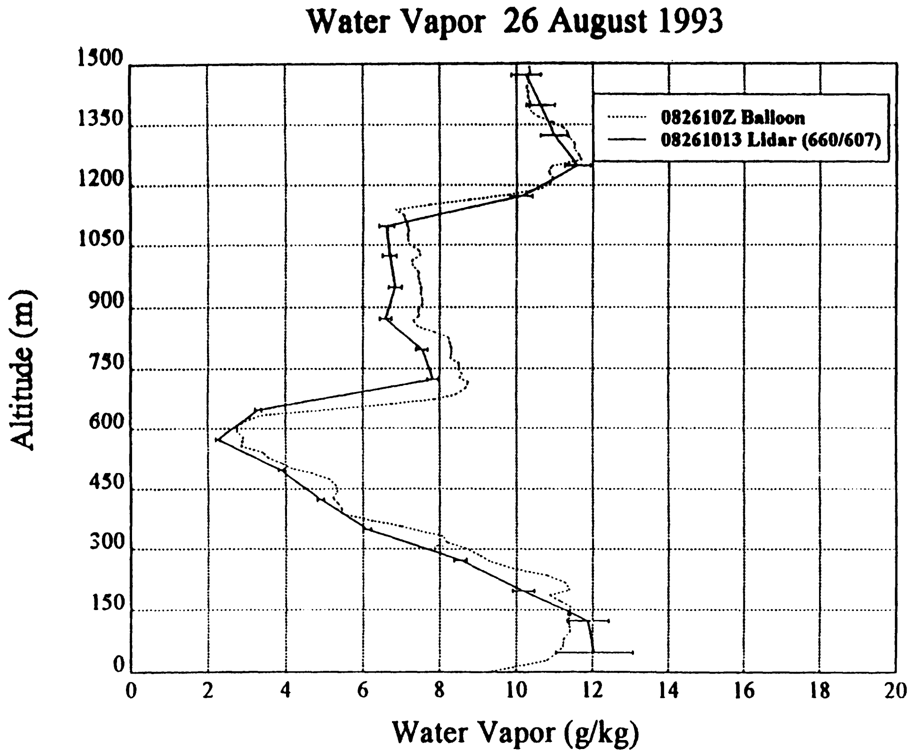

Fig. 3a. Same as Fig. 2 but to 1500 meters altitude

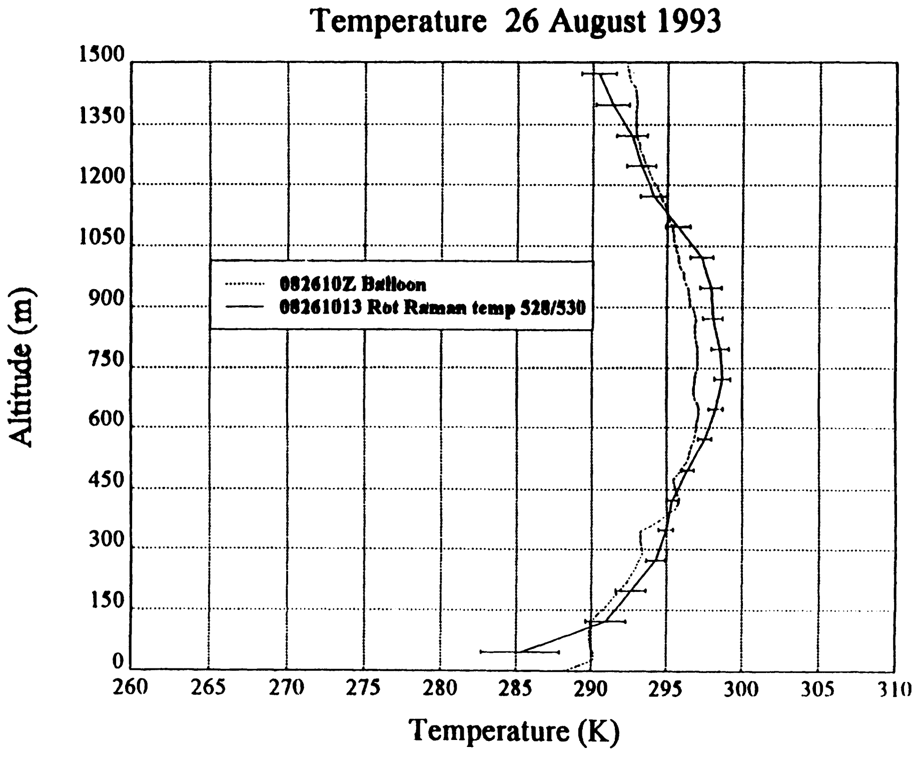

Fig. 3b. Temperature from rotational Raman (solid line, with error bars), and radiosonde (dotted line).

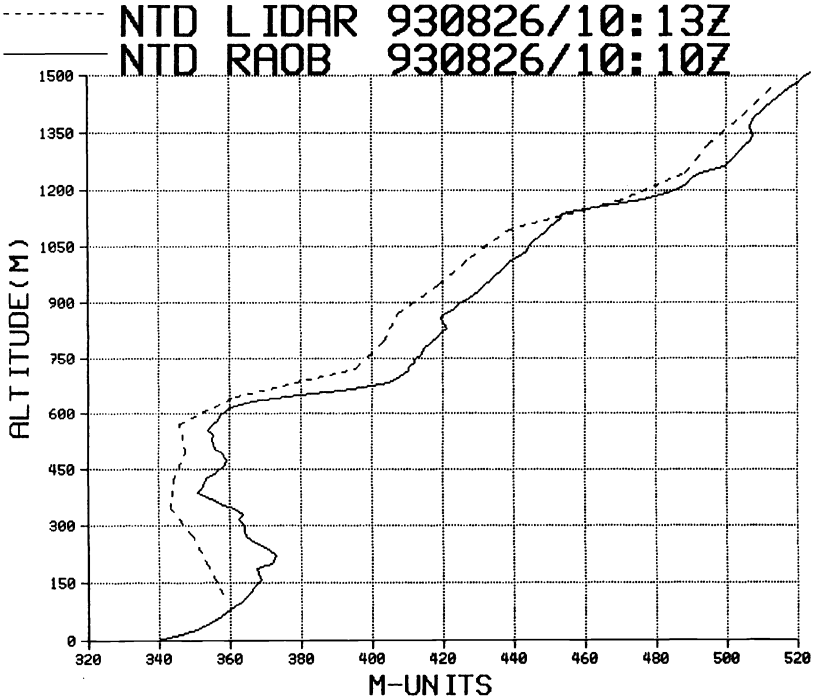

Fig. 4 . LIDAR/radiosonde M-profile comparison
for time: 26 Aug 93, 10Z
solid = radiosonde, dashed = LIDAR

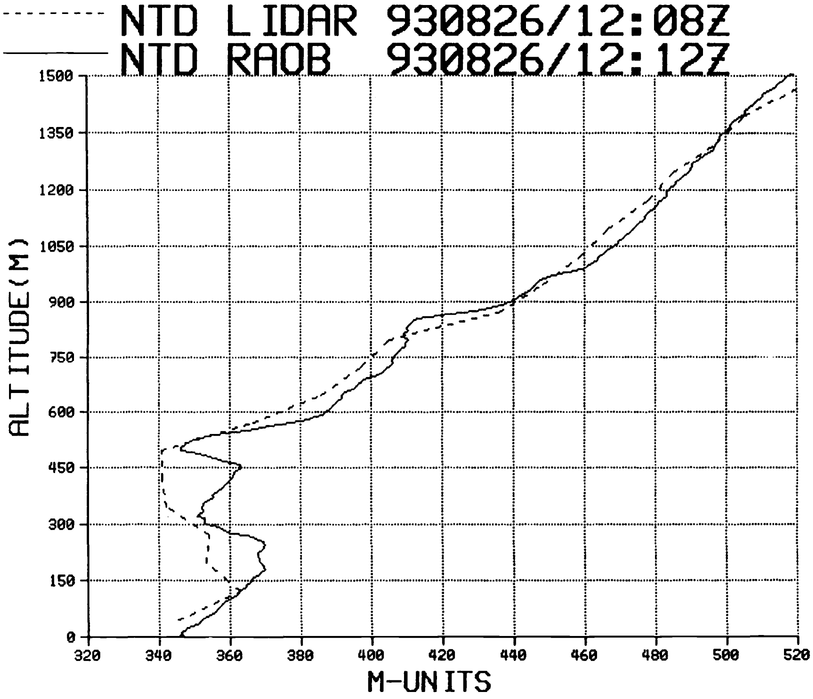

Fig. 5. Same as Fig. 4, but for time: 26 Aug 93, 12Z

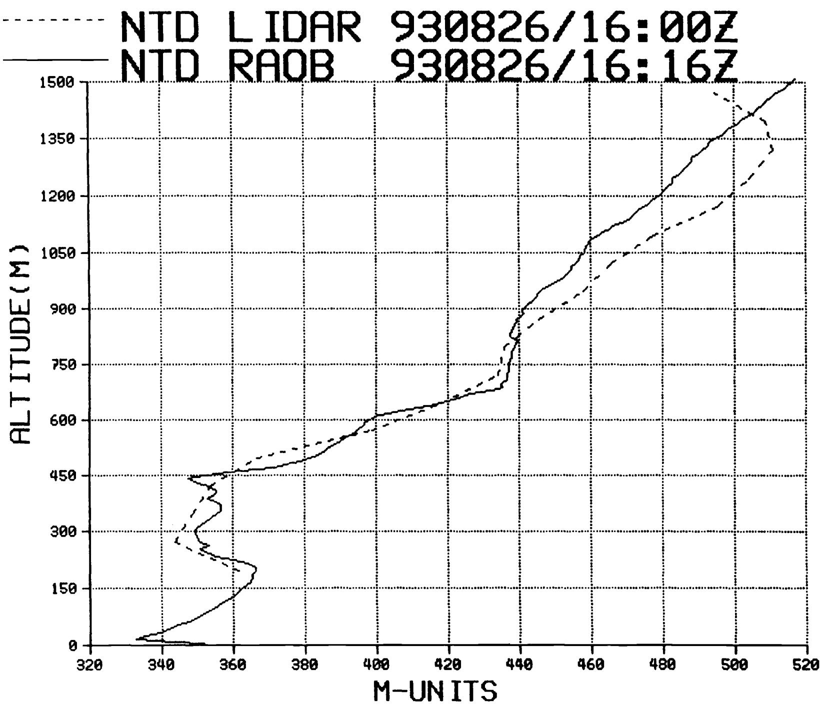

Fig. 6. Same as Fig. 4, but for time: 26 Aug 93, 16Z

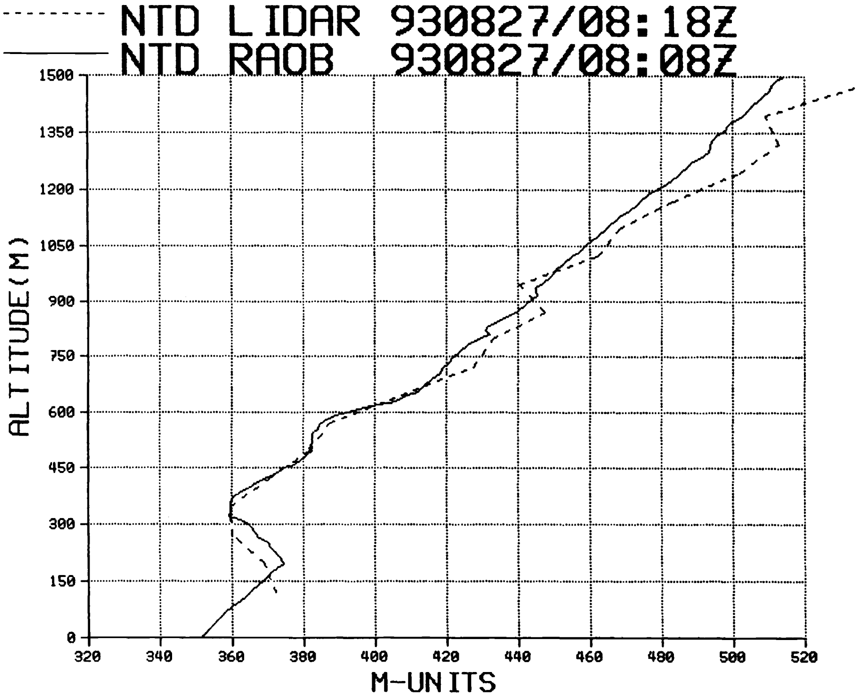

Fig. 7. Same as Fig. 4, but for time: 27 Aug 93, 08Z

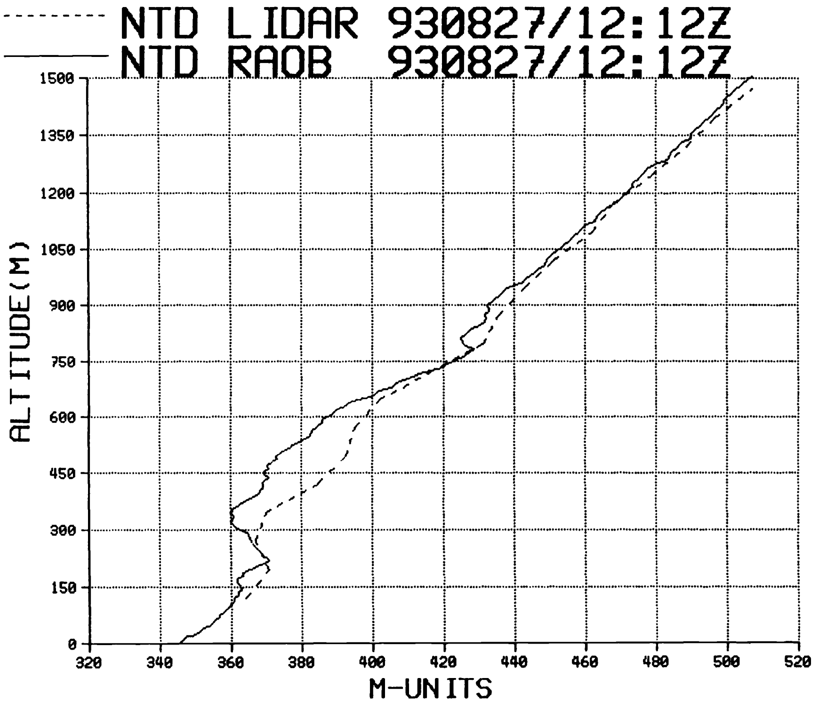

Fig. 8. Same as Fig. 4, but for time: 27 Aug 93, 12Z

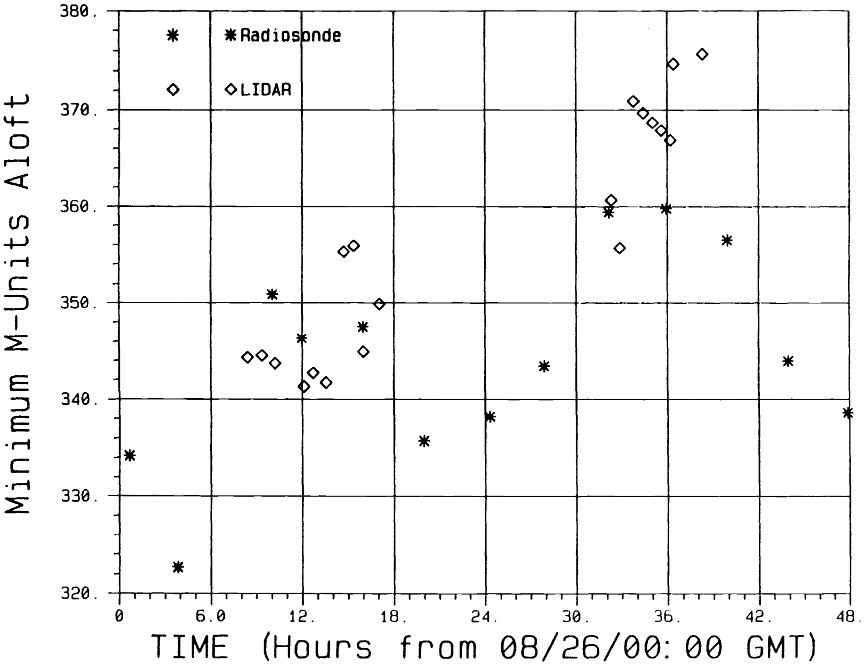

Fig. 9. Minimum M-units aloft, 26-27 Aug 93 (GMT)
asterisk = radiosondes
diamond = LAMP lidar