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Micro pulse LIDAR technique
Micropulse lidar technique

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2.0 Introduction to simple backscatter lidar

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 (particulate matter). The laser backscattered energy is directly proportional to the aerosol and molecular content of the observed air mass. Based on this, a backscattering lidar can provide information on the planetary boundary layer (PBL) structure, mixed-layer depth, entrainment zones, aerosol distribution, clear air layering, cloud-base altitudes, cloud depolarization properties, middle atmospheric temperatures, atmospheric transport, and other inferences of air motion (Stull 1998; Endlich et al 1979; Melfi et al 1985; Cooper et al 1994; Reagon et al 1992; Bhavani Kumar 2000). Elastic backscatter lidars are, by far, the most common and simple remote sensing instruments in the world today and this will continue to be true for the foreseeable future. Elastic backscatter lidar measurements exhibit all the desirable characteristics of remote sensing techniques. The measured values represent spatial averages over volumes that can be varied by proper design of the lidar system. Such spatial averaged values are usually more representative of the overall state of the turbulent atmosphere than the single point in situ measurement.

By using aerosols as the tracers of atmospheric dynamics, lidar can identify several dynamical parameters of the atmospheric boundary layer (ABL) such as boundary layer top and entrainment zone depth (Kunkel et al 1980; Boers et al 1984; Boers and Eloranta 1986; Crum et al 1987; Boers 1988; Cooper and Eichinger 1996; Bhavani Kumar 2006, 2008c) in real-time with high temporal and spatial resolutions.
2.1 Micro pulsing technique

The traditional lidar instruments used so far for boundary layer (BL) studies during the last three decades 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, poor reliability, lack of ruggedness, and high development and operational costs. There is a need for operational, practical lidar. Lidar is a fundamental 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. Micro pulse lidar (MPL) is a new generation simple backscatter lidar system. There are three basic differences between the MPL and the most previous lidars systems.

First 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 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.
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The MPL (Spinhirne, 1993) was originally developed at National Aeronautics and Space Administration – Goddard Space Flight Centre (NASA-GSFC) in early nineties. A number of articles have reported on the applications of MPL to environmental studies (Chen et al 2001; Purikh and Parikh 2002; Legrosos et al 2004). The temporal evolution of the boundary layer height and boundary layer aerosol can also be studied (Parikh and Parikh 2002; Legrosos et al 2004; Bhavani Kumar 2006a).

2.1.1 Applications of MPL

The health of the planet Earth and its inhabitants is highly dependent upon the health of the atmosphere. The MPL has a significant role in the atmospheric research, because it facilitates the autonomous monitoring of atmospheric clouds and aerosol scattering. The following are the potential application areas where MPL systems can be made use.

- **Atmospheric and climate research**: Continuous observation of aerosol distribution and atmospheric cloud profiling. There by building the aerosol climatology for future climate prediction (IPCC 2001).

- **Environment monitoring**: The evolution of the concentration of particulate pollutants is important requirement in air pollution control for public health and environmental safety.

- **Meteorological application**: Correct treatment of the physical parameter such as the atmospheric boundary layer depth is necessary for weather forecasting and numerical simulations of climate change.

- **Visibility at slant height**: It is of practical importance in air craft landing and marine navigation. A simple slope method assumes that the asymptotic decrease in the range compensated backscattering intensity is proportional to the round trip laser beam transmittance, in clear atmosphere.
2.1.2 **Boundary layer lidar (BLL)**

A micro pulse lidar system was successfully developed and made operational at the National Atmospheric Research Laboratory (NARL), an autonomous research institution under Department of Space, 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.

![Figure 2.1 Working principle of BLL system](image)

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 computer control and interface system (See Figure 2.1). 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.

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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 will produce increased backscatter (as a spike), 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. These lidars are smaller in size, reliable, and simple, coupled with its autonomous, eye-safe operation, save research money through simpler setup and reduced personnel needs, while producing higher quality data.

2.2 Boundary Layer Lidar – system details

A detailed schematic block diagram of the system and its pictorial view are shown in Figure 2.2a and 2.2b. The overall specifications of the system are given in Table – 2.1. The details on each subsystem are given below.

2.2.1 Laser source and Transmitting optics

The lidar transmitter system employs a Russian pulsed laser M/s Laser Export made, model LCS-DTL-314QT system. It is a microchip (all-in-one laser cavity) Nd:YAG laser employing second harmonic output. It is laser diode pumped and acoustic switched. The output pulse energy is adjustable in the range between 2 and 20 μJ depending on the repetition rate. The laser pulse energy reduces with increase in pulse repetition rate. The output laser characteristics are shown in Figure 2.3. Usually the output pulse energy is set at 10μJ at 2500 Hz repetition rate in the NARL developed boundary layer lidar. The laser beam diameter is 0.4 mm and its divergence is less than 1.5 mrad. The laser beam was expanded to 3 mm in diameter and collimated to have the beam divergence of about 200 μrad before transmission.
The eye safety is achieved with this beam divergence at heights above 250 m from the ground level. The maximum permissible emission (MPE) at 532 nm is 0.5 μJ/cm². The light output from laser is linearly polarized with the degree of polarization greater than 99%. The laser beam is sent into the atmosphere using two mirrors kept at 45° angles. The output energy of laser decreases as a function of the pulse repetition rate as shown in Figure 2.2.

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Figure 2.2b Pictorial view of BLL system at NARL, Gadanki

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2.2.2 Receiving optics

A monoaxial configuration was employed in the BLL system. The laser backscattered light was received by a classical cassegrainian telescope, whose diameter and F-value were 150 mm and 9, respectively. The geometrical form factor for a coaxial lidar having no apertures (other than the objective lens or mirror of the telescope) or obstructions is unity, provided the divergence angle of the laser beam is less than the opening angle of the telescope (Kovalev and Eichinger 2004; Measures 1984). Hence an iris diameter (pin-hole) of 0.5 mm was used to obtain a receive FOV of about 400 μrad. A narrowband interference (IF) filter was positioned in front of the photomultiplier tube (PMT). An IF filter, whose center-wavelength and bandwidth were 532 nm and 0.5 nm, respectively, was used to reduce background light. The filter used in the system is not a temperature controlled. However, as specified by manufacturer, the unit has to be maintained at a temperature of around 22 °C. This was done externally by keeping the system in a temperature controlled room as shown in Figure 2.2b.

Figure 2.3 Laser output energy vs pulse repetition rate characteristics
2.2.3 Detector unit

The detector system employed in the lidar was a high gain photomultiplier tube (PMT) (Hamamatsu R3234-01). It is a head-on type PMT with 10 mm aperture. This was selected for use in the system based on two important specifications; the first one is its low dark current (about 1 nA) characteristic and other one being the good pulse generation property (after pulse effect is 0.6%). Moreover, its rise time is exceptional, around 2 nsec. It has reasonable quantum efficiency (QE) of about 10% at visible wavelengths. The PMT output is delivered through a 50 ohm termination. The PMT output pulses are amplified and discriminated using a Phillips make pulse discriminator (Model 6908), whose BW is 300 MHz. The current source type of outputs is used for data acquisition.

2.2.4 Data recording system

The data acquisition system used in the BLI is a PC based multi-channel analyzer (EG&G Ortec model MCS-pci). A multi-channel scalar (MCS) records the counting rate of events as a function of time. When a scan is started, the MCS begins counting input events in the first channel of its digital memory. At the end of the pre-selected dwell time, the MCS advances to the next channel of memory to count the events. This dwell and advance process is repeated until the MCS has scanned through all the channels in its memory. A display of the contents of the memory shows the counting rate of the input events versus time. In repetitive measurements, where the start of the scan can be synchronized with the start of the events, multiple scans can be summed to diminish the statistical scatter in the recorded pattern. The MCS-pci can profile counting rates versus time, or it can function as a multiple-stop time digitizer for measuring flight times of multiple photons or particles. Typical applications are in time-resolved single-photon counting. It can count rates up to 150 MHz or 65,536 time bins (range bin channels). Dwell times selectable from 100 ns to 1300 s per channel. It can do
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single scan once, or average/sum on repeated scans. There is no dead time between channels and no double counting. There is no end-of-scan dead time. In BLL the range bin width is normally set at 200 ns. This corresponds to a height resolution of 30 m. Usually 3 lakh shot laser firings constitute a raw data profile. It corresponds to a time resolution of 120 sec.

Table 2.1 BLL system overall specifications

Transmitter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>LD pumped Q switched Nd:YAG</td>
</tr>
<tr>
<td>Model</td>
<td>LCS-DTL-314 QT,</td>
</tr>
<tr>
<td>Make</td>
<td>Laser compact, Russia</td>
</tr>
<tr>
<td>Wavelength</td>
<td>532 nm</td>
</tr>
<tr>
<td>Output energy per pulse</td>
<td>2 - 20μJ</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>0.2 – 10 KHz</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>&lt;10 ns</td>
</tr>
<tr>
<td>Beam size</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Polarization</td>
<td>linear</td>
</tr>
<tr>
<td>Beam divergence</td>
<td>&lt;1.5 mrad</td>
</tr>
<tr>
<td>Beam expander magnification</td>
<td>8X</td>
</tr>
<tr>
<td>Divergence of the expanded laser beam</td>
<td>&lt; 200 μrad</td>
</tr>
</tbody>
</table>

Receiver

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope geometry</td>
<td>Cassegrainian</td>
</tr>
<tr>
<td>Diameter</td>
<td>150 mm</td>
</tr>
<tr>
<td>Telescope F-ratio</td>
<td>9</td>
</tr>
<tr>
<td>Field of View</td>
<td>&lt;400 μrad</td>
</tr>
<tr>
<td>IF filter bandwidth (FWHM)</td>
<td>0.5 nm</td>
</tr>
</tbody>
</table>
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Detector - PMT, Hamamatsu R3234
PMT Gain @ 532 nm - 2.5 x 10^3
Quantum efficiency @ 532 nm - ~10%

Data acquisition system
Type - Single photon counting
Model - EG&G Ortec, MCS-pci
Maximum counting rate - 150 MHz
Dwell time selectable - 100 ns to 1300 s
Number of channels selectable - 65,536

Mechanical and environmental specifications of lidar housing
Cubical temperature - <22 °C
Overall dimension lidar (Tx & Rx optics) - 30 x 60 x 100 cm
Weight of lidar (Tx & Rx optics) - ~25 kg

2.3 Ranging of atmospheric boundary layer (ABL)

The ABL is the lowest layer (1–3 km) of the atmosphere that is directly affected by interactions at the Earth’s surface, particularly by the deposition of solar energy. Stull (1988) defined the boundary layer as the lowest part of the atmosphere that is directly influenced by the presence of the Earth’s surface, and responds to surface forcings with a timescale of about an hour or less. These forcings include frictional drag, evaporation, heat transfer, pollutant emission, and terrain induced flow. The processes occurring in this region greatly affect the lives of mankind. In this region, humans spend most of their life time. Figure 2.4 shows the schematic diagram of the boundary layer evolution over land surfaces (Piromen 1994). The boundary layer formed from sunrise to sunset and is characterized by the formation of thermal plumes from solar heating. These plumes carry moisture with them; which
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contributes to the formation of convective clouds. Solar heating is also responsible for the transport of heat and aerosols and thus responsible for mixing in this time frame. During these hours, an existence of convection dominated mixing layer formation is predicted. From sunset to sunrise, the boundary layer is characterized by a stable layer. The reason for formation of stable boundary layer (SBL) in nocturnal periods is due to occurrence of radiative cooling in the lowest part of the atmospheric boundary layer. Above the stable layer is the residual layer, which is the remnant of the daytime boundary layer.

![Diagram of the ABL](image)

Figure 2.4 Schematic diagram of the ABL variation over land

The ABL thickness is quite variable in space and time, ranging from hundreds of meters to a few thousand meters. It is practice in air pollution meteorology to use the term mixed layer (ML) since pollutants that are emitted into the ABL become gradually dispersed and mixed through the action of turbulence. The mixed layer depth (MLD) is the height of the top of the ML and is an important parameter to characterize the ABL and its structure. In some papers, the MLD is also called the mixing height (Seibert et al., 1998, 2000). Measurements, parameterizations and predictions of the MLD have many theoretical and practical applications such as the prediction of pollutant concentrations, in numerical weather...
prediction and climate modeling (Seibert et al. 1998, 2000) and the study of turbulence in ABL. Different mathematical methods were reported to determine or estimate the MLD (Endlich et al. 1979; Melfi et al. 1985; Boers et al. 1988; Hooper and Eloranta 1986; Senff et al. 1996; Hayden et al. 1997; Flamant et al. 1997; Menut et al. 1999; Cohn and Agevine 2000; Brooks 2003). During daytime, radiosoundings are the most common data source to retrieve the MLD based on wind, temperature and humidity profiles, but in most meteorological stations regular radiosonde launches are made only twice a day at predetermined synoptic times [00:00 and 12:00 universal time (UT)]. Consequently, radiosoundings can often be used as a reference for comparison with modeled ABL heights only around midnight and noon. However, nighttime measurements of ABL are still a gap region to modelers, which can be compensated from lidar soundings.

Active remote sensing systems such as lidars use aerosols as tracers of the ABL dynamics (Purikh and Purikh 2002). The optical power measured by a lidar device is proportional to the aerosol content of the atmosphere within BL. The lidar signal shows a strong backscattering within the ML, which decreases through a transition zone and becomes weak in the free troposphere (FT). These contrasts are the basis for the lidar estimations of the MLD. Under convective conditions, the ABL can be divided into three different layers: the surface layer, the ML and the entrainment zone (EZ). The latter represents a transition zone between the ML and the stable FT above. Usually, the EZ is defined in a horizontal average sense (Deardorff et al. 1980). It is important to distinguish between the instantaneous (or local) MLD that varies between the EZ top and the middle of the ML and the average MLD, which is the middle of the EZ (Stull 1988). Ground-based aerosol lidars give a high-resolution picture of the instantaneous ML top that is marked by a large contrast between the backscatter signal from aerosol-rich structures below and cleaner air above.
2.3.1 Determination of ABL height

The use of the lidar technique for ranging the BL depends on the altitude resolved measurement of atmospheric backscatter intensity from outgoing laser radiation. The functional expression (Measures 1984) that relates outgoing laser energy \( E_0 \) and the backscattered signal \( P(z) \) is given as

\[
P(z) = K E_0 O(z) \frac{\beta(z)}{2} T^2(z) + P_n
\]

where \( E_0 \) is the laser pulse energy, \( K \) represents the lidar system constant, \( O(z) \) represents the overlap function (for BLL system, \( O(z) = 1 \) for heights above 200 m AGL). Here AGL stands for above ground level. In the atmosphere, two types of optical scattering take place, scattering by the air molecules and solid particles or liquid droplets suspended in the air. The received laser radiation measured by lidar is proportional to the effective backscattering from particles and molecules present in the atmosphere. The term \( T(z) \) refers to the transmittance offered by the atmospheric path to the laser photons traveling from the ground to a given distance \( z \).

The term \( P_n \) relates to the sky background contributed as noise to the signal counts. It is the number of photons detected from the background including any light sources other than the emitted laser light such as airglow emission, star light, and photodetector dark counts. The dark count is caused by spontaneous emission of photoelectrons from the cathode in the PMT. It may be mentioned here that the return signals, from ranges much above the signal range, where the count level was stable and constant over the integration period are considered as background. In this work, the background is determined by utilizing the signal returns in heights above 30 km. The lidar signal is need to be background corrected and
transformed into a variable that removes the range square dependence, \( X(z) \) \((\text{Fernald 1984})\)
or its logarithm, \( S(z) \)(\(\text{Klett 1985}\)).

\[
X(z) = [P(z) - P_b]z^2
\]  
--- (2.2)

\[
S(z) = \ln[X(z)]
\]  
--- (2.3)

One can notice that the use of \( S(z) \) can lead to problems at low signal-to-noise ratio (SNR) values, where \( X(z) \) can be negative. However, rejecting such values or setting them equal to zero causes biased results, so only transformed variable \( X(z) \) is employed in the present study.

The boundary layer (BL) height from lidar profiles is defined differently by numerous researchers. \(\text{Susano et al (1985)}\) identified the BL height as the height where the signal backscatter begins to decrease from a relatively higher value to lower region. \(\text{Endlich et al (1979)}\) described BL height as the height at which a maximum negative gradient of laser backscatter in vertical direction occurs. \(\text{Flamant et al (1997)}\) also mentioned the BL height as a zone of minimum in the vertical gradient of the backscatter as defined by \(\text{Endlich et al (1979)}\). A general reliable method than that given above involves the direct comparison of the backscatter signal with a fitted model Rayleigh backscattering profile. The boundary layer height can then be defined as the first altitude point for which the measured backscatter profile exceeds the Rayleigh model profile by some fixed amount, \( \phi \). Following \(\text{Melfi et al (1985)}\), \( \phi \) is chosen to be 25%, although it is noted that the boundary layer height retrieved by this method is not particularly sensitive to reasonable values of \( \phi \). Figure 2.5a and b show this analysis on a typical trace. The lidar backscatter profiles recorded at 04:50 LT (during nighttime) and 08:51 LT (during daytime) on 06 January 2005 are shown in Figure 2.5a and 2.5b respectively. The Rayleigh model is fitted between the indicated altitudes.
Figure 2.5a. A lidar backscatter profile recorded at 04:50 LT (during nighttime) on 06 January 2005. The Rayleigh model is fitted between the indicated altitudes.

Figure 2.5b. A lidar backscatter profile recorded at 08:51 LT (during daytime) on 06 January 2005. The Rayleigh model is fitted between the indicated altitudes.
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The top of the PBL is characterized by a sharp increase in temperature and a sudden drop in the concentration of water vapor and particulates as well as most trace chemical species. The height profile of the range-squared signal at 14:00 LT (during daytime) on 8 December 2004 is shown in Figure 2.6, together with the profile of the atmospheric temperature and relative humidity obtained by a simultaneous radiosounding performed at the lidar site. The top of the ABL or the mixed layer can be identified from the radiosonde, as well as from the lidar profile.

![Figure 2.6 Comparison between the lidar range-squared data with radiosonde profiles (temperature and relative humidity) performed at the same hour on 8 December 2004 at 14:00 LT over lidar site Gadanki](image)

2.3.2 Description of Lidar site

The lidar site, NARL-Gadanki (13.5°N, 79.2°E, ~370 m MSI), is located in the east coast of Indian peninsula. It is in a rural environment surrounded by low-level hills and also agricultural fields. A map showing the terrain surrounding the lidar site is illustrated in Figure 2.7. The height levels of hills surrounding the site are about 300-800 m. As per the meteorological conditions, the seasons over India are divided into winter (January and February), pre-monsoon (March, April, and May), monsoon (June, July, August, and
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In winter, the wind conditions are the air masses recede south and are replaced by the cool tropical continental air. Usually in winter periods, the sky conditions are clear, which means that the atmosphere is free from precipitating clouds and the vertical motions are benign.

Figure 2.7 Terrain map showing the location of lidar site and its topography

2.3.3 Evolution of ABL over Gadanki site during winter period

An observation of evolution of ABL over Gadanki site was carried out for a period of continuous 48-hour in January 2005 during clear sky winter period. The time-height variation of range corrected signal (RCS) $S(r)$ is shown in Figure 2.8. Figures 2.8(a) and 2.8(b) represent the time-height evolution of lidar range corrected signal $S(r)$ from 0:00 LT on 6 January to 0:00 LT on 8 January 2005 and compared along with the surface temperature measurements respectively. For clarity, the lidar data is presented in day wise separately.

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Over land surfaces the boundary layer has a well-defined structure that evolves with the diurnal cycle (Stull 1988). Hence, the observations are discussed in terms of internal sub-layers of the ABL, the major components of the BL structure, such as the mixed layer, the residual layer, and the stable or nocturnal boundary layer. From figure 2.8(a), one can observe the mixed layer (ML) development during daytime from the lidar signal enhancement between 06:00 and 15:00 LT. The mixed layer (ML) or Convective Boundary Layer (CBL) is formed by the convection that arises from solar heating of the Earth’s surface and is associated with organized thermal transport due to highly developed vertical motion. The turbulence is essentially associated with the thermal transport from the ground to the upper layers during daytime (Stull 1988). On 6 and 7 January 2005, clouds are observed at the top of the ABL during its growth phase (06:00 to 10:00 LT on 6 January and 10:00 to 14:00 LT on 7 January 2005). During most of the morning and afternoon, surface heating
caused the lifting and mixing of the low level moist air with dry air aloft, leading to the development of cumulus clouds. On 6 January 2005, the ML has been observed reaching a maximum height of 1.5 km at 15:00 LT. The growth of the BL on this day was gradual. This may be due to a slow rise of ground temperatures recorded. The depth of mixed layer or convective boundary layer depends mainly upon the diurnal variation of surface temperature (Stull 1988). On 7 January 2005, the formation of ML has been found faster than the corresponding one on 6 January 2005. This may be due to quick rising of ground temperature than the previous day.

Figure 2.8b Diurnal evolution of ABL over Gadanki site on 07.01.2005

On 7 January 2005, the ML has reached a peak height of about 1.6 km at 15:00 LT. A thin residual layer, the remnants of previous day ML, is also seen and has been eroded completely by the ML around 12:00 LT. The residual layer (RL) is another mixed layer basically formed by the daytime turbulence and decays due to reduced surface heating after
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sunset. On 6/7 January 2005, the RL appeared at a height of 1.5 km initially and the later descended to 1 km at about 20:00 LT. An elevation of RL is observed close to 21:00 LT, which may be due to background dynamical conditions. The elevated RL is formed into a stratified structure later and appeared to decay in strength with time. In the early hours of the day, RL is generally represented as a neutrally stratified elevated layer, whose characteristics are generally observed to be initially those of the Mixing Layer (ML) from the previous day (Stull 1988). Soon after the sunset buoyant (eddy) production ceases and the atmosphere changes to a near neutral condition.

This is less turbulent RL containing the remnants of the daytime mixed layer. In the late night hours, as the surface gets cooled the elevated eddies are directed downwards. Due to the negative buoyancy, turbulent motions get damped. This causes formation of a stable region (stratified layer) near to the surface known as stable boundary Layer (SBL) or Nocturnal boundary layer (NBL). In Figure 2.7, the strong signal regions indicated in dark red/orange-red color as a layered structure indicated by the SBL or NBL. On 6/7 January 2005, the SBL is initially identified at about 500 m and is gradually elevated to about 800 m.

Thus, the BLL system has been successfully used to study the structure, dynamics and the evolution of atmospheric boundary layer using aerosols as atmospheric tracers. Using the BLL system, the internal sub-layers of ABL such as Mixed Layer (ML), Residual Layer (RL) and Stable Boundary Layer (SBL) or Nocturnal Boundary Layer (NBL) have been identified clearly over the tropical rural site Gadanki for the first time. However, using the lower atmospheric wind profiler (LAWP) available at Gadanki site, the evolution ABL was reported earlier by several researchers (KK Reddy et al 2001; Praveena Krishnan et al 2003), but could not able to explain the erosion and formation of RL. This shows the potential of the low-pulse energy lidar technique for evolution of ABL and related studies.
2.3.4 Methods of ABL height determination from lidar profiles

Several approaches have been used to estimate the MLD from lidar. Melfi et al (1985) and Boers et al (1988) used simple signal threshold values. It suffers from the need to define them appropriately taking into account that the signal strength varies within the dataset. Hooper and Eloranta (1986) used the height of the maximum of the variance of the lidar signal. Some authors detected that the results tended to be biased to higher altitudes due to humidity effects (Dupont et al 1991; Menu et al 1999). Derivative methods are the most common. Out of these, three methods are popular: Hayden et al (1997) and Flamant et al (1997) used the largest negative peak of the first derivative of the lidar signal as a marker for the instantaneous MLD. Menu et al (1999) compared the absolute minimum of the second derivative of the lidar signal with the maximum of the standard deviation profile of the signal and found that the latter method overestimated the MLD when compared to radiosoundings. In a similar way, Senff et al (1996) used profiles of the derivative of logarithm of the lidar signal. Steyn et al (1999) fitted an idealized profile to define the ML top and the transition zone depth, but Hägeli et al (2000) found that the technique produced biased results for complex backscatter profiles. Cohn and Angevine (2000) used a wavelet-based technique providing a scale-dependent gradient locator. The results were biased by gradients in the background signal. Recently, Brooks (2003) developed an alternative approach using multiple wavelet dilatations and capable of identifying the upper and lower limits of the transition zones, which are remain insensitive to vertical gradients.

2.3.4.1 Threshold method

A number of threshold methods have been proposed to determine the BL height from lidar signal profiles. One such method that involves a direct comparison of lidar backscatter signal, \( P(z) \), with a fitted Rayleigh molecular backscatter profile is discussed in section 2.3.1.
The boundary layer height can be defined as the first altitude point for which the measured backscatter profile exceeds the Rayleigh model profile by some fixed amount. Following Melfi et al (1985), \( \phi \) is chosen to be 25%, although it is noted that the boundary layer height retrieved by this method is not particularly sensitive to reasonable values of \( \phi \). Boers and Melfi (1987) and Dupont et al (1994) have also employed this method to estimate the BL height from the lidar backscatter. However, in practice, threshold methods will often misidentify particulate layers above or below BL as the top of the BL and are thus not recommended (Kovalev and Eichinger 2004).

2.3.4.2 Derivative methods

In this method of BL determination, the derivative of the signal will exhibit a strong negative peak. The BL height can be identified by the absolute minimum. Under derivative methods, gradient (GM), double gradient (DGM) and logarithmic gradient (LGM) are generally employed to determine the BL height from the lidar profiles.

2.3.4.2.1 Gradient Method

The lidar signal exhibits a strong backscattering within the BL, which decreases through a transition zone and becomes weak in the free troposphere (FT). This is explicitly clear for range corrected signal, \( X(z) \), shown as a typical example in Figure 2.9(a). The data presented is obtained from the lidar system on 11 January 2005 at 22:00 LT. One can see an abrupt drop in backscatter intensity at the top of the BL, which can be considered as a gradient in the range corrected signal that appears to be a good option for determination of BL height. The GM method looks for the altitude \( (h_{\text{GM}}) \) of the absolute negative minimum of the first derivative of the \( X(z) \)

\[
h_{\text{GM}} = \min \left[ \frac{d[X(z)]}{dz} \right]
\]  

\[--- (2.4)\]
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The application of gradient method to the lidar data is shown in Figure 2.9 (b). The estimated height $h_{BL}$ is obtained as 800m in this case. In late seventies, Endlich et al (1979) described BL height as the height at which a maximum negative gradient of laser backscatter in vertical direction occurs. Sasano et al (1985) identified the BL height as the height where the signal backscatter begins to decrease from a relatively higher value to lower region. Flamant et al (1997) also mentioned the BL height as a zone of minimum in the vertical gradient of the backscatter as defined by Endlich et al (1979). A number of researchers have calculated the gradient of the signal with height and used the change in gradient as an indicator of the BL height (Kaimal et al 1982; Hoff et al 1996; Hayden et al 1996). However, some times complex profiles show several minima exist over an extended height range and the absolute minimum does not always give the BL height. As the range corrected signal $X(z)$ is noisy, at heights near BL top, derivative of the $X(z)$can present several small negative peaks and there will be a difficulty to determine the lowest negative peak. The effect of presence of several negative peaks has been discussed by Stull (1988).

2.3.4.2.2 Double gradient method (DGM)

Another mathematically similar method uses the minimum of the second order derivative of the range corrected signal, which is location of the inflection point, as the height. This method is known as the inflection point (IPM) or double gradient method (DGM).

$$h_{IPM} = \min \left\{ \frac{d^2 X(z)}{dz^2} \right\}$$  \hspace{1cm} (2.5)

Menut et al (1999) used the absolute minimum of the second derivative that corresponds to the minimum of the second derivative of the range corrected signal $X(z)$located just below $h_{BL}$. Limitations of IPM are found in the presence of elevated humid aerosol-laden layers whenever the inversion capping the mixed layer is weak (Menut et al 1999). Figure 2.9(c)
shows the application of method to the lidar signal $X(z)$. The estimated height $h_{lim}$ is obtained as 750m in this case.

2.3.4.2.3 Logarithmic gradient method (LGM)

A variant method that uses the location of the maximum value of the logarithmic derivative of the range corrected signal is employed by White et al (1999) as the criteria for the BL height determination. The derivative of the logarithm of $S(z)$ is proportional to the aerosol extinction gradient and therefore it can also be used to detect the largest negative gradient.

The logarithm gradient method (LGM) consists in finding the altitude, $h_{lim}$, at which the minimum of the first derivative of the logarithm of $S(z)$ is reached (Sicard et al 2006).

$$h_{lim} = \min \left( \frac{d \log S(z)}{dz} \right)$$  -- (2.6)

Date: 05.01.2005

Figure 2.9 A well-mixed boundary layer is shown in panel (a) above 200m along with a transition to the relatively clean air. Application of derivative methods for determination of BL height (a) range corrected lidar signal (b) gradient method (c) double gradient method and (d) logarithmic gradient.

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Figure 2.9(d) shows the use of LGM to the lidar data. The calculated $h_{lmd}$ height in this case study is 800 m. In general, inflection point or maximum derivative methods have the advantage of being independent of any arbitrary threshold values and show good accuracy when turbulent fluctuations are present (Mennt et al 1999). However, as a practical matter, running derivatives are difficult to calculate in the presence of noisy data, particularly at longer ranges. Thus some type of spatial or temporal averaging is required (Kovalev and Eichinger 2004).

2.3.4.3 Variance method

![Figure 2.10 Plot showing several lidar range corrected signal profiles and the corresponding variance method output](image)

The backscatter signal, in the BL, is the culmination of scattering from aerosols and molecules within the BL. At any given height, there is much greater variability in the aerosol distribution in the BL. Therefore, it is possible to use variance, $\sigma^2$, of the backscattered signal to measure the BL height (Hooper and Eloranta 1986; Piironen and Eloranta 1995).
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This method is also called the variance centroid method (VCM). In this method, the standard deviation is calculated from the temporal fluctuations of the range squared signal $X(z)$ at each altitude, as follows

$$\sigma_{VCM} = \sqrt{\frac{1}{N} \sum_{m=1}^{N} [X(z)_m - \bar{X}]^2}$$

where $N$ corresponds to the number of profiles. The determination of BL height by this method is illustrated in Figure 2.10. The limitations of VCM are most obvious in the atmosphere, where shear-induced presence of turbulence within the residual layer (Cooper et al 1994) is responsible for false detections near the ABL.

2.3.4.4 Wavelet method

![Figure 2.11 Lidar range corrected signal and corresponding wavelet covariance transform (WCT)](image)

The wavelet covariance transform (WCT) technique is implemented for the BLL data to identify the ABL top height $Z_T$. The WCT is defined as
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\[ W_r(a, b) = \frac{1}{a} \int_{-b}^{b} f(z)h\left(\frac{z-b}{a}\right)dz \quad (2.8) \]

\[ +1, \quad b - \frac{a}{2} \leq z \leq b \]

where \( h\left(\frac{z-b}{a}\right) = \begin{cases} 1, & b \leq z \leq b + \frac{a}{2} \\ 0, & \text{elsewhere} \end{cases} \)

The covariance transform \( W_r(a, b) \) is a measure of the similarity of the range-corrected lidar backscatter signal and the Heav function (Brooks 2003). In the case of a clear lidar signal profile, shown in Figure 2.11, with high backscatter in the PBL and a low signal in the free troposphere, \( W_r(a, b) \) takes a local maximum at the height of the PBL top (for a dilation length of \( a = 10\Delta z = 300 \text{ m} \)) as 850 m. Because the dilation, \( a \), the extent of the step function, is chosen a priori, the wavelet covariance transform is a function of the translation \( b \), which is the location of the step.

![Correlation coefficient plot](image)

Figure 2.12 Correlation plotted between inflexion point and variance methods in estimation of BL height from lidar data. The comparison of correlation was carried out for the lidar data collected between 3 January 2005 and 31 March 2005 taken at mid-night hours.*

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Lidar signals, $S(r)$, measured within 5 min integration are sufficient to determine the ABL height with the GM, LGM and IPM methods. However, the variance method requires averaging of signal profiles over 5 to 60 minutes time frame. It was observed that both the GM and LGM retrieve higher MLD than compared to the IPM method. This is normal since the inflexion point of the first derivative appears just below the GM derivative minimum. A good agreement was found among the different BL determination methods with correlation coefficient larger than 0.96. Figure 2.12 shows an excellent agreement between IPM and variance lidar analysis methods for the lidar data collected between 3 January 2005 and 31 March 2005. The correlation comparison was carried out for the lidar data taken at midnight hours during cloud free nights of 2005 winter period.

![Figure 2.12](image)

Figure 2.13 ABL top heights determined using the gradient, IPM, and variance methods shown at 3 hour interval for clarity sake. The lidar data shown was a diurnal data collected on 7 February 2005 at Gadanki site.

The results of application of GM, IPM and variance methods to Diurnal variation of lidar data, $S(r)$, are shown in Figure 2.13. The study was carried out on lidar data collected on 7 February 2005. Computational results from different methods show that there is a fine agreement observed between gradient and IPM methods, where as the outcome of variance

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method with 5 min variability differs from other methods during RL presence. However, it was observed that after execution of higher time integration, the variance method meets the result of other methods. Near simultaneous MLD comparisons were carried out at Gadanki site in year 2007 and 2008 using the BLL system and the regular GPS radiosonde soundings. The GPS radiosoundings performed at 12:00 GMT time on regular basis at Gadanki site have been used for the comparison study. Relative humidity values from GPS radiosondes correlate very well with the layers detected by the lidar. Humidity effects can be important on the lidar data through a swelling of the aerosols and an increase of its effective cross section. MLD estimated from lidar using different analytical methods agrees reasonably well with those expected from radiosonde temperature and relative humidity profiles. The outcome of the mixer layer depth (MLD) comparisons between lidar (IPM and variance methods) and radiosoundings are shown in Figure 2.14 for a part of the study period conducted in January 2008.

![Figure 2.14 Comparison of lidar methods of MLD estimation (IPM and VCM) and the MLD retrieved from radiosoundings. The study was carried out using the near coincident lidar and GPS radiosonde data obtained during the measurement period January 2008.](image)

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2.3.5 *Entrainment zone (EZ) depth*

The top of the BL is generally associated with a transition region from rather polluted air in the ABL to mostly clean air in the free troposphere. Hence a strong negative gradient in lidar signal is observed at the transition region. The vertical gradient \(D(r)\) of the lidar signal \((\text{Endlich et al.} 1979)\) is expressed as

\[
D(r) = \frac{d[X(r)]}{dr} = \frac{d[S(r)]}{dr}
\]  

--- (2.9)

Figures 2.15(a) and (b) indicate the temporal variation of lidar signal \(S(r)\) and its first derivative \(D(r)\) from 06:00 to 18:00 Hrs LT on 6 January 2005. Figures 2.15 (a) and (b) demonstrate that this transition region is clearly detected from lidar signals, with high temporal and spatial resolutions.

![Figure 2.15 Time-Height section of (a) Lidar range corrected signal and (b) its spatial gradient. The spatial gradient shows clearly a time variation in transition region at BL top and also temporal variation in the entrainment zone depth. The Lidar data shown is diurnal data collected on 6 January 2005 at Gadanki site](image-url)
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The method of using $D(r)$ provides a precise description of the boundaries between air masses identified by difference in the aerosol content. Positive gradients of $X(r)$ correspond to increasing backscatter with altitude, and vice versa. A strong decrease with altitude in the aerosol concentration is expected at the entrainment zone (Endlich et al. 1979). The largest negative vertical gradient in the lidar signal, associated with a sharp transition from “polluted” to “clean” air, can be used to identify this layer. The Entrainment Zone is the region of statically stable air at the top of the ML, where there is entrainment of free-troposphere (FT) air downward and the overshooting thermals upward. From the Figure 2.15(b), one can observe that the entrainment is clear during early hours of morning and also late afternoon hours. But during strong convective period, from 09:00 to 15:00 LT, the Entrainment zone appeared to be patchy. This was clear that during this time the upward thermals were strong enough and thus preventing air entering from FT in to BL.

2.3.6 Special lidar observations in ABL over Gadanki site

2.3.6.1 Oscillation in BL

Ground-based LIDAR observations of the evening transition in the PBL have been observed since 2004 and revealed anomalous mixing at the top of the Residual Layer (RL). As an
example the case studies of 9 November 2004 and 14 January 2007 are presented here. Strong wave-like instabilities appear at the capping inversion of the RL. They seem to be due to convectively-driven internal gravity waves. Figure 2.16a shows an oscillating aerosol layer observed by the BLL system around 2.5 km height. The oscillation that produced the buoyancy waves was observed to start from 18:25 to 22:35 LT. In this time frame, the period of oscillation is found to about 12 min. Generally a stable environment supports buoyancy waves. Atmospheric oscillations, sometimes called gravity waves as a common occurrence in the atmosphere, are formed due to shear instability such as frontal acceleration, airflow over orographic regions, or geostrophic adjustments (Hertzog et al 2001). The morning transitions in PBL also cause anomalous mixing at the top of PBL. An oscillation observed in early morning hours is shown in Figure 2.16b.

![Figure 2.16b BLL time series show wave oscillations at the top of RL observed on 14 January 2007 in early morning hours.](image)

As shown in Figure 2.16b, the ML reaches 500 m and the RL height is approximately 1000 m between 0100 and 0400 LT. Waves of amplitude ranging from 50 m to 100 m are clearly visible at the base of the inversion layer. The wave characteristics i.e. frequency and amplitude can be retrieved from the BLL signal. After 0400 LT, mixing occurs at the
inversion layer. It is believed that the intermittence, found in stable boundary layers, is associated with larger-scale events, such as gravity waves (Fig. 2.16b), overturning Kelvin–Helmholtz (KH) waves, shear instabilities, or terrain-generated phenomena. Internal gravity waves and shear instabilities may propagate over long distances. (Einaudi and Finnigan 1981; Finnigan and Einaudi 1981; Finnigan et al 1984). As a result, turbulent events at the surface may occur because of an event that occurred tens of kilometers away and a kilometer or higher up in the atmosphere.

2.3.5.2 An observation of elevated BL during nighttime over Gadanki site

At nighttimes, the PBL tends to be lower in thickness while during the day it tends to have a higher thickness. The two reasons for this are the wind speed and thickness of the air as a function of temperature. Usually, the formation of PBL is dominated more by advection and thermal energy budgets than levels above the PBL. The earths gains most of its energy and lose most of its energy from the surface. It is warmed through solar heating and cooled through long-wave radiation emissions. Strong wind speeds allow for more convective mixing. This convective mixing will cause the PBL to expand. It can warm up significantly during the day and cool at night while the rest of the atmosphere stays at a fairly uniform temperature. At nighttime, the PBL contracts due to a reduction of rising thermals from the surface. Cold air is denser than warm air; therefore the PBL will tend to be shallower in nighttimes. An interesting observation of elevated boundary layer during nighttime has been observed over Gadanki on the night of 23 July 2006. This observation was carried out by lidar and supported by GPS data. Usually the determination of the depth of the PBL is done using the radiosonde data. The top of the PBL is often marked with a temperature inversion, a humidity gradient, and change in wind speed and/or a change in wind direction. However, there will be an abrupt change in air mass at the top of the boundary layer. This information
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is obtained from the lidar data. Figure 2.17 shows the lidar extinction profile, GPS sonde derived temperature, water vapor, wind speed and wind direction. The data panels of Figure 2.17 indicate that BLH observed on that night was around 4.2 km AGL. It can be seen from Figure 2.17 that the structure of aerosol distribution is closely related to the structure of atmospheric water vapor. It shows clearly that the vertical distribution of aerosol over Gadanki during this period of observation is hygroscopic in nature.

Figure 2.17 Elevated BL layer observed from coincident height profiles from BLL and radiosonde parameters such as water vapor mixing ratio, atmospheric temperature, wind speed and wind direction on the night of 23 July 2006

2.3.5.3 Multiple Layering phenomena

Layering phenomena are easily identified in lidar scans as the stratified layers present above the local BL. Figure 2.18a and b show the occurrence of thin stratified aerosol layers in the atmosphere. Mixing of the air and turbulence are strongly damped and pollutants emitted at the surface tend to remain concentrated in a layer only a few tens of meters thick near the surface. Figure 2.18a shows the layers of aerosol formed at height between 1 and 3 km observed using BLL. Each aerosol layer represents a different aerosol concentration. Stable boundary layers are easily identified in lidar scans by the horizontal stratification that is nearly always present. The bands are associated with layers that will have different wind speeds (and, possibly, directions), temperatures, and particulate/pollutant concentrations.
These layers are strongly depending on the local meteorological conditions and usually descend with time due to lowering of surface temperatures during nighttimes.

Figure 2.18a Height profile of lidar signal intensity showing the presence of elevated aerosol layers distributed up to 3 km in height observed on 16 November 2004 over Gadanki site.

Figure 2.18b Time-Height section of lidar range corrected signal $S(r)$ showing the presence of aerosol layering often found during stable atmospheric conditions. B.L.L. observation of elevated layers of aerosol was recorded at Gadanki site on 16 November 2004. Note that the aerosol layers were observed descending in height with time due to radiative cooling of the earth surface in night hours.
2.4 Remote sensing of Lower atmosphere aerosol

Remote sensing of the primary components of air pollution, such as ozone and airborne particulate matter ($PM$), is improving our understanding of the processes that control air pollution episodes. Air pollution has been demonstrated to affect health, influence our activities due to changes in visibility, and it is the focus of our concern for the global environment due to effects on the radiative energy balance between "greenhouse gases" and increasing particle scattering albedo. However, the scientific understanding of the aerosol radiative forcing magnitude remains very low (Albritton and Filho 2001). Although the lifespan of aerosols is about one week, persistent meteorological phenomena and anthropogenic activities can provide an environment of greater climate impact (Rasch 2001). Chemical species, which absorb infrared radiation, lead to global warming and airborne particulate matter reduces the direct and indirect flux of solar radiation at the surface. Increased scatter by airborne particulate matter can act to counter or enhance the changes from the greenhouse effect depending upon the particle sizes and leads to a complicated nonlinear response. As part of understanding the effects of aerosols on human lives and the environment, it is also equally important to study the optical properties and dynamics of aerosols in the boundary layer so that pollution transport and local atmospheric variation can be clearly elucidated. Because aerosols play an important role in radiation budget of the atmosphere, quite a number of studies were conducted on this area (Holben et al 1998; Dammann et al 2002, Rajeev and Ramanathan 2002, Birmili et al 1999) and Langmann et al (1998). By knowing the optical properties of the aerosols, we will be able to understand whether aerosols aid in the cooling or heating process (Kandel 1999) of the atmosphere.

Airborne particulate matter has been shown to be associated with increased hospital admissions for cardiovascular disease. The increase in airborne particulate matter has
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changed the optical properties of the atmosphere by decreasing visibility, thereby directly affecting air traffic patterns and landing frequency of commercial aircraft, and by reducing the aesthetic appreciation of the national parks (Hidy et al. 1998). Increased emissions into the atmosphere cause two competing mechanisms which affect the energy balance that controls our global climate. The increase in airborne particulate matter is principally due to combustion products from transportation and power generation (Albritton et al. 1998). The goal of present research is to improve our capabilities in obtaining meteorological data and understanding the physical processes that result in air pollution episodes.

The direct detection lidar, or simple backscatter lidar, is important for profiling the aerosol and molecular backscatter intensity. Backscatter lidar techniques are the simplest to apply because only a simple laser transmitter and receiver are required; however the signals generally provide more qualitative and less quantitative information on the atmospheric properties. Mie scattering lidars rely on the fact that Mie scattering have large scattering cross-sections \( \frac{d\sigma}{d\Omega} = 10^{-4} \text{ cm}^2 \text{ sr}^{-1} \). This means that even low concentrations or changes in the concentrations of dusts or aerosols can easily be detected (Measures 1984).

![Figure 2.19. Typical BLL signal profiles showing (a) Basic photon count data and the (b) corresponding range corrected data indicating the backscatter from cloud and aerosol load in the atmosphere.](image)

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This makes this system ideal for continuous atmospheric monitoring. In general, Mie lidars are utilized to monitor aerosols and to detect cloud base height (see Figure 2.19) and diurnal variations of the atmosphere. With a fine temporal resolution, a continuously operated lidar can easily detect real time aerosol dynamics in the atmosphere. Attempts have been made in the lower atmosphere to obtain optical extinction profiles by inverting the lidar equation and integrating along the lidar profile from a range of some distance beyond the volume being studied (Klett 1981). One of the particular applications of the backscatter lidar is to detect the plumes of dust or aerosols, in this case the atmospheric path can be used as a reference by measuring the scattered signals before and after plume injection. An application of this type of measurement has been used to investigate plumes of airborne dust particles (Li and Philbrick 2002).

2.4.1 Klett inversion algorithm

The retrieval of aerosol backscatter from B.L. returns (see Figures 2.19a and b) depend on the attenuation of the signal on its path through the atmosphere. The functional expression that relates the outgoing laser energy \( I_o \) and the backscattered signal \( P(z) \) is given by Collis (1969) as

\[
P(z) = KE_0 O(z) \frac{\beta_f(z)}{z^2} T^2(z) + P_b
\]

where \( E_0 \) is laser pulse energy, \( K \) represents lidar system constant, \( O(z) \) represents the overlap function (for B.L. system, \( O(z) \approx 1 \) for heights more than 200 m above ground level).

In the atmosphere two types of optical scattering takes place: scattering by the air molecules and solid particles or liquid droplets suspended in the air. The received laser radiation measured by lidar is proportional to the effective backscattering from particles and molecules present in the atmosphere.
In the Eq. (2.10), the term $\beta_T(z)$ represents the total volume backscatter coefficient, which is the sum of backscatter from air molecules $\beta_m(z)$ and particles $\beta_s(z)$ interacted by the laser photons. The term $T(z)$ refers to the atmospheric transmittance for the laser photons traveling from ground to a given distance $z$ in the atmosphere and back to the source. This is usually represented as

$$T^2(z) = \exp\left[-2\int_0^z \alpha_T(z)dz\right]$$ \hspace{1cm} (2.11)

where the term $\alpha_T(z)$ is the total volume extinction coefficient, given as the sum of integrated attenuation due to air molecules $\alpha_m(z)$ and particles $\alpha_s(z)$.

For any lidar system, the Eq.(2.10) can be modified and shown as

$$P(z) = C\beta_z(z)T^{-1}(z) + P_b$$ \hspace{1cm} (2.12)

where $C$ is the calibration constant and can be extracted from the lidar signal $P(z_r)$ at a reference calibration range $z_r$ by

$$C = \frac{z_r^2 P(z_r)}{\beta(z_r)R(z_r)T^2(z_r)E_0}$$ \hspace{1cm} (2.13)

Here $R(z_r)$ is the atmospheric mixing ratio at range $z_r$. In the present study, the calibration height range is considered at heights between 7 and 10 km. Since the signal counts in this height range is small, several range bins are averaged to obtain mean calibration constant. In Eq. (2.13), the term $P_b$ relates to the sky background contributed as noise to the signal counts. It is the number of photons detected from the background including any light sources other than the emitted laser light such as airglow emission, star light, and photo detector dark counts. In this work, the background is determined by utilizing the signal returns in heights above 30 km.
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Since the lidar equation has strong dependence on path loss (range square loss) due to the telescope etendue, eq (2.12) is often reduced to a form

\[ \beta(z) = \frac{[P(z) - P_{\infty}]^2}{C} = \beta_i(z)\exp][-2\int_0^z [\alpha_i(z)dz], \quad \cdots (2.14) \]

where the term \( \beta(z) \) is known as attenuated backscatter coefficient. By applying natural logarithm and differentiating on both sides of Eq. (2.14), one obtains

\[ \frac{d[\ln(\beta(z))]}{dz} = \frac{d[\ln(\beta_i(z))]}{dz} - 2\alpha_i(z) \quad \cdots (2.15) \]

The equation (2.15) is a function two variables, namely \( \alpha_i(z) \) and \( \beta_i(z) \). It cannot be solved unless a relation between extinction and backscattering coefficient is assumed. The relation is termed as lidar ratio \( (LR) \). For molecular (Rayleigh) atmosphere, the extinction to backscatter ratio \( (LR_m) \) is constant and fixed at \( \frac{8\pi}{3} \). The molecular backscatter cross section and Rayleigh extinction data can be obtained by using formulation given in chapter-1. The height profile of molecular components such as \( \alpha_m(z) \) and \( \beta_m(z) \) can be computed from pressure \( P(z) \) and temperature \( T(z) \) data given by meteorological Radiosondes or by using the standard model atmosphere data from the following relations

\[ \beta_m(z) = \frac{9\pi^4(n_m^2 - 1)^2(6 + 3\gamma)}{\lambda^2N^2_m(n_m^2 + 2)^2(6 - 7\gamma)} \frac{T_m}{P_m} \frac{P(z)}{T(z)} \quad \cdots (2.16) \]

\[ \alpha_m(z) = \frac{24\pi^4(n_m^2 - 1)^2(6 + 3\gamma)}{\lambda^2N^2_m(n_m^2 + 2)^2(6 - 7\gamma)} \frac{T_m}{P_m} \frac{P(z)}{T(z)} \quad \cdots (2.17) \]

where \( n_m \) represents the refractive index of air \( (n_m = 1.00027824 \text{ at } 530 \text{ nm}) \) (Penndorf 1957). \( \gamma \) indicates the air depolarization \( (0.0284) \) at the operating wavelength and corresponding to King’s factor of 1.049 at 530 nm (Bates 1984), and the factor \( N_m = 2.547 \times 10^{25} \text{ m}^{-3} \) gives the molecular number density for the standard atmospheric pressure \( (P_0 \)
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= 1013.25 mbar) and temperature \((T_0 = 288.15 \text{ K})\) conditions at the ground respectively. In the present study, the above empirical relations have been used in a computer code, see Figure 2.20 for flow chart of the code, for deriving the molecular profiles, such as backscattering coefficient \(\beta_m(z)\) and extinction coefficients \(\beta_m(z)\), from the atmospheric pressure and temperature data corresponding to the geographical coordinates of the lidar site given by the standard atmosphere CIRA-86 \((\text{Fleming \ et\ al} \ 1988)\).

However, the determination of aerosol extinction and backscatter \((LR_a)\) is not straightforward as in the case of air molecules, because their extinction and backscatter depends on the size distribution and refractive indices of the particles present in the atmosphere. Generally atmospheric aerosol/particles can be represented as homogeneous spheres and their optical properties can be predicted by Mie Theory as functions of size distribution and refractive index.

![Flow chart of the computer code developed for deriving the aerosol backscattering coefficient from BLL data](image)

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Several investigators have calculated \( LR_a \) values for tropospheric aerosols from size and chemical information either by measurement or by calculation. However, numerous evidences (Ackerman 1997; Anderson et al. 2000) indicate that lower \( LR_a \) values (less than 30) are associated with cases where the coarse mode is more dominant and that higher \( LR_a \) values (above 40) are associated with cases where pollution derived accumulation-mode particles are more prominent. As the lidar site is located in a non-polluted land-locked rural region, a representative value of 40 (Takamura et al. 1994) has been used in the present study as \( LR_a \) for the continental non-polluted type aerosol.

Once the lidar ratio for aerosol is assumed, the application of two component signal inversion to equation (2.15) allows determination of \( \beta_p \). Since this equation is a Ricatti type one (Bernoulli's form), the differential equation of first order and its solutions are given (Fernald et al. 1972) as

\[
\beta_p(z) = -\beta_a(z) + \frac{\beta(z) \cdot \text{term}_1}{\text{term}_2 - 2LR_a \int \beta(z) \cdot \text{term}_1 \, dz}
\]

Here

\[
\text{term}_1 = \exp \left( -2(LR_a - LR_p) \cdot \int \beta_a(z) \, dz \right)
\]

and

\[
\text{term}_2 = \frac{\beta(z_f)}{\beta_p(z_f) + \beta_a(z_f)}
\]

This solution is called the “forward” solution, since the proposed solution is based on a reference calibration point for the aerosol scattering coefficient and extinction-to-backscatter ratio at a distance less than the retrieval distance. This was convenient when auxiliary measurement of the light scattering coefficient (such as with an integrated nephelometer;
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were available in the near field. However, it has been pointed out by Fernald et al. (1972) and Klett (1981, 1985) that the solution of Eq. (2.18) could become unstable for cases of high extinction and would diverge with increased altitude, z. Thus a “backward” solution is generally more preferable, where the known calibration position was beyond the region where the retrieval is to be performed. To facilitate this, reordering of the orders of integration and the change of sign in the denominator are required in Eq. (2.18). This makes the solution more stable, provided the aerosol scattering coefficient in the calibration point can be estimated properly. The modified equation is given in Eq. (2.19) as

$$\beta_s(z) = -\beta_a(z) + \frac{\beta(z) \exp\left\{2(LR_a - LR_m) \int_{z_i}^{z} \beta(z) dz\right\}}{\beta_a(z_i) + \beta_s(z_i)} + 2LR_m \int_{z_i}^{z} X(z) \exp\left\{2(LR_a - LR_m) \int_{z_i}^{z} \beta(z) dz\right\}$$

(2.19)

The stable backward numerical solution to lidar equation has been discussed in the literature for more than two decades. Contributions to the solution of the problem have also been made by several researchers (Susano et al. 1988; Kovalev and Moosmüller 1985; Matsumoto and Takeuchi 1994; Bosenberg 1997). Using the backward integration method, a computer code has been developed for deriving the aerosol backscattering coefficient from the BLI data. Figure 2.20 shows the flow chart of the generated code. The developed code initializes from the mean calibration range bin with an indicated value of aerosol lidar ratio and an assumed value of aerosol scattering coefficient at the top as input parameters.

Figure 2.21 shows the derived height profiles of the total, molecular and the aerosol backscattering coefficient from lidar returns using the developed algorithm. However, the assumed value of aerosol backscatter coefficient at the calibration height plays an important role in the retrieval of aerosol profile and imposes an error in the derived aerosol backscatter. Hence, the developed lidar algorithm has been verified for different values of aerosol backscattering coefficient at the calibration point to check the sensitivity of the derived

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aerosol backscatter coefficient profile and also to estimate the error introduced in the derived aerosol backscattering coefficient. As a result, it turns out that the error in the aerosol backscattering coefficient is in the range of 5 to 10% for a variation of assumed aerosol input value by an order of 2. Moreover, the developed algorithm has also been verified for different theoretical values of lidar ratio LR, and also tested for different calibration heights. The derivation of the aerosol backscatter has shown less dependence on the choice of LR, and also on the altitude of calibration height chosen. The range of variation of in the derived aerosol scattering coefficient appears less than 2% for the changes of LR, and calibration height.

Figure 2.21 Derived height profiles of aerosol backscattering coefficient from BLL returns using Klett (1981, 1985) inversion method. The height profiles show total backscatter, molecular and aerosol backscatter coefficients.

2.4.2 Lower atmospheric aerosol observations over Gadanki site

BLL measurements are started at Gadanki site in end of the year 2004. Diurnal runs were carried out on several days in 2005, 2006 and 2007 for evolution of ABL and for the
requirement of special events. However, there are some gaps in the lidar data due to system level problems such as optical alignment, problems related to replacement laser source, and degradation in interference filter transmission etc. At the moment, we have collected more than 700 nights of data spanned between 2005 and 2007. Minimum duration of each night measurement is 60 min. Nevertheless, records of several hours, up to 48 hours, of continuous measurements have also been carried out to monitor special events or to follow the evolution of the Planetary Boundary Layer (PBL). Raw data are integrated over 120 sec, corresponding to 3 lakh laser shots, and recorded with a vertical resolution of 30 m provide the final aerosol backscatter profiles. Statistical variability is obtained from averaging 90 single measurements and deriving the standard deviation corresponding to 180 min time duration. The height profiles of lower tropospheric aerosols, at 532 nm wavelength, have been derived up to an altitude of 7 km using the standard Klett technique from the BLL nighttime data for the period between 2005 and 2007. Analysis of several nights of data collected in the month of January 2005 are shown in Figure 2.22 to indicate the variability in the day to day height profiles of aerosol distribution over the lidar site during the period of January 2005.

Figure 2.22 gives the mean profiles of aerosol backscatter observed on selective days plotted along with the variability in the data. It is noticed from these profiles that the standard deviation is high in the boundary layer than in the free troposphere. The most regular feature of all profiles shown in Figure 2.22 is the presence of a large particle layer in the lowermost troposphere. This layer most likely corresponds to the local mixing layer (ML). During the period of observations, the vertical extent of aerosol mixing, the top height of ML is varied between 1 and 5 km. The increase in the vertical extent of maximum aerosol amount could be the result of the increase in surface temperature during daytime, which pushes the vertical extent of the boundary layer up and gives more vertical space for aerosols to mix and move.
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through advection during nighttime. The increase in the vertical extent of the boundary layer thus results in diluting the surface level aerosol concentration. The height of the nighttime MBL is an important parameter for the characterization of the air exchange with the free troposphere and for an estimation of the aerosol dilution within the boundary layer (Stull 1988; Seibert et al. 2000).

Figure 2.22 Height profiles of mean aerosol backscatter observed on selective days to show the aerosol backscatter variability during the period of observation. The variability in the aerosol backscatter is shown as shaded lines about the mean aerosol profile.

2.4.2.1 Long-term observation

For the assessment of the climatic impact of aerosols (aerosol forcing) the knowledge of both the temporal and vertical distribution of the aerosol is essential (IPCC 2001). Lidar can provide vertically resolved measurements of aerosol backscatter and extinction coefficients on a long-time basis.

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Figure 2.23 Monthly mean profiles from lidar system showing aerosol distribution over Gadanki site during the period between 2005 and 2007. The variability in the aerosol backscatter is shown as shaded lines about the mean aerosol profile. A large variability in aerosol profiles indicates the influence of dynamical and meteorological conditions over Gadanki site during period of study.
At Gadanki site, regular measurements of lower atmospheric aerosols were carried using BLL system. The long term lidar data collected between 2005 and 2007 is reported in this thesis. The BLL data collected after sunset period is used in the present analysis. In the total data, around 25% period has been observed as the clear atmosphere. On the other days, it was either raining or the possibility for rain (cloudy atmosphere) was too high. The days that are attributed as “clear” days have been used for aerosol analysis. In the course of measurements, many different meteorological conditions and presence of special events, such as forest fires and Saharan dust, have been monitored.

The height profiles of aerosols have been obtained using inversion algorithm discussed in the section 2.4.1. The mean profiles of aerosol backscatter were prepared between 2005 and 2007 on monthly basis to show the long term variability in aerosol load over Gadanki site. The constructed mean profiles are shown in Figure 2.23. The monthly mean profiles along with the variability show the typical aerosol height and load distribution in the boundary layer at Gadanki site during the period of observation. During the winter months the aerosol height profiles are limited to around 2 km altitude region, where as one can observe an increase in aerosol height distribution during summer months, pre-monsoon period, beyond 2 km altitude range. This is due to rise in local boundary layer during summer months. This increase could be probably due to increased hygroscopic growth of aerosol particles in the 2 to 4 km altitude region. During monsoon months, there is a significant increase in boundary layer height due to large vertical winds and also increase in ground temperatures. But, this could also be the reason for reduction in the concentration of aerosols near surface and increase at higher altitudes.

Figure 2.24 shows the mean integrated aerosol backscattering coefficient (IABC) (sr\(^{-1}\)) for all the nighttime measurements during the clear sky nights between 2005 and 2007.
Figure 2.24 Mean integrated aerosol backscattering coefficient (IABC) ([sr]^{-1}) at 532 nm for all nighttime lidar measurements carried out over Gadanki site during the clear sky periods between 2005 and 2007.

The data have been integrated along the whole aerosol layer including the layers that are present at higher altitudes due to special conditions. The IABC gives a reference figure for amount of aerosols load present in the atmosphere, particularly in the boundary layer. The values of the IABC ranges from $4 \times 10^{-3} \text{sr}^{-1}$ to $23 \times 10^{-3} \text{sr}^{-1}$. A large amount of aerosol load is observed in month of May (pre-monsoon month), whereas a minimum observed during the month of July (rainy or monsoon month).

2.4.2.2 Long-range transport of aerosol

Lidars have been 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 also capable of detecting the deep pollution layers above the boundary layer (Aermann et al. 2000). The BLL system at Gadanki site has
been observing the elevated aerosol layers since 2005. An observation of elevated layer of aerosol over Gadanki during winter in 2005 is presented here. Figure 2.25a shows the altitude profile of aerosol backscattering coefficient derived from the lidar data. The profile shows an occurrence of thin aerosol layers observed above the ground boundary layer between 2 and 3 km altitude.

![Figure 2.25(a) BLL observation of elevated aerosol layers detected over Gadanki site on 4 January 2005 (b) 10-day back trajectories shown for air mass advection at 2.5 and 3.0 km altitudes indicate the transport from the Far East.](image)

Usually the formation of air masses and their passage over different parts of globe cause collection of particles emitted from sources. The properties of air masses strongly depend on their history, which is quite useful, in conjunction with lidar measurement, to better characterize vertical structure and temporal evolution of aerosol layers. Here we rely on the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) calculation (Draxler and Hess 2004) developed by the NOAA Air Resources Laboratory to implement the three dimensional air mass backward trajectory analyses. Trajectories shown in figure 2.25b represent the movement of air mass that reaches the Gadanki site at 14:00 UTC (19:30 LT) on 4 January 2005. Figure 2.26 shows the height time section of aerosol backscattering

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Micropulse lidar technique coefficient derived from the lidar data on 4 January 2005 between 19:00 and 22:00 LT. The height-time section clearly shows the presence of two distinct layers above the local BL layer. The trajectories at 2.5 (Red line) and 3.0 km (Blue line) height pass over the Bay of Bengal and are characterized by isentropic type. The 10-day HYSPLIT air back trajectories show the air mass pathway from the Far East region that represents long-range transport of aerosols. It has been reported that the air mass advecting from these regions often contains significant contribution of carbonaceous aerosol (remnants of biomass burnt).

Figure 2.26 Height time section of aerosol backscattering coefficient observed over Gadanki site on 4 January 2005 between 19:00 and 22:00 LT presents the occurrence of elevated aerosol layers above the local boundary layer. Such elevated aerosol plumes were also observed over the northern India and also over southern India, particularly during winter season due to dry convective lifting of pollutants at distant sources and subsequent horizontal, long-range transport of upper air (Niranjan et al 2007; Ramana et al 2004). The aerosol layers found above the boundary layer could be
transported over several thousands of kilometers without significant removal and can contribute appreciably to the column aerosol optical depth, at times more than the boundary layer (Franke et al. 2003).

![Graph](image)

Figure 2.27(a) B.L. observations of elevated aerosol layer detected over Gadanki site on 24 March 2007 (b) 8-day back trajectory at 3.5 km height showing the air mass advection from the Arabian region (c) OMI satellite data showing dust aerosol (Green color) spread over India on 24 March 2007

Transport of Saharan dust from the Arabian Peninsula or dust generated on the Indian Subcontinent is often mixed with large concentrations of locally generated pollution aerosols.
Micropulse lidar technique (Middleton 1986). The local pollution alone can enhance the solar heating of the lower atmosphere by ~50% (Ramanathan et al. 2007). Passive satellite sensors, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Ozone Monitoring Instrument (OMI), etc., can provide measurements of aerosol column optical properties on a global scale. However, no information on the vertical distribution of aerosols can be obtained from these measurements. Backscatter lidars can provide this information with good spatial and temporal resolution. Dust aerosol can also undergo, over the course of transport, changes in mineralogical compositions (Jeong 2008) and hygroscopic and heterogeneous reactions (Seinfeld et al. 2004). These processes can alter the dust physical and optical properties and hence change the dust radiative properties. BLL detection of dust transport over Gadanki site is shown in Figure 2.27a. The eight-day back trajectories (see Figure 2.27b) were computed using the NOAA HYSPLIT model (Draxler and Hess 2004), and initialized at altitudes of 0.5 km (red), 1.25 km (blue) and 3.5 km (green) above ground level (AGL) at 17:00 UTC (22:30 LT) for 24 March 2007 and 12:00 UTC for 17 March 2007. Figure 2.27(c) shows the Ozone Monitoring Instrument (OMI) satellite observations of dust aerosol over India on 24 March 2007.

The height time section of aerosol backscatter coefficient measured at 532 nm using BLL on 24 March 2007 between 1900 and 0600 LT is shown in Figure 2.27d. Since the dust aerosols have a large volume depolarization ratio (VDR) value due to nonsphericity, while they also have a large color ratio due to their relatively large particle size (Liu et al. 2008). On the other hand, the other types of aerosols have small VDR values. Because dust particles are relatively large when compared to other aerosol species and because the spectral dependence of their extinction coefficients is relatively small and backscattering coefficients are significant. The aerosol backscattering coefficient as large as \(1 \times 10^{-5} \text{ m}^{-1} \text{sr}^{-1}\) (see Figure
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2.27a) are detected at heights above the local boundary layer, which can contribute considerably to the radiation budget of the Earth's atmosphere.

Figure 2.27(d) Height-Time section presents the aerosol backscattering coefficient derived from the lidar data. The height-time section clearly shows the presence of elevated dust layer at altitudes between 1 and 4 km above Gadanki site during the night of 24 March 2007.

2.5 Profiling of atmospheric clouds

Research in the last few years has shown that clouds are a major variable in Earth's climate system. The climate is very sensitive to small changes in cloud properties. This sensitivity is very important in trying to figure out what man-made changes, such as increasing carbon dioxide, will do to Earth's climate. Depending how these changes affect clouds, their influence on climate could be either enhanced or damped out. We all know that the energy to the Earth comes from the sun. An equal amount of energy must go back into space, otherwise Earth's temperature will change. One can think of clouds action as thermostat that sets Earth's temperature. If, suppose, there is an increase in the average thickness of low clouds a little (i.e., make them more reflective), the Earth's temperature will decrease a little. Thus clouds
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can act to either warm or cool the Earth. High clouds are often thin and not very reflective. They let lots of the sun's warmth in. They also sit high in the sky, where the air temperature is quite cold, so they do not emit a lot of heat. On balance, high clouds tend to warm the Earth (Liu, 2002). Low clouds are often quite thick and reflect lots of sunlight back to space. They are also lower in the atmosphere where the air is warmer so they emit more heat. On balance, low clouds tend to cool the Earth (Hartmann et al. 1992). Hence, it is essential to build regional cloud climatology to properly access the Earth's radiation budget. In order to do so, proper instruments are needed on different platforms.

One of the potential applications of lidar as a ground instrument is in the studies of characterization of clouds. Usually strong backscattering arises from clouds due to relatively large scattering cross-sections of cloud particles and huge number density of scatterers. A typical observation of low level cloud returns from BLL during daytime is shown in Figure 2.28a. Two cloud layers, one at 1 km height and other at about 2 km, are detected as sharp enhancements in the lidar signal returns. During nighttime, the lidar visibility extends deep into the atmosphere due to presence of dark background. Figure 2.28b shows the BLL detection of high altitude cloud returns, at 12 and 16 km altitudes, during the nighttime observation.

Figure 2.28 BLL observations of low and high-level clouds passage over Gadanki during (a) day and (b) nighttimes.
Figure 2.29 Height time section of range corrected signal showing BLI detection of low-level cloud during a light rain period observed on 4 November 2004. The lidar beam was directed at an elevation angle of 18° from the zenith and operated continuously for 14 hours.

The formation of clouds comes from rising air parcels. Air rises because of orographic lift, convective lift, and convergent lift. Orographic lifts are formed when air is forced to move upward as it encounters a cooler, denser body of air or when it meets high landforms such as a mountain. Convective lift occurs when air encounters a warm surface, heats up and becomes less dense compared to the surrounding air. This usually occurs during daytime when the sun drives the convective circulation on the ground. As air parcels rise, they cool down and condense. Rain clouds occur when the clouds start to produce moisture. Examples of these types of clouds are the nimbostratus and the cumulonimbus. Nimbostratus clouds are layered, uniform, rain clouds. These clouds are generally dark, and associated with large areas of continuous rain. In the case of cumulonimbus clouds, they are formed by the upward
movement of warm air currents. These types of clouds are accompanied by compensating
downdrafts of cold air and are common in warm and humid weather (Wallace and Hobbes
1977). For raindrops to occur there must be particles in the air, such as dust or aerosols, at
temperatures above freezing. When particles are cooled below the freezing temperature,
water condenses on them. As this happens, the particles become heavy and start to fall. Rain
clouds can also be formed locally when air rising over a moist area causes the formation of
cumulus clouds. As the moisture condenses, the clouds begin to grow darker. The movement
of these rain clouds can be tracked using radar (Crane 1996). Figure 2.29 shows the BLL
observation of streaks formed from falling raindrops. By measuring the vertical displacement
of the streak and the time for the streak to cover the vertical displacement, the average speed
of the streaks can be estimated. The value of the average speed can then be used to
approximate the raindrop size (Legrosas et al 2004). Lidar is a potential instrument for rain
rate measurements (Shipley et al 1974).

2.5.2 BLL observation of High level cloud

It is well established that lidar has the capability to delineate the position and spatial structure
of clouds in the atmosphere. Because of its high spatial resolution, it can be used to locate
cloud base and its top with a good precision that is not possible with any other remote sensing
technique. This feature of the lidar has attracted more researchers recently in investigations of
clouds at various height regions as clouds play a critical role in the radiation budget of the
Earth atmosphere. The appearance of deep cumulus clouds during convective periods is a
common phenomenon at tropical latitudes. Usually the upper portion of convective cumulous
clouds constitutes ice portion that extends in the fibrous anvil, which at a later stage takes the
form of cirrus (Bhavani Kumar et al 2006b). The formation of high altitude clouds such as
circular in the tropics plays a particularly important role in the Earth-atmosphere radiation budget.

Tropical cirrus develops in a variety of forms, ranging from optically thick anvil cirrus that is closely associated with deep convection to optically thin cirrus layers frequently observed near the tropopause. A typical lidar observation of cirrus system in the night of 11 September 2006 is shown in Figure 2.30. Figure 2.30 represents the height-time section of high altitude cloud layer presented in terms of backscatter ratio. The observation was made on the night of 11 September 2006. The lidar derived backscatter ratio (BSR) is defined as the ratio of attenuated backscatter to the molecular backscatter (see Eq 2.14 for reference). It is an indicator of the strength of scattering in a cloud layer or an aerosol layer compared to the
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molecular scattering at that altitude. Note that the occurrence of strong scattering at the base of the clouds is due to presence of larger cloud particles. Smeared structures in the cloud are due to background wind influence on clouds.

Date: 17-18 January 2007
Time: 18:00 - 06:00 LT

Figure 2.31 Height time section of range corrected signal showing the observation of K-H structures in the high altitude cloud layer that moved over lidar site on the night of 17 January 2007. Generally, winter clouds are found with such structures above Gadanki site.

A peculiar high altitude cloud layer shown in Figure 2.31 was detected above Gadanki site on the night of 17 January 2007 with structures similar to the Kelvin-Helmholtz (K-H) instabilities. These structures appear as intertwined or spiral pattern as shown. K-H instabilities are result of strong wind shear and turbulence in the tropical cirrus (Bhuvan Kumar et al 2001). Such types of structures are frequently observed in the high altitude clouds during the winter period over Gadanki site. K-H structures resemble as well-organized waves that appear to be breaking like ocean waves. Atmospheric gravity waves cloud also

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Micropulse lidar technique responsible for the formation of such type structures in clouds at high altitudes (Parameswaran et al. 2003).

2.5.3 Validation of BLL detected cloud heights

2.5.3.1 BLL and Indo-Japanese UTLS Lidar comparison

Validation of lidar derived parameter height profiles require comparison with another profiler such as radar, radiosonde or any another lidar system. NARI operates several lidar systems. One such system is Indo-Japanese upper troposphere and Lower stratosphere (UTLS) polarization lidar (Bharani Kumar et al. 2001; 2006), which is used for profiling aerosol and clouds in the UTLS region. The UTLS polarization lidar system, discussed in detail in Chapter 3, can profile the atmosphere above 10 km altitude only due to limitation in the system geometrical construction. The lidar system operates at the same wavelength of BLL system i.e. at 532 nm. However, the UTLS lidar vertical resolution is 300 m, which is 10 times more compared to the BLL system.

![Graph](image.png)

Figure 2.32a. Graph presents the vertical profiles of aerosol backscatter ratio derived using the UTLS polarization lidar and BLL data for the period of coincident atmospheric observation. Both the systems were operated simultaneously on 3 January 2005 between 19:35 and 19:55 LT for the purpose of intercomparison. An occurrence of high altitude cloud was detected by both the systems at the altitudes between 11 and 14 km.
Figure 2.32b. Graph shows the detailed intercomparison between the UTLS lidar and BLL in presence of high altitude cloud. Note that the UTLS lidar and BLL have detected cloud peak BSR as 4.5 and 4 respectively.

The simultaneous measurements between UTLS lidar and BLL were carried out on 3 January 2005 during the occurrence of high altitude cloud condition. All the measurements were carried out during late evening hours between 19:35 and 19:55 LT. Though UTLS lidar has the limitation in providing aerosol profiles below 10 km, the altitude region covering 10 to 15 km is considered for intercomparison. The high altitude cirrus clouds were present during the intercomparison period, which were regarded as "aerosol" for the purpose of this study. But high altitude cirrus is usually much more inhomogeneous than the aerosol layers, so one has to be careful when comparing cirrus backscatter from different lidar systems having different field of views (FOV). The full range of intercomparison between the lidars is shown in Figure 2.33a. Figure 2.33b illustrates the detailed comparison between the lidars in the height range of occurrence of cirrus cloud. The intercomparison of cloud BSR obtained from the BLL and UTLS lidar have shown good agreement for both in height as well in cloud backscatter during the period of comparison. Slight deviations in BSR between the two systems are due
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to difference in the system’s FOV and built-in technology. The UTLS lidar system operates at 20 Hz repetition rate with 600 mJ energy per pulse, where as BLL functions with 2500 Hz pulse repetition rate at 10 μJ energy per pulse.

2.5.3.2 BLL and MODIS cloud top comparison

The Indian Institute of Technology (IIT), Kharagpur and NARI, Gadanki were jointly carried out a study on cloud top height comparison. This study was conducted over Gadanki site in 2005 using the BLL and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite pass data during the months of January and April.

![Comparison of cloud top height pressures using two independent techniques. The comparison was carried out between January and April 2005 over lidar site Gadanki jointly by IITK and NARI.](image)

The BLL detected cloud top height was converted to standard pressure level for comparison with that of the MODIS satellite derived cloud top pressure. The Moderate
Resolution Imaging Spectroradiometer (MODIS) satellite passes over Gadanki site at around 16:00 in the evening and at 04:00 LT at morning respectively. From this study it was found that the comparison of cloud top pressures between BLL and MODIS matched well (R=0.9975). A linear regression analysis of comparison shows that the slope of the linear fit is very close to unity, however, on overall there is a only a slight underestimation of cloud top pressure by MODIS. Figure 2.33 shows the comparison between the cloud top pressures from BLL and MODIS satellite.

2.5.3.3 BLL and CALIPSO-Satellite Lidar comparison

The tropics are characterized by warm sea surface temperatures and frequent convection. This convection occurs on a wide range of scales, from hundreds of meters in the case of fair weather cumulus to thousands of kilometers in the case of mesoscale convective systems. Deep convection often reaches the tropopause, which is found at 16 km to 18 km in the tropics. Clouds in the tropics are ubiquitous in nature and their vertical and temporal distributions are very complex. Cirrus clouds occupy a special place among the Earth's cloud formations. Their impact can be manifested through atmospheric warming or cooling (Cox 1971). Recurrence of cirrus clouds and their morphological and microphysical structures undergo significant variations as functions of latitude, season, and orography. Associated with convection are large-scale cirrus layers that are present much of the time. Cirrus clouds have been recognized as a fundamental factor influencing the climate. It is impact on the Earth radiation budget and consequently on the climate has been addressed so far (Liou 1986). Cirrus clouds can absorb long-wave outgoing radiation from Earth's surface while reflecting short-wave incoming solar radiation (McFarquhar et al 2000). The radiative forcing of cirrus clouds is determined by macro and microphysical properties. Cirrus radiative forcing is not well understood because the incomplete knowledge of such
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properties. Lidar measurements are useful in deriving geometrical and optical properties of cirrus clouds, which are essential for understanding the cloud-radiation effects. BLL at Gadanki site has been observing the high altitude clouds passage since 2005. However, the comparison of high altitude clouds passage over Gadanki site with Cloud-Aerosol Lidar and Infrared Pathfinder Satellite (CALIPSO) satellite was for the first time.

![Image of world map with trajectory](image)

Figure 2.34a. The trajectory shows the pass of Satellite lidar (CALIPSO) over India on 10 June 2007 during the time between 20:26 and 20:37 UTC.

A comparison of cloud heights was made during the passage of CALIPSO over India in monsoon period of 2007. The CALIPSO satellite lidar derived cloud attenuated backscatter is compared with that of lidar-derived range corrected data to compare the cloud top and base heights, in particular. However, both the systems use the same laser wavelength at 532 nm, which is visible part of light spectrum. The pass details of CALIPSO satellite lidar (during nighttime condition) over India on 10 June 2007, typical monsoon period, were shown in Figure 2.34a. The pink line shows the path trajectory. The timings of pass were between 20:26 and 20:37 UTC, which is 01:56 to 02:07 in LT, the early hours of 11 June 2007.

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Figure 2.34b. Height-Time section of attenuated backscatter obtained from CALIPSO-the Satellite lidar during its pass over India on 10 June 2007 during the time between 20:26 and 20:37 UTC.

During the pass time, the satellite lidar detected a band of thick layers of cirrus at heights between 15 and 19 km right from 12° to 25°N latitudes, which is shown in Figure 2.34b. The occurrence of these clouds is due to the onset of tropical easterly jet (TEJ) during the period over Asian tropics. The TEJ is responsible for the long-range transport of convectively generated cirrus in the Asian tropics during the NE monsoon period (Sahityamourthy et al 2004). Moreover, the horizontal transport carried by the winds appears to be responsible for widespread coverage of cirrus in the Asian tropics during the monsoon period. However, during the period of observation the satellite lidar images do not reveal the presence of mixing layer due to extinction of laser from satellite lidar by the presence of thick clouds. However, the satellite lidars can provide accurate information on cloud top heights.
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The BLL system located at Gadanki site (13.5°N) has detected the high altitude cirrus layers at heights between 15 and 19 km on early hours of 11 June 2007 between 00 and 05 local standard time. Using this BLL data, the height profiles of attenuated backscatter coefficient (m$^{-1}$ sr$^{-1}$) were calculated by applying Klett (1985) inversion algorithm. The time series of derived attenuated backscatter coefficient is presented in Figure 2.34c (Bhuvan Kumar et al. 2008b).

![Figure 2.34c](image)

Figure 2.34c. Time series of attenuated backscatter (m$^{-1}$ sr$^{-1}$) show the occurrence of high altitude clouds layers above Gadanki site on the night of 11 June 2007 between 00 and 05 LT. The local mixing layer tops around 4 km due to strong vertical winds in the monsoon period.

It is observed that the BLL derived cloud attenuated backscatter profiles are compared with that of the satellite lidar. This information is much useful for satellite lidars calibration and much useful in filling the gap regions of understanding of atmosphere. The ground lidar

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system detects the high altitude cirrus layers above the local mixing layer. The local mixing layer tops around 4 km during the monsoon period due to prevailing large vertical winds. The ground lidar data is complimentary to the satellite lidar, from which one can derive the cloud base and local mixing layer information accurately.

2.5.4 Cloud base detection methodology

Clouds induce a crucial modulation of terrestrial shortwave reflectivity and long-wave absorptivity and emissivity. Therefore, the knowledge of distribution of cloud cover is essential in understanding the radiative budget of the atmosphere. Significant progress has been made in understanding of global cloud systems and their effect on the radiation fluxes at the top of the atmosphere with the powerful technique of scanning radiometry onboard satellites. These passive radiometry techniques have been used in the High resolution Infrared Radiation Sounder (HIRS), Advanced Very High Resolution Radiometer (AVHRR), and the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra and Aqua satellites. Such techniques have given extensive views of cloud systems, and much effort has been expended on interpreting the satellite images. However, some of the main problems involved with clouds and their radiative interactions remain. These include cloud brokenness, cloud structure, cloud-top and base heights, and cloud extinction and optical depth. The retrieval of a value for the cloud base height was not as straightforward as it was first anticipated. For surface radiation budget studies, it is the radiatively important cloud base that is required.

The technique of lidar has provided a powerful new tool for investigating clouds, particularly when used with passive radiometers (Platt et al 1987). Lidars at ground can detect base of the cloud layers with very good accuracy. Gradient method of measuring cloud-base and cloud-top altitudes has been used successfully in the analysis (Pal et al 1992).
The gradient methods works well where there is an unambiguous and appreciable increase in signal above cloud base. BLL system is capable of detecting clouds at different height levels in the atmosphere on continuous basis (Bhavani Kumar 2006b). The cloud detection algorithm employs application of gradient technique to the lidar data. In the cloud detection algorithm, an averaged attenuated backscatter profile is computed for a selected time segment. Generally, the lidar derived attenuated backscatter profiles are compared with the Rayleigh profiles as shown in Figure 2.35a to identify the cloud base. The spatial gradient is applied to see the vertical variability in the attenuated backscatter. The lidar backscatter echo from a cloud is detected as a strong positive signal gradient as shown in Figure 2.35b.

Figure 2.35(a) BLL derived attenuated backscatter superimposed on Rayleigh signal (b) Cloud layer boundary detection using gradient method. The derivative changes sign from negative to positive, signifying the cloud base altitude.

Figures 2.36a and b present detection of a high altitude cloud layer and the estimates of cloud base for the detected cloud layer using the gradient method (Pal et al 1992). Figure 2.36a show the time series of range corrected signal height profiles. The lidar data shows detection of a cloud layer at altitudes between 11 and 14 km in the early hours of 15 February 2006. To obtain the representative cloud base estimates on continuous basis, all scans in the observation are inspected for cloud echoes and the spatial gradient method is applied to the
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cloud contained signals. The time series of computed positive gradient is presented in Figure 2.36b.

Figure 2.36 Top panel shows a) Height-Time lidar range corrected data showing the occurrence of high altitude cirrus cloud at altitudes between 11 and 14 km over Gadanki site on the night of 14 February 2006 and bottom panel b) gives the cloud base estimates from lidar backscatter data using gradient method Pai et al (1992)
2.5.5 Study on generation and transport of tropical cirrus during monsoon period

The dynamical and optical properties of tropical cirrus clouds are essential to the understanding of the radiation balance and climate related studies. Cirrus clouds play a substantial role in regulating the exchange of long wave radiation in the vicinity of the tropical tropopause and thus are radiatively important (Hartmann et al. 2001). Cirrus clouds near the tropical tropopause occur frequently and have been detected by satellite measurements (King et al. 1992), ground-based lidar (Bhuvani Kumar et al. 2001), and Lidar-in-Space (Winker and Trepte 1998; Omar and Gardner 2001). Cirrus clouds are normally located in the Upper Troposphere (UT) and rarely at the Lower Stratosphere (LS) region. In fact, cirrus clouds are one of the most uncertain components in the atmospheric research because of their high locations, optically thin nature, and the nonsphericity of ice crystals.

The fundamental mechanism of generation of these clouds, especially in the tropics is basically due to outflow of the optically thick cumulonimbus tops and the transport of their remnants by the background wind (Jensen et al. 1996; Bhuvani Kumar et al. 2001). The mechanism of formation of tropical cirrus is illustrated using a picture shown in Figure 2.37.

Figure 2.37 An illustration showing the mechanism of formation of tropical cirrus from deep convective activity.
The upper troposphere during the tropical monsoon period is characterized by jet streams, a region usually associated with strong vertical and lateral wind shear. The Jet streams are 1000km long and 100km wide. Particularly the Tropical Easterly Jet (TEJ) is a unique UT easterly wind in the Asian monsoon region and is not found prominently anywhere else in the tropics (Sathiyamurthy et al 2004). The easterly regime starts around 400hPa and its strength increases upward up to 100hPa with horizontal winds reach 40 m/s or more. This region is the zone of frequent appearance of cirrus in the tropics. The TEJ over Gadanki has been found to be active during the period between June and August, the cycle of southwest (SW) monsoon. The statistical studies showed that the zonal winds are westerly up to 10 km and change to easterly at heights above 10km altitude and reach a maximum of 45 m/s in the height region between 14 and 16 km.

The BLI system is equipped with the capability to profile a variety of atmospheric clouds (Bhavani Kumar et al 2006b) and has been monitoring the high altitude clouds since 2005 (Bhavani Kumar et al 2008c). The BLI was made operational on continuous basis, only during nighttimes, in the month of July 2006 for a period of 27 days (around 252 hours) to find the role of TEJ on the frequent occurrence and appearance of tropical cirrus. Figure 2.38 shows the height-time representation of cloud observational data collected during the month of July 2006. The lidar data is presented in Figure 2.38 in segments. Each segments is about 8 to 12 hours of observational period and the remaining hours of the day is shown as blank. The role of TEJ on the frequent occurrence of high altitude clouds over the tropics, using a point observation, was carried out at the tropical station, Gadanki (13.5°N, 79.2°E) using simultaneous observations of MST radar, BLI and Radiosonde data collected during the period of SW monsoon (Kulakarni and Bhavani Kumar et al 2007).
Month: JULY 2006

Figure 2.38 Time-height section of range corrected data shows B.I.L. observations in the month of July 2006 presented in form of segments. Each segment represents 8 to 12 hours of each observational day. Black periods indicate no data periods.

The Vaisala Radiosonde RS80 provides in situ observations of temperature and humidity along with the GPS derived winds that are useful for characterizing the humid layers in the presence of cirrus. These near real-time data sets provide the confidence in locating the zone of TEJ, the region of tropical cirrus and presence of humid layers, and hence enable us to understand the mesoscale structures of TEJ and the Tropical cirrus in the
UT. Further to this, the investigation has been extended to synoptic level analysis using the NOAA outgoing long wave radiation (OLR) data and MODIS data to look into the strong TEJ pruned regions and the associated cirrus occurrence in the tropics during the monsoon season.

Figure 2.39a Measurement details on investigation made during a case study observed on 30 June 2006 (a) MST radar derived zonal winds and their variability (b) BL lidar detection of tropical cirrus (c) Sonde observed GPS winds, Temperature and RH (%).

Figure 2.39a presents the a case study made using the near real-time data sets employing the Indian MST radar, BL lidar, and GPS sonde to show that TEJ region is the source region of tropical cirrus. This case study is presented in Figures 2.39a and b. Panel (a) of Figure 2.39 indicates the MST radar derived zonal winds. BL lidar observation of tropical cirrus on the night of 30 June 2006 and GPS radiosonde derived zonal winds, atmospheric temperature and relative humidity profiles at 12 GMT. Figure 2.39b shows MODIS satellite derived zonal winds and NOAA OLR data over the Asian tropical region. These panels clearly indicate that the TEJ region is the region of enhanced humid layers, which is the source region for the occurrence of tropical cirrus. The possible generation mechanism for the occurrence of tropical cirrus in the TEJ region is explained using the concept of horizontal...
transport suggested by Holton (2001). The strong horizontal winds cause advection and play an important role in the formation of tropical cirrus in the humidity-enhanced zones.

Figure 2.39b MODIS observed zonal winds at 150 mbar pressure level and NOAA OLR data showing strong convective regions. The data is obtained on 30 June 2006.

2.6 Observations of BLL systems at parts of the country

Due to the importance of studies related to boundary layer, aerosol and clouds, a network of BLL was initiated at NARL, Gadanki in year 2006. As a part of the network, several BLL systems were developed at NARL site and were installed at many different locations across the country. These locations include ARIES- Nainital, IIT(M)-Chennai, NRSC-Hyderabad, ...
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and TIFR-Hyderabad. Apart from these, a BLL system was developed for ISRO-Balloon lidar programme based on ISRO's requirement.

2.6.1 **BLL observations over a high altitude station Nainital**

A BLL system was installed in year 2006 at Aryabhatta Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital (29° 22' N, 79°27' E, elevation - 1960 m MSL), a high altitude location in central Himalayas for joint studies on aerosol backscatter profiles and clouds between NARI and ARIES (See Appendix-A). Nainital, owing to its large elevation, is a hill station that considered to be free tropospheric site. As the site is located geographically in free troposphere and is reasonably sparse from the point of view of major pollution, the investigation from such a remote, sparsely inhabited regions have the importance of providing a sort of background level against which the aerosol loading impact in the atmosphere can be assessed. Observations of range corrected photon count profiles have shown the frequent occurrence of cirrus clouds at an altitude ranging from 8 to 10 km AGL above Nainital. Among the total observations in ~60% of the cases the occurrence of cirrus clouds were detected. Meanwhile cloud climatology studies based on SAGE II observations have indicated the frequency of cirrus occurrence (AOI =0.03), in the tropical and the subtropical regions is up to 70% indicating the radiative effects of cirrus clouds are very large in these regions (Whiteman et al 2004).

Lidar photon count data in the presence of cirrus clouds indicated that the cloud base and top heights are found to be 8.2 km and 9.1 km, respectively. The corresponding temperatures at these heights are found to be 238 K and 242 K, respectively based on radiosonde measurement on 6 March 2007 (Heyde, Pant and Bhavani Kumar 2009). The region where these cirrus clouds are observed is found to be highly turbulent (sometimes wind speed up to 68 m/s), indicating that the region of divergence followed by a
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convergence, showing the favourable conditions for cirrus formation (Parameswaran et al. 2003).

![Image](image_url)

Figure 2.40 Typical altitude-time contour plots of range corrected photon count on 17 May 2006 showing the presence of cirrus clouds.

Over the study region the vertical extent of cirrus was found minimum during winter, indicating that the cirrus clouds observed during the dry period are generally thin in comparison to those observed during the southwest monsoon period (Sunit Kumar et al. 2003). Typical altitude-time contour plot of range corrected photon count on 17 May 2006 is illustrated in Figure 2.40 showing the presence of cirrus cloud over the hill station detected using the BLI system: It is quite discernible from the figure that the cirrus is started to be appeared around 2020 (IST) having the base height of 8 km AGL, which gradually becomes think and denser and reaches up to a summit of 9.7 km AGL. The cloud continuously remained strong throughout the observation period. Similarly, the observations on different nights reveal the presence of the cirrus clouds with different structures and patterns with
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varying vertical extent. Sunil Kumar et al. (2003) have reported the preferred range for these
clouds as 12 to 16 km amsl with a vertical extent ranging from 0.4 to 4 km, on the basis of
extended lidar observations at Gadanki (13.5°N, 79.2°E). They also calculated that infrared
radiative forcing by this tropical cirrus is significantly larger than that due to subtropical
cirrus. The observations on aerosol and clouds using BLL data were investigated over the
high altitude station during the year 2006 and 2007 (Hegde, Pan1 and Bhavani Kumar 2009).

2.6.2 BLL observations over marine site - Chennai

![Figure 2.41: Height profiles of aerosol observed over IIT-M, Chennai using the BLL system during midnight hours on 15 June 2006](image)

A BLL system was set up at the Department of Physics, Indian Institute of Technology-
Madras (IIT-M) by NARI under a joint scientific collaborative programme between IITM
and NARI, Gadanki during the year 2006 (See Appendix-B). The lidar system was oriented
at a slant angle to profile the pollution layers in and around IIT-M, Chennai. The lidar system
started regular atmospheric observations from first week of June 2006. During the
observations the lidar system has collected backscatter returns from the lower atmospheric
aerosol and the high altitude clouds such as cirrus passed over the site. These are the first
observations taken from a marine station located south-eastern part of India. During the
period of observations over IIT-M, Chennai, the peak of the local mixing layer was observed

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to reach altitude of 700 m with nocturnal boundary layer (NBL) reaching about 200 m during nighttimes. A large amount aerosol was seen above boundary layer during the period of observation in the clear nighttime conditions. The high altitude clouds were also observed in the height ranging between 10 and 12 km. An event-showing enhancement in aerosol concentration in the free troposphere during pollution outbreak was observed on night of 15 June 2006. The observation is shown in Figure 2.41 (Bhuvan Kumar 2008c).

2.6.3 BLL observations over midland urban site- Hyderabad

A BLL system was installed at National Remote Sensing Centre (previously known as National Remote Sensing Agency-NRSA), Hyderabad in 2007 to monitor the transport of pollution aerosols in the lower troposphere over the Hyderabad region (See Appendix C).

![Aerosol extinction profile](image)

Figure 2.42. Vertical profile of aerosol extinction observed above the lidar site at NRSC, Hyderabad on 22 August 2007

The lidar system was operational since September 2007 at the atmospheric science section of NRSC. A height profile of aerosol extinction obtained on August 2007 between 20:00 and 21:00 LT time period is shown in Figure 2.42. The profile shows the distribution of aerosol
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up to 3 km altitude above ground level (AGL). The shaded horizontal lines show the variability in the observed aerosol extinction profile.

Figure 2.43a ISRO balloon lidar experiment from TIFR, Hyderabad conducted on 16 April 2009

During month April-2009, the Indian Space Research Organization (ISRO) has conducted a high altitude balloon experiment with BII as the payload (See Figure 2.43a) (the technical configuration of lidar onboard is similar to BII system, except that the system is flight qualified – see Appendix D) to make a study on troposphere aerosols and clouds. This experiment was carried out for the first time in the country to understand the lidar data and to prepare the inversion algorithms for future ISRO's space borne lidar needs. The flight was carried out from Balloon Test Facility-Tata Institute of Fundamental research (TIFR), Hyderabad on 16 April 2009 at midnight hours. During this period, a BII system was installed at TIFR, Hyderabad to make the ground support for the flight operations planned.
Figure 2.43b Time-height section of lidar range corrected data obtained at Balloon Facility, Hyderabad during ISRO's balloon lidar flight programme conducted at midnight hours of 16 April 2009.

During the flight period, the BLI system at ground was operated continuously from 21:00 LT on 16 April to 05:30 LT on 17 April 2009, covering the whole night period. During the period of observation, the ground BLI has detected a high altitude cloud layer at heights between 11 and 15 km much above the local mixing layer (See Figure 2.43b). On that night, an elevated local mixed layer was detected at about 5 km height level. The simultaneous balloon radiosonde profiles support the occurrence of elevated BL layer, such as the existence of temperature, inversion and sharp humidity gradient at 5 km level (see Figure 2.43c). An enhancement in RH at heights above 11 km in radiosonde data indicates the presence of tropical cirrus layer at these heights. The detected cloud layer was found to be having similar vertical structure that appears commonly over Gadanki site and was found to be influenced by K-JI structures due to presence of local turbulence (Parameswaran et al 2003).
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Figure 2.43c Altitude profiles of atmospheric temperature and relative humidity derived from Radiosonde that launched along with the ISRO balloon lidar flight at midnights hours on 16 April, 2009 at TIFR, Hyderabad.

2.7 Filling of BLL, patent and transfer of its technology to industry

BLL is an innovative concept and novel technique based lidar system, the first of its kind of development in India, has been successfully developed and made operational at NARI, and other sites in the country. The lidar was developed at one third of the cost of commercially available micro pulse lidar systems with comparable nighttime performance. Basically, micro pulse lidars (MPL) are constructed for the purpose of unattended measurements of cloud and aerosol. The original MPL (Srinivas 1993) and BLL (Bhuvan Kumar 2006a), both the systems, are meant for the atmospheric profiling. However, ISRO-NARL developed BLL system is quite different in technical configuration than compared to the NASA-GSFC developed MPL system (see Figure 2.44) and has over come several problems of NASA developed MPL system (Bhuvan Kumar 2008c). Based on this, the invention of BLL was filed for patent rights under ISRO. The filed patent has a number corresponds to 597/CH/2009 and the present status of patent is pending for examination.
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Figure 2.44 Schematic block diagram of (a) NASA-GSFC developed MPL system (b) ISRO-NARL developed MPL-BLI system

The BLI has tremendous applications in the field of atmospheric sciences because of its excellent capability in profiling the atmospheric aerosol and clouds. Hence, a BLI network across the country meeting requirement of Indian Space Research Organisation (ISRO)/Indian Meteorological Department (IMD) /Department of Science and Technology (DST) / Airports Authority of India (AAI) and other government agencies has been proposed for implementation. Based on the concurrence from the Atmospheric Science Programme (ASP) office-ISRO HQ, Chairman, ISRO has approved the transfer of BLI technology to the Indian industry. Under this programme M/s General Optics (Asia) Limited (GOAL) located at Pondicherry has been identified for development of Industrial grade BLI systems for field use in the country.

The industrial grade BLI systems were named as “LAMP” - “Lidar for Atmospheric Measurement and Probing”. The pictorial view of prototype LAMP system operational at NARL site is shown in Figure 2.45 along with its major specifications. The LAMP system has been in working at NARL site since February 2009 and has completed successfully 1000 hours of operation in six months period between February and August 2009. At present, the LAMP system was operational only during nighttimes due to large Rx FOV setting. During

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the period of observation between February and August 2009, the LAMP system has detected several cloud layers passage over the lidar site.

**Industrial grade BLL system - LAMP**

**Specifications of LAMP**

- **Transmitter**
  - Laser: Diode Pumped Nd YAG laser
  - Wavelength: 532 nm
  - Output Pulse Energy: 10 micro-Joule
  - Pulse Repetition Frequency: 2500 Hz
  - Pulse Duration: 10 ns
  - Polarization: >100:1
- **Receiver**
  - Transmitter Field of View: 200 μrd
  - Telescope: 15 cm diameter
- **Detector**
  - Type: Photon counting - high gain
  - PMT
- **Data acquisition**
  - PC Based MOS card

**Figure 2.45** Picture of industrial grade BLL system (LAMP) and its specifications

**Figures 2.46a and b** show the statistics of observed cloud occurrence and appearance. **Figure 2.46(a)** shows two dominant peaks in the occurrence statistics.

**Figure 2.46** Statistics showing (a) clouds occurrence and (b) cloud appearance derived from LAMP data collected between February and August 2009 over Gadanki site
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The first peak corresponds to the boundary layer clouds and later peak is due to the frequent occurrence of tropical cirrus clouds. The higher occurrence statistics shown in Figure 2.46(a) is in favor of boundary layer clouds probably due to orographic conditions, however, the higher occurrence statistics for high altitude clouds such as tropical cirrus could be due to transport of humid layers from the convective dominant zones (Parameswaran et al. 2003; Sunil Kumar et al. 2003; Kulakarni et al. 2007).
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