DEVELOPMENT OF LIDAR
TECHNIQUES FOR ENVIRONMENTAL
REMOTE SENSING

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Abstract:
This paper describes different LIDAR techniques developed for remote sensing the Earth’s environment. The optical radar techniques like micro pulse, polarization, resonance and Raman have been successfully developed and demonstrated for deriving the atmospheric parameters like boundary layer (BL) height, backscattering and depolarization properties of airborne particles and clouds, profiles of mesospheric sodium density, and water vapor mixing ratio in the atmosphere from the intensity profiles of lidar data. These established LIDAR techniques are vital for understanding the dynamics, structure and composition of the atmosphere.

Keywords: Lidar techniques; Environment; Remote sensing.

1. Introduction
LIDAR is an acronym for light detection and ranging. It is the optical counter part of more familiar radar technique and uses laser light for remote sensing the atmosphere. Hence, it has been referred as Laser Radar. A lidar system transmits a pulse of light into the atmosphere and analyzes the backscatter signal intensity as a function of time. Because the laser pulse travels at the speed of light, it is possible to convert time into range and consider the lidar signal backscattered intensity as a function of range. Lidar is one of the active remote sensing techniques for the environment. It has proven to be an essential tool to monitor the structure, composition and dynamics of the Earth’s atmosphere. Lidar has largely contributed to our knowledge of the Earth’s atmosphere during the past decades [Measures (1984); Kovalev and Eichinger (2004); Weitkamp (2005)]. High spatial and temporal resolution of measurements, the possibility of observing the atmosphere at ambient conditions, and the potential of covering the height range from the ground to more than 100 km altitude make up the attractiveness of lidar instruments. It is particularly useful for the investigation of highly variable atmospheric parameters. Simple elastic backscatter lidars have been used to investigate turbulent processes and the diurnal cycle of the planetary boundary layer [Kovalev and Eichinger (2004)]. Polarization Lidar systems are used to distinguish water droplets from ice crystals in clouds [Sassen (1991)]. Rayleigh scatter lidars provide middle atmosphere temperatures and present long-term variability in the thermal structure [Bhavani Kumar (2006)]. Resonance lidars probe the mesospheric region and provide the winds driven metal layer densities [Chu and Papen (2005)]. Raman lidars work on the principle of Raman Effect and provides an approach to the range resolved measurements of atmospheric trace species [Weitkamp (2005)].

This paper describes the indigenous development of several different lidar techniques for remote sensing the Earth’s environment. These techniques have been successfully demonstrated at the National Atmospheric Research Laboratory (NARL), an autonomous institution under Department of Space, located at Gadanki in India. Some of the developed techniques are innovative in nature and have been offered for commercialization. These techniques are useful for remote measurement of environmental parameters like (i) atmospheric boundary layer (ABL) height, (ii) Scattering and depolarization properties of high altitude clouds, (iii) altitude profiles of aerosol backscatter and extinction in the troposphere and stratosphere, (iv) profiles of temperature in the lower and middle atmosphere, (vi) vertical profiles of mesospheric sodium density, and (iv) water vapor mixing ratio profiles in the lower atmosphere from the profiles of laser backscattered intensity data. Each technique is presented with brief instrument details along with some sample observational data.
2. Indigenously developed LIDAR techniques

2.1. Micro pulse lidar technique

Over the last thirty years, lidar instruments have been developed to study the structure of the atmosphere by means of the elastic scattering of light from constituents of the atmosphere such as air molecules and aerosol. The traditional lidar instruments used so far for boundary layer (BL) and upper atmospheric studies have typically been high-energy pulse, low repetition rate systems. Pulse energies are in 0.1 to 1.0 J range and repetition rates from 0.1 to 20 Hz. While such systems proven to be good research tools, they have a number of limitations that prevent them from moving beyond lidar research to operational, application oriented instruments. These problems include a lack of eye safety, very low efficiency, and poor reliability, lack of ruggedness, and high development and operational costs. There is a need for operational, practical lidar. Lidar is a basic tool for observing the atmosphere.

Recent advances in the solid-state lasers, detectors and data acquisition systems have enabled the development of a new generation of lidar technology that meets the need for routine, application oriented instrumentation. It is known as Micro pulse lidar (MPL) and has been referred as a new generation simple backscatter lidar system [Spinhirne (1993)]. There are three basic differences between the MPL and the most previous lidar systems. Foremost the laser pulse repetition frequency (PRF) is much higher, kilohertz range than Hertz, and the pulse energies are much lower, micro-Joules than milli-Joules or greater. The low pulse energy is the key factor that permits the systems to be eye-safe. The second difference is that the laser is diode pumped rather than flashlamp pumped. The solid state lasers are much more efficient and smaller. The third difference is that the signal detection is by photon counting. Usually the photon counting technique is far superior than compared to the conventional analog method of detection, because it is more sensitive to the long-range echoes. Though photon counting has a drawback of limited dynamic range in signal acquisition to analog method, the use of high repetition rate of laser operation overcomes this limitation.

One such micro pulse lidar system was successfully designed and demonstrated at the National Atmospheric Research Laboratory (NARL) in 2004 for monitoring the boundary layer aerosol as the tracers of atmospheric dynamics. The lidar system was developed under a project titled boundary layer lidar (BLL). The location of lidar site is Gadanki (13.5°N, 79.2°E; 375 m mean sea level) situated close to Tirupati, a famous temple town, in the southern part of India. The BLL employs a diode-pumped Nd-YAG laser system, a co-axial transceiver for transmitting the laser pulses and detecting the collected photons, a dedicated data acquisition system and a complete software package to generate and display the lidar reflectivity profile.

Fig. 1 (a) Simple block diagram of indigenously developed portable micro pulse lidar system and (b) its photograph. The lidar system is located at NARL site, Gadanki

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system, and a computer control and interface system. Fig. 1(a) provides the simple schematic block diagram of the developed lidar system. Fig. 1(b) shows the photograph of lidar system present at the NARL site. In BLL, pulses of light energy are transmitted from the telescope into the atmosphere. As the pulse propagates, part of it is scattered by molecules, water droplets, ice crystals, dust and haze aerosol in the atmosphere. A small portion of the light that scattered back is collected by the telescope and then detected. The distance to the particle layers is inferred based on the time delay between each outgoing transmitted pulse and the backscattered signal. The detected signal is stored in bins according to how long it has been since the pulse was transmitted, which is directly related to how far away the backscatter occurred. The collection of bins for each pulse is called a profile. Since a cloud produces enhanced scattering, it is evidenced as an increase or spike in the backscattered signal profile. Besides real-time detection of clouds, post-processing of the lidar returns can also characterize the extent and properties of aerosol or other particle-laden regions. The detailed BLL technical configuration and specifications were given elsewhere by Bhavani Kumar [2006]. The lidar system has been employed in the studies related to boundary layer ranging (Bhavani Kumar and Purushotham 2010), profiling of atmospheric clouds [Bhavani Kumar et al 2008] and characterization of aerosol distribution in the lower atmosphere [Bhavani Kumar and Varma 2010].

Fig. 2 Scientific capabilities of portable lidar system (a) Detection of passage of high altitude clouds, (b) temporal evolution of ABL and (c) evidence of long-range transport of thin aerosol layers in the free troposphere during winter period observed over lidar site

Figures shown in 2(a) - (c) indicate the scientific capabilities of the portable lidar technology. The lidar system remote detection of thin cirrus cloud, shown at altitudes between 12 and 14 km, above the thick nocturnal boundary layer (NBL) illustrated in Fig. 2(a) indicates the meteorological application of the system. This type clouds are not possible to detect by any other remote sensing techniques due to the sub-visible nature of these clouds. Fig. 2(b) shows the temporal evolution of ABL over Gadanki site recorded by the lidar system for a period of continuous 24-hour in January 2005 during the clear winter sky condition. The time height variation of range corrected signal (RCS) $S(r)$ was presented along with the surface temperature measurements to indicate the remote ranging ability of ABL height. Earlier sophisticated aerosol lidars were used to identify
the advection of aerosol plumes and transport of particles in the free troposphere that originate from remote areas such as arid and semi-arid regions [Muller et al. (2001)]. These systems are equipped with the capability to detect the deep pollution layers above the boundary layer [Ansmann et al. (2000)] on continuous basis. Fig 2(c) shows the capability of portable lidar technology in detecting the elevated aerosol layers that advected over the lidar site during winter period. The altitude profile of aerosol backscattering coefficient [Bhavani Kumar and Varma (2010)] derived from the lidar data shows an evidence of thin aerosol layers above the local boundary layer. A 10-day air parcel trajectory obtained from the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) analysis shown in Fig 2(d) provides the information on the history of long-range transport of aerosols layers in the atmosphere. These long-range transported aerosols layers play a significant role on climate and environment.

2.2. Polarization lidar technique

Simple backscatter lidars provide unmatched height resolution and sensitivity to the detection of mixed layer depth, airborne particle distribution, meteorological phenomena, cloud and its vertical extent.

An addition of extra receiver channel to measure the degree of depolarization in backscatter, however, proved to be a significant advantage for the studies on boundary layer aerosols, particles in cloud, precipitation (i.e., hydrometeors) and characteristics of polar stratospheric clouds [Weitkamp (2005)]. Measurements of degree of depolarization provide information about the shape and/or thermodynamic phase of the particles in the scattering medium [Bhavani Kumar et al. (2006)], and for this reason polarization lidars have been widely used and studied in the atmospheric sciences. The polarization lidar technique dates back to the early 1970s, when the depolarization of backscattered laser light was shown to provide effective discrimination between ice clouds and water clouds. Later studies augmented the technique by using depolarization signatures to identify regions of horizontally aligned hexagonal plates in altostratus clouds. Depolarization ratios have also been used to identify and distinguish between volcanic ash and sulfuric acid droplets in the volcanic plumes. The polarization-sensitive lidars are frequently used to detect the presence of dust and thin clouds in the atmosphere [Weitkamp (2005)]. Lidar depolarization has also been used to identify desert dust in the free troposphere and to study its role in ice nucleation.

A compact dual polarization lidar (CDPL) system [Bhavani Kumar (2009)] was developed at NARL site in 2009 for profiling the atmospheric aerosols and clouds in the lower atmosphere. The lidar system performs polarization diversity measurement in receiver for detection and discrimination of various suspended particles/aerosols of interest. As shown in Fig.3 (a) the lidar system employs a laser transmitter that generates a monochromatic spectrum of light beam having a predetermined state of polarization. Light scattered from the atmospheric aerosol/ cloud particles are detected using a polarization sensitive receiver and thereby the degree of change in polarization of the scattered light is determined. The ratio of the depolarization at the exciting wavelength is then calculated and used to discriminate between the various cloud particles/aerosols. The newly developed polarization lidar at NARL site is shown in Fig.3 (b). It is an independent lidar system that contains a pulsed laser transmitter that operates at 532 nm wavelength, a 150 mm receiver telescope, polarization optics, dual detectors, signal digitizers, timing and power supply electronics, and a computer for control and data recording. The lidar system employs a rigid biaxial configuration. The transmitter and receivers are closely

![Fig. 3(a) Operational block diagram of compact dual polarization lidar system and (b) its photograph.](image-url)
spaced, hence does not require any optical alignment. It is easy to orient at any angle, even at horizontal direction, for purposes of measurement during rain and also in calibration requirements.

The dual polarization lidar (DPL) provides vital information of the polarization characteristic of cloud particles. The change in the polarization state of laser light backscattered from clouds and precipitation contains unique remote-sensing information related to the shapes of the hydrometeors [Sassen (1991)], and for this reason dual polarization lidars have been widely used in the studies related to clouds. Clouds of mixed water and ice phase composition, which occur commonly in winter and convective storms, alto cumulus, and in some cirrus clouds, obviously represent the interesting situation for investigation. At temperatures between 0° and -40°C, liquid water droplets and ice crystals may coexist in a single-layered cloud. Ground-based remote sensing observations of mixed-phase clouds have the potential to contribute a significant amount of knowledge with which to better understand, and thereby more accurately model, clouds and their phase-defining processes. The unique application of polarization lidar emerges in the identification of cloud phase in the mixed phase clouds. An observation of passage of mixed phase cloud by CDPL is shown in Fig. 4. On 11 March 2009, a precipitating alto cumulus appeared over Gadanki site at the late evening hours and gradually dissipated at the end of night when high clouds moved in. The observation is presented as height-versus-time zenith-lidar displays of the linear depolarization ratio $\delta$ along with lidar range corrected data from the 532 nm channels. The observed cloud is associated with liquid water droplets and ice crystals coexist in a single-layered cloud. The precipitations of the ice particles that typically trail below super cooled mixed-phase clouds, a phenomenon called virga, were clearly seen at the cloud base. The precipitating ice virga is associated with relatively high depolarization ratio $\delta$, and small backscatter signal. The liquid cloud base position can be identified by the start of strong backscattering and the corresponding near-zero depolarization $\delta$ that appeared between 2100 and 2200 LT. Subsequently the cloud layers gradually descended while the alto cumulus $\delta$ values decreased and the upper cirrus layers were again detected.

2.3. Resonance lidar technique

The middle and upper atmosphere is a complex photochemical region. This region is usually referred to as the MLT region (i.e., the mesosphere and lower thermosphere), and is also called the mesopause region. It contains a wealth of important geophysical phenomena, for example, the Earth’s coldest environment -the mesopause, polar mesospheric clouds (PMCs) and noctilucent clouds (NLCs); the meteoric metal layers of Na, K, Ca, Li, and Fe; the airglow layers of OH, O, and O$_2$; and planetary, tidal, and gravity wave activities that play vital roles in overall global atmosphere circulation [Chu and Papen (2005)]. The existence of metal layers near mesopause is a natural phenomenon. Meteoric ablation is believed to be the major source for the formation of mesospheric sodium and the other metal layers in this region of the atmosphere. As meteors enter the atmosphere, they burn-up or ablate and leave debris in their path. This ablation typically occurs near altitudes of 80 to 100 km, where the average temperatures of the atmosphere allow the metal atoms to be freed [Chu and Papen (2005)]. The metal atoms, such as sodium, potassium, lithium, iron and calcium, exist as neutral atoms, in this region, which is a unique characteristic of this location. This region of atmosphere also hosts the airglow layers. Since the mesospheric region is difficult to directly measure, being too low for satellites and too high for balloons, and rocket flights are too infrequent, most of the studies rely on remote-sensing techniques.

The metal atoms are useful for remote sensing as they have a high scattering cross-section at specific resonant wavelengths. When a laser is tuned to a resonant line, an atom will absorb a laser photon and then re-emit through spontaneous emission. Electronic transitions of these metal atoms fall in the wavelength range of available laser sources. The resonant wavelength for sodium, which appears bright orange in color, is 589 nm. It corresponds to the frequency of the Na atomic transition from the ground state to the first-excited state. The
resonance scatter occurs when the absorbed radiation is reemitted by the Na atoms. A resonance lidar system employing a YAG pumped pulsed dye laser scheme was implemented at NARL in 2005 [Bhavani Kumar et al (2007a)]. The lidar system was developed to probe the natural layer of atomic sodium exists at mesospheric heights. The initial observations of the mesospheric sodium were made on 10 January 2005.

The in-house developed sodium resonance lidar system employs the biaxial configuration. The laser transmitter subsystem consists of a tunable dye laser pumped by a YAG laser. The pump laser is a Continuum, USA make Power Lite model Nd:YAG laser system. The pump laser is a Q-switched laser that outputs the second harmonic of Nd:YAG at 532 nm wavelength. This system outputs laser at 20 Hz repetition rate with a pulse energy of about 200 mJ. The dye laser is pumped via a 45° high-energy mirror. The dye laser employed is a Continuum make Jaguar model D90DMA dual grating system made in Germany. In order to achieve a long-term operation with a narrow linewidth (< 0.05 cm⁻¹ or about 2 pm), the dye laser is equipped with two 90 mm holographic gratings. The dual grating system with 2400 lines/mm, used in first order diffraction, has a theoretical resolving power of 432000 that implies a wavelength resolution of about 2 pm at 589 nm wavelength. Fig. 5(a) shows the picture of YAG laser pumped Dye laser setup at NARL site. In the receiver side, the laser backscattered light is collected using a fixed 750 mm diameter Newtonian telescope. The receiving telescope is situated about 2 m away from the steering mirror, hence the transmit-receive full overlap takes place at altitudes 5km above the surface level. The focus of the telescope is located at the 2 mm pinhole aperture F, which limits the FOV to about 1 mrad. A narrowband interference filter (IF) is positioned in front of photon detector. An IF filter, whose center-wavelength and bandwidth are 589 nm and 1.0 nm respectively, is used to reduce background light. Photon counting is employed due to weak signal returns. A high gain photomultiplier tube (PMT) is used as the photon detector. An electronic gating to PMT is employed to protect the photon detector from strong signals arise at lower heights. The pulse signals from PMT are passed through a discriminator (Phillips model 6908) and then fed to a PC based multichannel analyzer (EG&G Ortec model MCS-PCI). The instrumental bin width is normally set at 2 μs, corresponding to a height resolution of 300 m. A basic photon count profile is generated for each 2400 laser shot integration period, corresponding to a time resolution of 120 sec. A personnel computer is used to store the generated photon count profiles. A typical photon count profile is shown in Fig.5(b). The resonant scattering from the Na layer is clearly seen at altitudes between 80 and 100 km. The nonzero count level is caused primarily due to background light. The signal returns above 30 and below 60 km are due to Rayleigh backscatter from air molecules. An abrupt change in signal returns below 12 km is due to application of electronic gating of the PMT.

Fig.5 (a) Picture shows the In-house developed sodium resonance lidar system configuration. The green laser from YAG pumps the Dye laser. The dye laser generates orange color laser. The 589 nm laser beam is steered into the atmosphere to resonate the sodium metal atoms at the mesopause region (b) the basic photon count profile data from the resonance lidar system.

An interesting and current topic of interest with the mesospheric Na layer is the sporadic occurrence of thin layers of enhanced number density superposed on the regular background layer [Bhavani Kumar et al (2007b)]. These sporadic layers generate sharp sodium abundance peaks of full width at half maximum (FWHM) typically between several hundred meters and less than a few km thick with number density equal to or greater than twice that of the background Na layer. These layers persist for a period of few minutes to several hours. These sporadic layers appear to be related to the ion layers known as sporadic E, or Es. Fig. 6 shows the altitude/temporal variation of the Na layer observed during the sporadic event on night of January 11, 2005. The experimental observation shows the peak of Na layer moved downward from about 96 km to 90 km with a constant velocity. During the entire measurement period, the observed Na temporal variation has undergone a remarkable peak sodium distribution.
2.4. Raman lidar technique

The Raman lidar technique is based on the Raman Effect. In Raman scattering, the scattered light is frequency-shifted with respect to the excitation frequency, but the magnitude of the shift is independent of the excitation frequency. The magnitude of the shift is unique to the scattering molecule, while the intensity of the Raman band is proportional to the molecular number density.

When the atmosphere is illuminated with a high-powered laser, it is possible to obtain the frequency shifted backscattered radiation of the Raman components [Weitkamp (2005)]. In Raman lidars, the vibrational Raman backscattered returns from the atmospheric constituents like Nitrogen (N\textsubscript{2}), Oxygen (O\textsubscript{2}) and Water molecules (H\textsubscript{2}O) are collected as Raman-shifted frequencies along with the elastic lidar signals using an optical receiver like telescope. Wavelength separation using Dichroic mirrors and processing of lidar returns allow measurements of meteorological properties of the atmosphere with high spatial and temporal resolution. Raman lidar systems are designed to detect the various wavelength-shifted photons from molecules in the atmosphere. Tab.1 provides the Raman wavenumber shifts for various gaseous constituents of the atmosphere. This illustrates one of the advantages of the Raman lidar approach to atmospheric measurements: a single wavelength is transmitted into the atmosphere exciting shifts in a wide variety of molecules enabling simultaneous measurements of water vapor, liquid water content, temperature and optical extinction due to airborne particulate matter.

<table>
<thead>
<tr>
<th>SI No</th>
<th>Atmospheric molecular constituent</th>
<th>Raman wavenumber shift (in cm\textsuperscript{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Nitrogen</td>
<td>2331</td>
</tr>
<tr>
<td>02</td>
<td>Oxygen</td>
<td>1555</td>
</tr>
<tr>
<td>03</td>
<td>Water vapor</td>
<td>3652</td>
</tr>
<tr>
<td>04</td>
<td>Liquid water</td>
<td>3425</td>
</tr>
<tr>
<td>05</td>
<td>Carbon dioxide</td>
<td>1285</td>
</tr>
<tr>
<td>06</td>
<td>Sulphur dioxide</td>
<td>1152</td>
</tr>
</tbody>
</table>

The calculation of wavelengths corresponds to different molecular Raman shifts can be obtained using the following relation

\[
\lambda_R = \frac{\lambda_L}{1 - \Delta \nu_R} \cdot \Delta \nu_R
\]

where \(\lambda_R\) and \(\lambda_L\) are correspond to Raman shifted and exciting laser wavelengths respectively. The term \(\Delta \nu_R\) represents Raman wavenumber shift in cm\textsuperscript{-1} for a particular molecular component of interest. Tab.2 provides the calculated Raman wavelengths for N\textsubscript{2} and H\textsubscript{2}O molecules for different exciting laser wavelengths generally used in the atmospheric studies.
Table 2. Nitrogen and water vapor Raman shifted wavelengths for different atmospheric excitation wavelengths

<table>
<thead>
<tr>
<th>Atmospheric excitation Wavelength $\lambda_\text{L}$ (nm)</th>
<th>Shifted N$<em>2$ Raman wavelength $\lambda</em>\text{R}$ (nm)</th>
<th>Shifted H$<em>2$O Raman Wavelength $\lambda</em>\text{R}$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>532</td>
<td>607</td>
<td>660</td>
</tr>
<tr>
<td>355</td>
<td>387</td>
<td>408</td>
</tr>
<tr>
<td>266</td>
<td>285</td>
<td>294</td>
</tr>
</tbody>
</table>

The Raman lidar technique is a very robust technique that makes low demands concerning spectral purity of the emitted laser light and frequency stabilization of the receiver. However, it suffers from the low cross sections of Raman scattering and thus from the comparably small signal-to-noise ratios of the measurements. The water vapor Raman lidar technique uses the ratio of rotational-vibrational Raman scattering intensities from water vapor and nitrogen molecules, which is a direct measurement of the atmospheric water vapor mixing ratio [Melfi et al (1969); Whiteman et al (1992)]. It can measure the vertical distribution of the water vapor mixing ratio from near the ground to the upper troposphere with a vertical resolution of a few tens of a meters and a temporal resolution of a few minutes in the absence of optically thick cloud [Weitkamp (2005)].

Fig.7 Typical height profiles of Nitrogen and Water vapor Raman backscatter signals obtained using Indo-Japanese lidar system on the night of 10 June 2003 at lidar site. The height profiles were obtained by integrating the photo counts between 19:39 and 20:12 LT.

The Indo-Japanese Lidar (IJL) system located at NARL employs a high power pulsed laser source for profiling the atmosphere for middle atmospheric studies. The system uses two independent receivers for collecting elastic laser backscatter in the range resolved manner covering the height range from 8 to 80 km. The scientific capabilities of the lidar system were described elsewhere by Bhavani Kumar et al [(2006)]. The IJL system configuration was modified on temporary basis to obtain Raman signals in addition to the elastic backscatter returns at 532 nm. The modification in the lidar configuration was carried out during 2003 on an experimental basis to check the capability of the system for profiling the atmospheric water vapor. A critical point in the retrieval of water vapor from the atmosphere lies in the signal separation optics skirt characteristics that reject the strong Rayleigh line. A set of Dichroic mirrors were employed in the receive system as spectral separators and also act as Rayleigh signal rejecters. The skirt characteristics of mirrors reject the Rayleigh line by an order of five. The IF filters used in the Nitrogen and Water vapor Raman channels provide four more orders of rejection. The overall Rayleigh signal rejection is about 9 orders. The full width half maximum (FWHM) bandwidths of these filters are at 3.0 nm and 10.0 nm filters with 607 and 660 nm central wavelengths respectively. The photomultiplier units are used as detectors and are operated in photon counting mode. The elastic and Nitrogen Raman Channels were operated with R3234 PMT, while the water vapor Raman channel was used with R7400 PMT unit due to spectral limitation of R3234. The data acquisition was performed using MCS-plus PC based data acquisition system working at 100 MHz sampling rate. Typically, an acquisition file contains 5000 shots averaged for each wavelength in photon counting mode of 1024 bins. This corresponds to a spatial resolution of 300 m at a time resolution of 250 sec. The basic signal profiles of laser backscatter from water vapor and Nitrogen Raman obtained on 10 June 2003 is presented in Fig.7. The profiles shown were integrated over more than 30 minute duration due to weak Raman backscatter from the water vapor molecules and also due to smaller receiver aperture.
The height profiles of water vapor mixing ratio were obtained on several days during clear sky nocturnal conditions in 2003 [Bhavani Kumar et al (2009)]. The mixing ratio profiles were corrected for molecular extinction using the standard model atmosphere data. A sample case study is presented in Fig.8. Fig.8(a) provides typical height profile of water vapor obtained from lidar during nighttime on 9 May 2003 at the lidar site. Fig.8(b) shows the temporal and spatial distribution of the water vapor mixing ratio measured on the same night between 21:44 and 22:12 LT. The distribution shows relatively high water vapor mixing ratio around 1.5 g/kg up to about 4000m height, and a much drier region above where the water vapor density is smaller than 0.5 g/kg. The boundary between these two layers changes rapidly, indicating the presence of local mixing layer. The mixing zone extends to roughly about 4000m height. The pattern shows clearly that there exists a stable layer formation during the period of observation.

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One of the authors, Dr Y. Bhavani Kumar, would like to thank the officials of National Atmospheric Research Laboratory (NARL) and Atmospheric Science Programme (ASP) office of Department of Space for funding the lidar projects such as Boundary Layer Lidar (BLL), Sodium Resonance Lidar, Dual Polarization Lidar, Raman water vapor lidar and also support provided to complete the projects in time at NARL site, Gadanki. Some the laser radar techniques presented in this paper are a part of the Thesis work titled “Development of LIDAR techniques for environmental remote sensing and mathematical analysis of atmosphere data” carried out by the author, Y. Bhavani Kumar, at Sri Venkateswara University, Tirupati during the period between 2005 and 2009.

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