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The lidar system used for the present work is located at Gurushikhar, Mt. Abu (24.5°N, 72.7°E), near the PRL's infrared (IR) observatory, in the Aravalli range of the mountains. It is a range of mountains in the western part of India, running ~ 450 km from northeast to southwest across Rajasthan state. The highest peak, rising to ~ 5653 feet (~ 1.7 km) from mean sea level, is Gurushikhar situated near the southwestern extremity of the range. Location of Mt. Abu is shown on a topographic map of India in Figure 2.1.

2.1 Techniques of the Middle Atmospheric Probing

There are broadly two types of atmospheric probing techniques (a) in-situ (balloon, rocket etc.), and (b) remote sensing (radar, lidar, optical and radio telescopes, etc.)
2.1.1 In-situ Techniques

2.1.1.1 Balloon

Balloon-borne measurements are very effective for the study of the vertical distribution of trace gases, aerosols and temperature profiles in the middle atmosphere with good vertical resolution. Balloons use thermistor/capacitive transducer for the measurement of atmospheric temperature. Several balloon-borne studies of trace gases, ion conductivities, dynamics in the lower and middle atmosphere in the Indian tropical and sub-tropical regions were carried out [e.g., Thomas and Bhattacharya, 1980; Nagpal, 1988; Lal et al., 1989, 1994, Chakrabarty et al., 1994; Patra et al., 2000; Gupta, 2000]. However, the upper height coverage of the balloon-borne sensors is limited to ~ 35–40 km.
2.1.1.2 Rocket

Rocket provides very good altitude coverage with remarkable vertical resolution. Measurement of the neutral density, temperature and pressure were carried out by rocket-borne probes viz., Pitot tube [Ainsworth et al., 1961], falling spheres [Wright, 1969], thermistors [Ballard and Rofe, 1969]. An excellent review of these techniques can be found in Heath et al., [1974]. Using a variety of rocket borne sensors several studies on middle atmospheric composition, temperature and dynamics were carried out [e.g., Lal et al., 1979; Raghavarao et al., 1990; Sinha, 1992; Subbaraya et al., 1994a; Chandra et al., 2008; Das et al., 2009 and reference therein]. Major shortcomings of the rockets are that they are expensive and only a snap shot of the atmospheric feature under investigation is obtained. Therefore, long term continuous atmospheric surveillance is not feasible using rocket borne sensors.

2.1.2 Remote Sensing Techniques

Remote sensing is a technique for observing/monitoring a process or object without physical contact with the object under observation. Optical and radio telescopes, cameras, radars, lidars etc. are various types of remote sensing devices. Basically, there are two types of remote sensors to probe the atmosphere- (a) active sensors, and (b) passive sensors. Active sensors provide their own energy source for illumination viz., radar, lidar, sodar, sonar etc. Advantages of active sensors include the ability to make measurements regardless of the time of day or season. Remote sensing systems which measure energy that is naturally available are called passive sensors viz., Sun-photometers, radio telescopes, etc.

2.1.2.1 Satellite

Satellite borne instruments are very efficient tools for global coverage and quasi-continuous probing of the atmosphere. For obtaining vertical profile, solar occultation technique is exploited. This technique involves the measurements of the attenuated solar radiation, reaching to satellite after passing through the Earth's atmosphere along an almost horizontal path Measurement at successive satellite
positions corresponding to the ray traversing the atmosphere at different heights can provide a vertical profile of the absorbing constituent and that can be used to derive required physical parameter viz., density, temperature, etc [e.g., Venketswaran et al., 1961; Rawcliff et al., 1963]. Satellite observations revolutionized the era of the atmospheric probing with the galaxy of instruments on-board and with their remarkable coverage [e.g., Dudhia et al., 1993; Leblanc et al., 1995; Randel et al., 1995; Patra et al., 2003 and references therein]. However, these are also limited by poor vertical resolution, limited number of passes over a given location and cloud covers [Leblanc and Hauchecorne, 1997].

2.1.2.2 MST Radar

Mesosphere-Stratosphere-Troposphere (MST) radars are good for the study of variety of atmospheric processes with good vertical and temporal resolution. Temperature can be derived upto ~ 20-25 km using MST radar data. Radar observed vertical velocities are subjected to fast fourier transform analysis to obtain Brunt-Vaisala frequency, from which the temperature profile is obtained [e.g., Revathy et al., 1996]. But MST radars are also blind to 30-60 km height range due to absence or very weak turbulence, which is the main scatterer, in this altitude region [e.g., Woodman and Guillen, 1974; Balsley and Gage, 1980].

2.1.2.3 Lidar

Light Detection And Ranging (LIDAR) emerges as a very good tool for ground based long term middle atmospheric probing with very good vertical and temporal resolution. Lidar operations are mostly done at night and are limited by weather condition.

It was first suggested by Synge, [1930] that the scattering of light from a searchlight beam could be utilized to determine the atmospheric density. The field of lidar was revolutionized by invention of the first pulsed laser by Maiman [1960], and it became an ideal light source for the lidar operation. The introduction of these new lasers meant that spectrally narrower filters could be used at the receiver. This, coupled with small beam divergence resulted in a reduction in the
background noise level by several orders of magnitude. In addition, a pulsed source meant that the transmitter and receiver could be co-located in a mono-static arrangement, with the range at which the backscattered signal originated was determined by the time delay between the transmitted and received signals. The subsequent introduction of Q-switching led to high power short laser pulses, improving the range achieved and the spatial resolution.

Atmospheric measurements using this method were first made by Fiocco and Smullin, [1963], who observed scattering from above 30 km. Laser radar technique operates on a principle similar to that of normal radar. Over the past few decades, Rayleigh lidar has emerged as a powerful method for studying the middle atmosphere, and early results were presented by Hauchecorne and Chanin, [1980]. The Rayleigh lidar method has also been used to extract temperature for the stratosphere and mesosphere [Measures, 1984]. The height range (30–60 km) in the atmosphere observed by Rayleigh lidar is one which is relatively inaccessible to other techniques.

The strength of the lidar technique is that it is capable of making continuous measurements of lower and middle atmospheric parameters with good temporal and spatial resolutions. Lidars are used in a variety of applications in the field of atmospheric sciences employing different scattering/absorption mechanisms. On the basis of different scattering/absorption mechanisms, lidars are of various types e.g., Rayleigh lidar, Raman lidar, Differential Absorption Lidar (DIAL), etc. A Nd-YAG laser based Rayleigh-Mie backscatter lidar was developed at PRL and operated for the study of aerosols and temperature over Ahmedabad (23°N) [Jayaraman et al., 1995a, b; Jayaraman et al., 1996]. Bencherif et al., [1996] developed a lidar for the atmospheric probing over Reunion Island (20.8°S, 55.5°E). In the following section a brief description of different types of scattering mechanisms are presented.

2.2 Scattering of Light in the Atmosphere

In the atmosphere, a light beam suffers a loss of energy due to two mechanisms: scattering and absorption. This loss is termed as attenuation or extinction. In ab-
sorption, the light is lost to gases or particles, and its energy contributes to the internal energy of the atoms or molecules. Scattering, which is caused by atmospheric gases and particles results in the loss of light from its original direction.

There are two broad types of scatterings which have been utilized in lidar studies of the atmosphere and these are termed elastic and inelastic. Elastic processes refer to those in which there is no change of frequency/wavelength, and include Rayleigh, Mie, and resonance scattering. Inelastic processes involve a change in the frequency /wavelength between the incident and scattered light and are limited in their applications; these include Raman and fluorescence scatter.

In the following sections, two assumptions are made. The first is that the scattering particles are far enough away from each other such that the light scattered from one particle is unaffected by that from the others (independent scattering). The second is that the photon is scattered only once (single scattering) rather than two or more times, as in the case of multiple scattering.

2.2.1 Elastic Scattering

Elastic scattering refers to scattering in which there is no change in wavelength between the incident and the scattered light. The most important parameter for elastic scattering is the ratio of size of the scattering particles to the wavelength of the incident light.

2.2.1.1 Rayleigh Scattering

Lord Rayleigh, [1890], demonstrated for the first time that the scattering of light by air molecules is responsible for the blue color of the sky. Rayleigh scattering occurs when the dimensions of the scattering particles are much smaller than the wavelength of the incident light, and the frequency of the radiation does not correspond to a specific electronic transition. The backscatter cross-section has a $\lambda^{-4}$ dependence and the mechanism is only effective for particles with radii $\leq 0.03\lambda$ [e.g., Cerny and Sechrist, 1980]. This latter condition is satisfied by the atmospheric molecules.
Rayleigh Scattering Cross-section

The Rayleigh scatter cross-section is defined as the total energy scattered by a particle in all directions. Stratton, [1941] showed that for an incident wave of unit intensity, the scattered intensity at a distance $r$ from the scatterer is given by

$$I = \frac{16\pi^4 a^6}{r^2 \lambda^4} \left( \frac{n^2 - 1}{n^2 + 2} \right)^2 \sin^2(\psi) \tag{2.1}$$

where $n$ is the relative refractive index (the ratio of the scatterers' refractive index to that of the surroundings).

Rayleigh scattering cross section is obtained by integrating (2.1) over a sphere for an incident beam of unit intensity and is given by

$$\sigma_R = \frac{128\pi^5 a^6}{3\lambda^4} \left( \frac{n^2 - 1}{n^2 + 2} \right)^2 \tag{2.2}$$

The differential Rayleigh backscattering cross-section is the probability of scattering in the backward direction per unit solid angle ($\theta = \pi, \psi = \pi/2$);

$$\frac{d\sigma_R^{(\theta=\pi)}}{d\Omega} = \sigma_R = \frac{16\pi^4 a^6}{\lambda^4} \left( \frac{n^2 - 1}{n^2 + 2} \right)^2 \tag{2.3}$$

Hence, from (2.2) and (2.3):

$$\sigma_R = \frac{8\pi}{3} \sigma_R^\pi \tag{2.4}$$

For a mixture of gases present in the atmosphere below 100 km, Collis and Russell [1976] have indicated that the differential Rayleigh backscattering cross-section is

$$\sigma_R^\lambda(\lambda) = 5.45 \times \left( \frac{550}{\lambda} \right)^4 \times 10^{-32} \text{ m}^2\text{sr}^{-1} \tag{2.5}$$

where $\lambda$ is the laser light wavelength in nm.

This shows the $\lambda^{-4}$ wavelength dependence of the elastic scattering cross section characteristics of Rayleigh scattering and neglects the effects of atmospheric dispersion. If this effect is taken into account, the exponential factor changes from $-4$ to $-4.09$ [Elterman, 1968], corresponding to a change in the cross section of less than 3%. Shardanand and Rao, [1977] have shown that this relation (2.5) holds for a number of gases over the visible wavelength range. For the laser wavelength of $\lambda$ 532 nm employed in this study, $\sigma_R^\lambda$ is given by:
\[ \sigma_R = 6.24 \times 10^{-32} \text{m}^2\text{sr}^{-1} \]  

(2.6)

The total intensity scattered by a volume of gas is the sum of the scattered intensities from each scatterer within the volume. If all scatterers are considered to be identical, then the total scattered intensity is described by the volume molecular scattering coefficient, \( \alpha_{m,s} \):

\[ \alpha_{m,s} = N_m \sigma_R \]  

(2.7)

where \( N_m \) is the number of gas molecules per unit volume.

The volume molecular backscatter coefficient \( \beta_{m}^\pi \) is similarly defined as

\[ \beta_{m}^\pi = N_m \sigma_R^\pi \]  

(2.8)

With \( \sigma_R^\pi \) known, a measurement of \( \beta_{m}^\pi \) can be used to determine atmospheric density using (2.8).

Hence, for pure molecular scattering, the Rayleigh backscatter coefficient is a constant multiple of the Rayleigh molecular scatter coefficient:

\[ \beta_{m}^\pi = \frac{3}{8\pi} \alpha_{m,s} \]  

(2.9)

The total volume backscatter coefficient \( \beta_T^\pi \), is the sum of both the molecular and the particulate components,

\[ \beta_T^\pi = \beta_{m}^\pi + \beta_p^\pi \]  

(2.10)

Above the stratospheric aerosol layer (height > 25 km, under normal conditions) this term is dominated by the molecular component.

Modern Rayleigh lidars typically have a maximum range of around 90 km, while the lowest height for pure Rayleigh scatter depends on the maximum height of the aerosol layer in the stratosphere (~30 km). Measurements of the Rayleigh backscatter in this height interval can be used to derive vertical profiles of molecular density, pressure, and temperature.

### 2.2.1.2 Mie Scattering

As the size of the particles increases beyond the Rayleigh limit, the differential scattering cross-section becomes a complicated function. This form of scattering...
is characterized by a large differential backscatter cross-section and a very pronounced component of forward scattering. Mie (1908) developed a full treatment for the diffraction of a plane monochromatic wave by a homogeneous sphere situated in a homogeneous medium. His method was based on electromagnetic theory, and has been discussed in detail by several authors [e.g., Kerker, 1969; Liou, 1980, 2002].

2.2.1.3 Resonance Scattering

Resonance scattering is sometimes referred to as atomic or resonance fluorescence. It occurs when the frequency of the incident laser light corresponds to a specific transition of an atomic or molecular species, and results in an enhancement of the scattering cross-section. Collisional quenching by other constituents may result in a small signal; hence the technique is best applied to studies of some of the trace constituents in the upper atmosphere [Clemesha, 1984]. The use of tunable dye lasers has made it possible to observe scattering from neutral and ionized metal species from between ~ 80 and ~ 100 km.

2.2.2 Inelastic Scattering

Inelastic scattering refers to scattering mechanisms which produce a change in wavelength of the incident radiation, due to transitions within the scattering molecules. These interactions have also been utilized for lidar studies of the Earth's atmosphere.

2.2.2.1 Raman Scattering

Raman scattering involves a change in frequency between the incident and the scattered radiation characteristic of the stationary states of the scattering molecular species, regardless of the illuminating wavelength. As compared to the Rayleigh scattering, the Raman cross-sections are a few orders of magnitude smaller. This technique has a large potential for atmospheric studies, as the scattered signal can be clearly distinguished from that due to other scattering particles, and it does not require a tunable laser. If the scattered wave is examined spectrally, a series
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of sidebands shifted up and down in frequency by equal amounts are observed. The lower frequency components are due to the molecule gaining energy from the incident light, and are termed Stokes lines. Conversely, the higher frequency component represents a net loss of energy from the molecule to the radiation, and these lines are called the anti-Stokes lines. Raman lidar techniques have been effectively used in measurements for atmospheric temperature, water vapor and aerosols [e.g., Whiteman et al., 1992; Girolamo et al., 2004 and references therein].

Measurement of the Raman scattered signal selected by the use of suitable filters has thus proved to be a useful tool for atmospheric studies, although the weak returns do limit the height coverage. The frequency shift is unique to the scattering species, and the intensity of the scattered signal is proportional to the concentration of the scattering molecules. Hence, this method has also been employed to monitor atmospheric constituents [e.g., Inaba, 1976; Melfi et al., 1997; Whiteman and Melfi, 1999].

Using rotational Raman returns from molecular nitrogen and oxygen, it is possible to derive temperature profiles for height ranges in the lower troposphere. These returns are free from aerosol backscatter, and the ratio of the intensities of two different parts of the received Stokes spectra are approximately proportional to the atmospheric temperature [e.g., Mitev, 1984].

2.2.2.2 Fluorescence Scattering

Fluorescence scattering arises from the spontaneous emission of a photon following the excitation an excited state by the absorption of the incident radiation at a frequency which lies within a given absorption line or band of an atomic or molecular species. These excited states decay by the emission of a photon to different levels. As for resonance scattering, this form of inelastic scattering is better achieved in a tunable laser. Although it has a large differential backscatter cross-section ($\sim 10^{-20}$ m$^2$ sr$^{-1}$), collisional quenching often substantially reduces the received signal, even at stratospheric heights. This method has been employed for balloon-borne observations of OH fluorescence [Heaps and McGee, 1983, 1985]. This technique was shown to be useful for stratospheric temperature measurements.
2.2.2.3 Differential Absorption

Differential absorption is a method which provides a high sensitivity combined with good spatial resolution for measuring a particular atmospheric constituent. The idea was first suggested by Schotland, [1966] for evaluating the water vapor content in the atmosphere. He termed the technique Differential Absorption of Scattered Energy (DASE). It has subsequently been termed as DIfferential Absorption Lidar (DIAL).

![Ozone deviation from annual mean (in percent) over Mouna loa (1993-1999 reduced to a single composite year) as a function of altitude and month of the year. The contour interval is 4% (from Leblanc et al., 2000).](image)

The technique involves a comparison of the backscattered radiation when the laser is tuned close to an absorption line of the molecule of interest, with that received when it is tuned to lie in the wing of the line. Both radiations are returned by Rayleigh and possibly Mie scatter, and these data are then used to examine the contribution of molecular absorption to the extinction of the received signal. It has mainly been applied to water vapor studies in the lower troposphere, and
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ozone measurements in the upper stratosphere [e.g., Megie and Pelon, 1983; McDermid et al., 1995a; Grant et al., 1998]. Figure 2.2 shows a contour plot of ozone climatology using DIAL over Mauna Loa during 1993–1999. The ozone concentrations were lower during winter months in the altitude region of ~ 30 km [Leblanc and McDermid, 2000]. Association between ozone and stratospheric temperature over Mt. Abu are described in chapter 3. Important scattering/absorption cross-sections and their respective applications in different atmospheric height regions are given in Table 2.1.

Table 2.1: Comparison of optical interaction processes applicable to laser remote sensing methods in the atmosphere (source, Hinkley, 1976)

<table>
<thead>
<tr>
<th>Technique</th>
<th>Cross-section, $\frac{d\sigma}{d\Omega}$ [cm$^2$/sr]</th>
<th>Applications in the atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rayleigh scattering</td>
<td>about 10$^{-26}$</td>
<td>Density/Temperature (above ~ 30 km)</td>
</tr>
<tr>
<td>Mie scattering</td>
<td>about 10$^{-8}$ to 10$^{-26}$</td>
<td>Aerosols/clouds etc. (below ~ 30 km)</td>
</tr>
<tr>
<td>Raman scattering</td>
<td>about 10$^{-29}$</td>
<td>N$_2$, CO$_2$, H$_2$O, Temperature etc. (upto ~ 15-20 km)</td>
</tr>
<tr>
<td>Absorption</td>
<td>about 10$^{-20}$</td>
<td>Trace species, O$_3$, CO$_2$, H$_2$O etc. (upto ~ 50 km)</td>
</tr>
<tr>
<td>Fluorescence</td>
<td>about 10$^{-26}$</td>
<td>Trace species mainly NO$_2$, SO$_2$ (upto ~ 5 km)</td>
</tr>
</tbody>
</table>

2.3 Attenuation and Absorption

A loss of energy is also caused by the absorption of light by gases and particles. The total volume extinction coefficient ($\alpha$) is given as

$$\alpha = \alpha_{m,s} + \alpha_{m,a} + \alpha_{p,s} + \alpha_{p,a}$$

[2.11]

[e.g., Collis and Russell, 1976], where $m, p, s, a$ represent molecular (gaseous), particulate, scattering and absorption, respectively. This represents the fraction by
which the flux of energy in the direction of propagation per unit volume of the atmosphere is reduced.

For molecules, the scattering component \( (\alpha_{m,s}) \) is dominated by elastic scattering as the size of the molecules is small compared to the laser light wavelength and is given by equation 2.7.

The molecular absorption coefficient \( (\alpha_{m,a}) \) is strongly wavelength dependent. Atmospheric molecules absorb strongly at specific wavelengths when the photon energy corresponds to an energy level transition of the electrons in an atom or molecule. For laser radiation close to such wavelengths, this effect dominates \( \alpha \). However, these wavelengths are mainly found in the ultra-violet (\( \lambda < 300 \text{ nm} \)) and infra-red (\( \lambda > 900 \text{ nm} \)) regions of the electromagnetic spectrum. In the visible region, scattering is the main cause of molecular attenuation. The only atmospheric molecular component which absorbs light at the laser wavelength used in this study (532 nm) is ozone [Liou, 1980, 2002]. The volume molecular absorption coefficient \( (\alpha_{m,a}) \) may therefore be considered as being solely due to ozone

\[
\alpha_{m,a} = N_{O_3} \sigma_{O_3}
\]  \hspace{1cm} (2.12)

where \( N_{O_3} \) is the ozone number density, and \( \sigma_{O_3} \) is the ozone absorption cross-section. Hence, for a Rayleigh scattered laser pulse,

\[
\alpha = \alpha_{m,s} + \alpha_{m,aO_3}
\]  \hspace{1cm} (2.13)

In the case of particles, the volume particulate extinction coefficient \( (\alpha_p) \) is

\[
\alpha_p = \sum_{i=1}^{N} (\alpha_{p,s} + \alpha_{p,a})_i
\]  \hspace{1cm} (2.14)

This represents the sum of all contributions of \( \alpha_{p,s} \) and \( \alpha_{p,a} \) for each of the \( i \) species in the atmosphere. Each particle species has its own characteristic size distribution, number density and refractive index. Estimates of \( \alpha_p \) are therefore difficult to make. For particles, the effect of particle shape on the attenuation \( (\alpha_{p,s} \text{ and } \alpha_{p,a}) \) terms is not as marked as that on the corresponding backscatter coefficient \( \beta_p^w \), and such attenuating particles may, therefore, be considered as being spherical.

The volume particulate extinction and backscattering coefficients are related by

\[
\alpha_p^w = k \beta_p
\]  \hspace{1cm} (2.15)
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Figure 2.3: A panoramic view of PRL’s IR observatory and the atmospheric sciences laboratory at Gurushikhar, Mt. Abu.

(Pinnick, 1980), where $k$ is the attenuation to backscatter ratio.

2.4 PRL’s Lidar System

PRL’s lidar system is located at a hill top, Gurushikhar at Mt. Abu. The prime objective of operating the lidar at a hill station was to explore middle atmosphere up to the highest possible altitude. Mt. Abu has very little light pollution and is relatively cloud free. In addition, surrounding hill terrain provides an opportunity to explore the orographically generated dynamical features. A panoramic view of PRL’s IR observatory at Gurushikhar is shown in Figure 2.3. The inside view of the lidar laboratory along with Atmospheric Sciences Laboratory building is shown in Figure 2.4.

Regular lidar measurements for temperature studies were started at Mt. Abu with a 90 cm telescope in November 1997 and the lidar was normally operated
for about 5-10 nights each month around new moon period. Temperature profiles can be derived up to 70–75 km altitude with an integration time varying from one hour to six hours, depending upon the system status and local weather conditions. During the monsoon period, (mid June to mid September) regular measurements were not possible and only a few nights of observations could be made during June and September.

2.4.1 System Block Diagram

The block diagram of the lidar system is shown in Figure 2.5. It consists of a Nd-YAG laser, a beam expander and a beam steering mirror, comprising the transmitting section. The receiver consists of a Cassegrain telescope and a photomultiplier tube (PMT) which is connected to a photon counting system. The transmitting and receiving optics are non-coaxial, being separated by a distance of ~ 1.5 m. Thus the backscattered signals are not seen by the telescope until the transmitted beam
is fully inside the telescope’s field of view, that is beyond \( \sim 400 \) m in the present setup. The signal received from the lower heights is very strong, therefore it is necessary to use a gated PMT or a mechanical shutter to avoid saturation induced effects in PMT from the large backscattered signal from lower heights. The receiving section is separated from the rest of the laser transmitting gadgets by using black panels. The laser beam passes through pipes to protect users from exposure to hazardous laser radiations inside the laboratory. This also serves to prevent light from the transmission section reaching the receiving units. Detailed specifications of the lidar system are presented in Table 2.2.

### 2.4.2 Transmitting System

#### Laser

The first laser system pumped with the flash lamp was a Q-switched ruby laser, later it has been implemented in other lasers (as Nd-YAG laser). Use of solid-state lasers are popular in the atmospheric lidars due to their ruggedness, long life, less maintenance and reasonably good efficiency (e.g., Nd:YAG laser). Nowadays, with
Table 2.2: Major specifications of the lidar system operational at Mt. Abu.

<table>
<thead>
<tr>
<th>Lidar system</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Laser</strong></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Nd:YAG (581C-10 Quantel, France)</td>
</tr>
<tr>
<td>Average Power</td>
<td>4.4 Watt at 532 nm</td>
</tr>
<tr>
<td>Energy per pulse</td>
<td>440 mJ at 532 nm</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>10 Hz (Maximum)</td>
</tr>
<tr>
<td>Pulse width</td>
<td>7 ns</td>
</tr>
<tr>
<td>Beam Divergence</td>
<td>0.6 mrad</td>
</tr>
<tr>
<td><strong>Telescope</strong></td>
<td></td>
</tr>
<tr>
<td>Telescope type</td>
<td>Cassegrain</td>
</tr>
<tr>
<td>Effective focal length</td>
<td>737 cm</td>
</tr>
<tr>
<td>Diameter (Primary mirror)</td>
<td>90 cm</td>
</tr>
<tr>
<td>Diameter (Secondary mirror)</td>
<td>25 cm</td>
</tr>
<tr>
<td>Field of view</td>
<td>1 mrad</td>
</tr>
<tr>
<td>Power aperture product</td>
<td>2.6 Wm$^{-2}$</td>
</tr>
<tr>
<td><strong>Optics</strong></td>
<td></td>
</tr>
<tr>
<td>Interference filter</td>
<td>532 nm</td>
</tr>
<tr>
<td>Central wavelength</td>
<td>1 nm</td>
</tr>
<tr>
<td>Filter bandwidth</td>
<td>100%</td>
</tr>
<tr>
<td><strong>Photomultiplier</strong></td>
<td>9813A (Electron Tubes, UK)</td>
</tr>
<tr>
<td>Mode of operation</td>
<td>Photon counting mode</td>
</tr>
<tr>
<td>Dark counts</td>
<td>$\sim 300$ counts/sec at 20° C</td>
</tr>
<tr>
<td><strong>Signal processor</strong></td>
<td>SR430 Stanford Research Systems, USA</td>
</tr>
<tr>
<td>Type</td>
<td></td>
</tr>
<tr>
<td>Bin width</td>
<td>640 ns ($\sim 96$ m)</td>
</tr>
</tbody>
</table>
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Diode array pumping, efficiencies up to ~ 10%-20% have also been achieved.

The laser used in PRL’s lidar is Q-switched Nd-YAG laser (581C-10, Quantel, France). It has two main parts, the optical heads and the power supply. These are connected by cables, wires and hoses running through an umbilical. In addition to energizing the optical heads, the laser power supply provides all logical functions necessary to operate the laser, and cooling device to dissipate the heat generated in the optical heads by the operation of flashlamps. A remote control box is provided for smooth/safe operation of the laser.

The fundamental wavelength of the Nd-YAG laser is in the infrared region, at 1064 nm. It employs highly deuterated (99%) KDP crystals for 2\textsuperscript{nd} and 3\textsuperscript{rd} harmonic generation of radiation at 532 nm and 355 nm, respectively. The crystals are mounted on a mechanical holder and oriented along a horizontal plane and can be tuned separately using thumb wheels for maximum power output. The output signal strength is stabilized (less than 3% fluctuations from pulse to pulse) over hours of operation using temperature controllers. In order to synchronize the signal detection with laser firing, a synchronization pulse of 15 volts is derived from Q-switch for triggering the time delay generator, PMT gating circuit and the photon counter. The laser output at 532 nm and 355 nm, share same output port. However, they have an angular separation which enables the use of two separate reflectors, which reflect more than 99% at both the wavelengths. In the present study, laser radiation at wavelength of 532 nm (2\textsuperscript{nd} harmonic of Nd-YAG laser) was used. The fundamental wavelength of 1064 nm was not used for measurements due to its reduced degree of Rayleigh scattering, and also because of the low quantum efficiency of photomultipliers in this part of the electromagnetic spectrum. The third harmonic of 355 nm would be Rayleigh scattered more efficiently, but was not used for this work primarily because of the lower power output from the laser, the less efficiency of the filters and the increased absorption of this wavelength by ozone.

For the present study, maximum available laser repetition rate of 10 Hz was used. The individual pulses were of 7 ns duration, corresponding to a pulse length of 1.05 m. Such short pulses can provide a very good height resolution which is one of the important features of the lidar technique. The highly monochromatic nature of the transmitted laser light permits us to use narrow band width filters at
the receiver end to reject background light, thereby improving the signal-to-noise ratio.

2.4.2.2  Beam Expander

The output laser beam was passed through a beam expander. The Laser Beam Expander (LBX) consist of afocal, de-centered pupil and Dall-Kirkham telescope. The primary mirror is a de-centered section of a concave ellipsoid and the secondary mirror is a convex sphere. The unexpanded input beam enters the unit through an aperture located adjacent to the primary mirror mounting plate, at the rear end of the housing. The diameter of this aperture is oversized with respect to the diameter of the input beam. The collimated input beam strikes the convex sphere and diverges to fill the concave primary mirror, which acts as the system aperture stop. The primary mirror re-collimates the wave, and the expanded beam then exits through an oversized aperture at the front of the unit. The beam expander is pre-aligned such that the input and the output beams are parallel to each other, and the input beam is centered at the entrance aperture. The surface accuracy of mirrors is about λ/20 at 532 nm. The full angle of output beam divergence due to errors in alignment is less than 8 micro-radian. This LBX is combined to form an expanding telescope with a magnifying factor of 10, which reduces the beam divergence from 0.6 mrad to 0.06 mrad. This further increases the altitude coverage of the laser beam and in turn improves the signal to noise ratio of the observed photon counts.

2.4.2.3  Beam Steering Mirror

The laser beam is transmitted into the atmosphere vertically with the help of a 6" diameter, 45° incidence beam steering mirror, having ultra-hard dielectric coating, high density. This reflecting mirror is kept on a two-axis mounting which allows fine adjustment of the mirror, while aligning the lidar system.
2.4.3 Receiving System

The main components of the receiver system are telescope, photomultiplier and photon counting system.

2.4.3.1 Telescope

A Cassegrain telescope is deployed for collecting laser induced backscattered signal from different altitudes. It has a front-silvered parabolic primary mirror of 90 cm diameter and a secondary mirror of 25 cm diameter with effective focal length of 737 cm. Though this is basically a light collector, it has been shown that good optical quality mirrors are highly desirable for such studies [e.g., Hauchecorne and Chanin, 1980]. The backscattered radiation collected by primary mirror and after reflecting from the secondary mirror, is sent to the aperture of the photomultiplier assembly through an interference filter.

2.4.3.2 Filter Wheel Assembly

There is a filter wheel assembly in which four interference filters can be deployed. For the present study a filter, having central wavelength at 532 nm, is used for receiving Rayleigh backscattered signal.

2.4.3.3 Photomultiplier Tube

The photomultiplier tube (PMT) used is 9813A (Electron Tubes, UK) with 52 mm diameter (46 mm effective cathode diameter). It is a 14 stage gated tube with a fused silica front window and is cooled to about – 25 °C by a thermoelectric cooling device. It is of the type which is used in fast photon counting. The quantum efficiency is 9% at wavelength of 532 nm.

Intensity of the observed backscattered signal is very high from lower heights and requires shutting off the detector mechanically or electronically to avoid intense exposure of the PMT. In the present system gating of PMT is used. Therefore, appropriate delay was introduced by a delay counter (which can produce delay up to 999 μs in steps of 1 μs). The main purpose was to protect the PMT from overload-
ing due to large backscattered signal from the lower regions of the atmosphere. A delay of 150 μs which corresponds to ~22.5 km has been used in the present study (for the Rayleigh mode). The light then was allowed to pass through an optical interference filter with central wavelength at 532 nm and bandwidth of 1 nm (full width at half maximum). The maximum transmission was about 20% at 532 nm.

All detection instruments used for counting have a dead time or recovery time \cite{Evans1955}. The dead time represents the time between the receiving system counting one pulse, and recovering to be ready for the next one. For very high count rates, this may lead to incorrect counting, as a portion of the real signal arrives before the receiving system is ready to count again and consequently is not detected. The receiving system dead time is 100 ns in the present setup. This was calculated in the following manner. If the system recovery time is \( t_r \), and total \( n \) pulses arrive from the photomultiplier, then the fraction of time during which the system is dead is \( nt_r \). Hence the fraction of time during which the system is active is \( 1 - nt_r \), which is the fraction of the true number of events, \( n_o \), that the system can actually count,

\[
\frac{n}{n_o} = 1 - nt_r
\]  

(2.16)

As \( n_o \) increases, the observed count rate \( n \) rises uniformly and approaches the value of \( n_{\text{max}} = 1/t_r \) asymptotically.

2.4.3.4 Amplifier-Discriminator

The amplifier-discriminator is used to interface the PMT with the counting equipment. It generates a single output pulse of defined width and amplitude for every input pulse exceeding a set threshold voltage. Its role is to ensure that genuine signal pulses are counted. It is also used to convert the varied signal pulses from the photomultiplier into pulses of approximately uniform amplitude and width.

However, the PMT also produces noise counts which need to be disregarded. Some of these originate further down the dynode chain and so are amplified less, leading to smaller pulses than those generated by genuine backscattered signal. This sets a lower limit, eliminating the majority of the noise counts, as well as any
background electrical noise.

2.4.3.5 Signal Induced Noise

It is also possible that noise is generated by the mechanism of Signal Induced Noise (SIN) in the photomultiplier. It has been noted [e.g., Pettifer, 1975; Acharya et al., 2004] that the signals themselves can induce an increase in the dark count of the photomultiplier. This need not be an overloading effect, as it exists for small and large counts and is proportional to the number of signals detected. One further source of noise pulses is the ion after-pulse mechanism, due to the gas inside the photomultiplier tube. Electrons ionize the gas, and these ions are attracted to the sides of the tube leading to a larger than normal pulse occurring approximately 1-2 ms after the actual count pulse. Such pulses only constitute less than 1% of the total counts, and are taken care of at the discriminator, to prevent these being counted. The number of system noise counts are minimized by the discriminator and hence have little effect on the derived density/temperature profile.

2.4.3.6 Counting System

A multichannel photon analyzer (SR430) manufactured by Stanford Research System has been deployed for photon counting. It is a multichannel scaler and counts incoming pulses in successive time bins. A trigger starts a record of up to 32,704 time bins. The bin width is programmable from 5 ns to 10.5 ms. This offers flexibility to choose the desired vertical resolution. In the present study a bin width of 640 ns, which corresponds to vertical resolution of 96 m, has been used throughout the observation period, 1997-2007.

A software has been developed to control the SR430 to run and collect the photon counts profile in automatic mode. In a given raw data profile there are two columns. First column represents the bin number and other has the total number of photon counts collected in each bin during an integration period of 5/10 minutes. This raw data profile is then used for further calculation of density and temperature.
2.5 Operational Procedure

While setting up the lidar system, utmost care has been taken in the alignment of both the laser and the telescope. Prior to actual lidar observation sessions, all the necessary system checkups and proper alignments were made. It was ensured that the transmitted beam intersected with the receiver field of view at the desired height. A pre-set program of SR430 is used for recording the counts received in each height channel for a given number of laser shots and height resolution. In this study we have used mostly 3000/6000 laser shots (5/10 minutes profile) with an altitude resolution of 96 m which corresponds to bin width of 640 ns. All the alignments and system performance checkups were carried out during the observations whenever the need was felt to do so.

2.5.1 Alignment of the System

For maximum collection efficiency the transmitted beam should lie fully in the field of view of the telescope in the region of the atmosphere to be investigated. The alignment of the system was carried out in two steps. Firstly, alignment was done using simple mechanical alignment techniques. Afterward, the backscattered signal from 600 laser shots were examined in the height range of 30 to 80 km. This value was then maximized using the fine adjustment of the beam steering mirror.

As mentioned earlier, the gating of PMT is done for initial delay of 150 \(\mu s\), which corresponds to \(\sim 22.5\) km. This also represents the lowest height above which density/temperature can be derived with high degree of confidence (free from possible contamination due to Mie scattering from stratospheric aerosols).

2.6 Lidar Data and Method of Analysis

In this study, lidar data for about 10 years, 1997-2007, collected at Mt. Abu have been used. Observations were taken during the new moon period of every month, for about 5-10 nights (limited by local weather and seeing conditions). Monthly distribution of the observations over Mt. Abu is given in Table 2.3. In order to
analyze the lidar data, it was first necessary to transfer the photon count files from
the SR430 to the PC. SR430 records data in binary format. While transferring data
from SR430 to a PC, a program is used to convert data from binary to ASCII format.

Table 2.3: Statistics of monthly observation over Mt. Abu during 1997-2007, including the observations during INDOEX campaigns, 1998-1999

<table>
<thead>
<tr>
<th>Year</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Total Nights</th>
</tr>
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<tbody>
<tr>
<td>1997</td>
<td>0</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>1998</td>
<td>0</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>11</td>
<td>22</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>49</td>
</tr>
<tr>
<td>1999</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>19</td>
<td>8</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>36</td>
</tr>
<tr>
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<td>7</td>
<td>7</td>
<td>0</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>42</td>
</tr>
<tr>
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<td>10</td>
<td>8</td>
<td>7</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>6</td>
<td>5</td>
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<td>53</td>
</tr>
<tr>
<td>2002</td>
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<td>4</td>
<td>3</td>
<td>5</td>
<td>8</td>
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<td>5</td>
<td>6</td>
<td>6</td>
<td>54</td>
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<tr>
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<td>6</td>
<td>8</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>4</td>
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<td>2004</td>
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<td>5</td>
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<td>7</td>
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<td>4</td>
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<td>3</td>
<td>0</td>
<td>49</td>
</tr>
<tr>
<td>2006</td>
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<td>6</td>
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<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>0</td>
<td>43</td>
</tr>
<tr>
<td>2007</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>7</td>
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<td>5</td>
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<td>0</td>
<td>36</td>
</tr>
<tr>
<td>Total</td>
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<td>44</td>
<td>55</td>
<td>58</td>
<td>70</td>
<td>66</td>
<td>54</td>
<td>36</td>
<td>14</td>
<td>480</td>
<td></td>
</tr>
</tbody>
</table>

This further facilitates checking the quality of data, on line, and gives an option to correct the system parameters/alignments if required. Before the data are analyzed to yield values of density and temperature in the height range of 30 to 75 km, these are corrected for background noise, dead time and range.

2.6.1 Lidar Equation

The theoretical basis of the Rayleigh lidar technique is relatively straightforward. Monochromatic laser pulses are transmitted vertically into the atmosphere and variation of the backscattered signal with height provides information on atmospheric structure. Further reduction of the background ‘sky noise’ is possible due
to the highly collimated transmitted beam, which allows a narrow receiver field of view to be used. For studies of molecular density using Rayleigh scattering, the laser wavelength selected is one which is away from any atmospheric absorption bands or resonance lines.

The basic scattering lidar equation can be derived, with the following assumptions:

i) The photons which are scattered out of the volume of air being investigated have suffered only one scattering event before leaving the volume (absence of multiple scattering).

ii) The scattering is incoherent.

iii) The detector response time $t_D$ must satisfy the equation

$$\Delta h \gg \frac{ct_D}{2}$$

so that the height region $\Delta h$ can be resolved unambiguously.

iv) The laser pulse itself should be of proper shape; for truncated pulses, a small correction is necessary [Measures, 1984].

If the above mentioned conditions are satisfied, then the intensity of the beam at a height $z$ is given by equation

$$I_0 = \frac{N_0\Pi}{tz^2\Omega}$$

where $N_0$ is the number of photons contained in a solid angle $\Omega$ steradian from a square pulse of $t$ seconds duration, and $\Pi$ represents the transmissivity, defined by.

$$\Pi = I = \frac{I}{I_0} = \exp \left( -\int_0^z \alpha(z) \, dz \right)$$

according to the Beer-Brouger-Lambert law. When a beam of light of wavelength $\lambda$ travels through the atmosphere, it is attenuated exponentially according to

$$I = I_0\exp(-\alpha z)$$
where \( I \) represents the intensity after traveling a distance \( z \), and \( I_0 \) is the incident intensity at \( z=0 \). The volume extinction coefficient \( \alpha \) is assumed to be constant over the distance \( z \).

The backscatter intensity from the volume \( dV \) is then given by

\[
I^w = I_o \left( \beta_m^w + \beta_p^w \right)
\]  

(2.21)

Where, \( \beta_m^w \) is the volume molecular backscatter coefficient and \( \beta_p^w \) is volume particulate backscatter coefficient.

Combining (2.18) and (2.21) gives the number of photons backscattered per second per unit steradian from a height \( z \) as

\[
N(z) = \frac{N_o \Pi}{t z^2 \Omega} \left( \beta_m^w + \beta_p^w \right) dV
\]  

(2.22)

If \( A \) is the effective surface area of the receiving mirror, then the solid angle subtended at a height \( z \) by the receiver is

\[
\Omega_z = \frac{A}{z^2}
\]

(2.23)

and the scattering volume \( dV \) is

\[
dV = z^2 \Omega \, dz
\]

(2.24)

At the receiver, the photons have again passed through the atmosphere of transmissivity \( \Pi \), and the power backscattered from the scattering volume \( dV \) into the receiver field of view \( A/z^2 \) is

\[
P_r(z) = \frac{P_o \Pi^2}{t z^2 \Omega} \left( \frac{A}{z^2} \right) \left( \beta_m^w + \beta_p^w \right) dV
\]

(2.25)

which may be written as

\[
P_r(z) = \frac{P_o \Pi^2 A}{t z^2} \left( \beta_m^w + \beta_p^w \right) dz
\]

(2.26)

For a laser pulse of duration \( t \), and with the speed of light denoted by \( c \), the pulse length is \( c t \) and

\[
dz = \frac{ct}{2}
\]

(2.27)

The quantity \((ct/2)\) is termed the 'effective pulse length', and is the interval from which signals are received at any instant. This is half the distance covered by the
light pulse in time $t$, as the pulse must travel a two-way path. For a reception time of $t_D$, (corresponding to a scattering height region $dz = (ct_D/2)$), the power received per unit time into the field of view of the receiver is

$$P_r(z) = \frac{P_o \Pi A}{t z^2} \left( \frac{ct_D}{2} \right) (\beta_m^\pi + \beta_p^\pi)$$  \hspace*{1cm} (2.28)

Also, if the detection system has an efficiency $Q$, which includes a geometrical factor for the system, and a factor describing the detector efficiency, (both of which may be wavelength dependent), then (2.28) becomes

$$P_r(z) = \frac{P_o AQ}{t z^2} \left( \frac{ct_D}{2} \right) (\beta_m^\pi + \beta_p^\pi) \Pi^2$$  \hspace*{1cm} (2.29)

Therefore, using equations (2.13) and (2.19) for $\Pi$, and assuming that there is no contribution from Mie backscatter or absorption by particles, this becomes

$$P_r(z) = \frac{P_o AQ}{z^2} \left( \frac{ct_D}{2} \right) (\beta_m^\pi) \exp \left( -2 \int (\alpha_{m,s} + \alpha_{m,a0a}) \, dz \right)$$  \hspace*{1cm} (2.30)

Rigorous derivations of the generalized lidar equation for elastic backscatter have been presented by several authors in different forms [e.g., Kent and Wright, 1970; Measures, 1984; Thomas, 1987]. Equation (2.30) represents the basis for the present analysis. Provided that the received signal is due solely to Rayleigh backscatter, it is then proportional to the molecular density. If the atmosphere is assumed to obey the perfect gas law and to be in hydrostatic equilibrium, then atmospheric temperatures may also be derived.

The method used in this derivation follows that of Chanin and Hauchecorne [1981]. The atmospheric density at the center of an atmospheric layer which is 96 m thick is given by

$$\rho(z) = \frac{M(z_i)}{M(z_o)} FA(C(z_i) - N) z_i^2$$  \hspace*{1cm} (2.31)

where $M(z_i)$ and $M(z_o)$ are the mean molecular weights at height $z_i$ and the ground level $z_o$ respectively. These are taken to be equal in the height range studied, due to the constant mixing ratio. The integrated photon count is given by $C(z_i)$, and $N$ is the background noise photon count (consisting of the photomultiplier dark count and the sky background); both are corrected for the system dead time. The term $F$
is a factor which takes into account the attenuation of the laser beam by Rayleigh scattering and absorption by atmospheric ozone and $A$ is normalization constant.

From the derived density profile, the atmospheric pressure can be calculated. The pressure $P(z_i - \Delta z/2)$ at the bottom of each successive layer, descending in height, is given by

$$P\left(z_i - \frac{\Delta z}{2}\right) = P\left(z_i + \frac{\Delta z}{2}\right) + \rho(z_i)g(z_i)\Delta z$$  \hspace{1cm} (2.32)

For the first calculation, $P(z_i + \Delta z/2) = P_m(z_i + \Delta z/2)$ (i.e. equal to the model pressure at the maximum useable height). The profile is then calculated downwards, with the pressure at the top of a layer being set equal to the pressure at the bottom of the layer above (i.e. $P(z_{i-1} + \Delta z/2) = P(z_i - \Delta z/2)$).

The temperature of each layer may then be calculated from

$$T(z_i) = \frac{M(z_i)g(z_i)\Delta z}{R\log_e(P(z_i - \Delta z/2)/P(z_i + \Delta z/2))}$$  \hspace{1cm} (2.33)

where $M$ is mean molecular weight of the neutral atmosphere and $R$ represents the universal gas constant.

The use of a model pressure at the upper height limit does introduce a systematic error in the derived pressure and temperature profiles. This error, however, decreases rapidly with decreasing height due to the exponential growth of density. Although the values of density derived are relative, the temperature values themselves are absolute. There may be some errors in the derived temperature at the uppermost levels due to the assumed model pressure values up to the maximum of two scale heights $\sim 10$-12 km. Therefore, in present study temperature profiles, only up to the altitude of 70 to 75 km are used for the fitted value of pressure at 85 km.

### 2.6.2 Dead-time Correction

Dead-time correction was applied to each sample of the backscattered signal. The greatest effect on the received signal occurred at the lower heights (near 30 km) where the backscattered signal count rate was the highest. Consequently, it would be more likely that the backscattered signal arrived during the dead time of the
system, and was undetected. At greater heights, the count rate decreased and virtually all of the backscattered signal was detected. Prior to density/temperature calculations, all profiles were corrected for the dead-time.

2.6.3 System Noise/Background Signal Correction

It was also necessary to correct the data for systematic noise, which was present in each height channel. This was independent of range, possibly time varying, and had several possible origins. One source was 'sky noise' such as the light from the moon, stars and unavoidable stray lights near the observatory. Spurious counts could also have arisen from the electrical equipment used, and thermal noise from the photomultiplier. The contribution of the total systematic noise to the recorded signal was estimated by calculating the mean number of counts for the top 100 height channels where there were only noise counts. These mean number of counts were then subtracted from the counts in all the height channels to be used in the subsequent data analysis.

2.6.4 Rayleigh and Ozone Attenuation

It was also necessary to take into account the effects of Rayleigh and ozone attenuation on both the transmitted and the backscattered signals through the height range studied. The total increase in the received signal over this height range (30-80 km) was less than 1% due to Rayleigh and ozone attenuation and hence had negligible effect on calculated temperature profiles.

2.6.5 Range-corrected Profile

The range corrected profile is defined as the total number of counts for a given height channel multiplied by the square of the height to which the height channel corresponds, and (under several basic assumptions) is proportional to the atmospheric neutral air density. An example of the raw data on 24 March 2001, along with range corrected profiles at 96 m and 480 m range resolutions are shown in Figure 2.6. The variation of the range corrected profile for the observation session
Figure 2.6: An example of raw-data (upper panel) and range corrected signals at 96 m and 480 m range resolution (lower panel) over Mt. Abu on 24 March 2001. To have better feel of the signal from higher heights, the raw data from range bins 600 to 1064 are also shown on inflated scale along Y axis.

on the night of 22 October 2001 is shown in Figure 2.7. This particular recording session consisted of 12 consecutive 10 minute profiles. On this occasion, delay generator for PMT gating was adjusted such that the signal from the lower height of up to approximately 22.5 km was not amplified by PMT. In each case, the individual samples were corrected for counter resets and the system dead time. The total profile itself has been smoothed over 480 m (5 range bins) in the vertical direction to reduce the small scale variability and finally a 5 point running average is applied to the temperature profiles. Relative atmospheric density is derived under the assumption that the atmosphere obeys the perfect gas law, is in hydrostatic equilibrium, and that the returns are due only to Rayleigh scattering from
molecules. This is represented by an approximately linear section between 30 and 75 km which represents the decrease of neutral air density with height. The mean background noise signal was calculated from the top 100 height channels (i.e. 90 to 100 km), and subtracted from the counts recorded in all the lower height channels used in the analysis.

The corresponding density and temperature profiles derived for the total observation session are also shown in Figure 2.7. The data were fitted at both the upper and lower height limits to model pressure values taken from the CIRA-86 reference model atmosphere, interpolated for Gurushikhar’s latitude and for the particular
month. The model values are also indicated in the figures, and it can be seen that there is an agreement between these and the lidar derived values. The density and temperature profiles used in this study were derived from the raw data using a C-language based program. The method followed in the present study is similar to that of Chanin and Hauchecorne [1980, 1984].

2.6.6 Selection of the Upper Height Limit

The upper height at which the data were fitted to the model could be varied depending on the level at which the signal to noise ratio is good. The fitting height had a small effect on the derived density profile due to the model values used, although the derived pressure and temperature profiles were more sensitive to such changes. Generally, these values converged at heights below ~ 10 km at which the upper level pressure was fitted. This represented the height at which the value of the fitted pressure became negligible compared with the derived pressure. It was typically found that the received signal was dominated by noise for heights greater than ~ 75-80 km, and this level was adopted as the upper height limit for the subsequent derivation of the profiles of density and temperature from the data.

2.7 Errors in Lidar Measurements

Photon count rate in lidars closely follows a Poisson distribution. Hence, in each height channel, the number of counts recorded has a counting error derivable from Poisson statistics. For a Poisson distribution, one standard deviation is equal to the square root of the total number of counts for that height channel. This allows an estimate to be made of the error in the derived values of density and temperature. As the number of counts detected obeys the inverse-square law, the proportional error is largest at greater heights from where the total number of received counts is relatively small. The derivation of the errors in the measured density and temperature from the lidar data follows that of Hauchecorne and Chanin [1980].
The relative uncertainty on the density measurements is given by

\[
\frac{\Delta \rho}{\rho} = \frac{\Delta N_L(z)}{N_L(z) - B(z)}
\]

where \(N_L\) is the signal from an altitude \(z\), \(B(z)\) is the total background signal due to the dark current (the signal generated within the system itself) and the sky background. The total background signal is estimated from the uppermost heights at which the signal is dominated by the noise. If \(B(z)\) is negligible, then it corresponds to \((\Delta N_L/N_L)\) or \((N_L)^{-1/2}\).

It can then be shown that the derived temperature has a statistical standard error of

\[
\frac{\delta T(z_i)}{T(z_i)} = \frac{\delta \log(1 + X)}{\log(1 + X)} = \frac{\delta X}{(1 + X) \log(1 + X)}
\]

where

\[
X = \frac{\rho(z_i) g(z_i) \Delta z}{P(z_i + \Delta z/2)}
\]

and

\[
\left(\frac{\delta X}{X}\right)^2 = \left(\frac{\delta \rho(z_i)}{\rho(z_i)}\right)^2 + \left(\frac{\delta P(z_i + \Delta z/2)}{P(z_i + \Delta z/2)}\right)^2
\]

\[
\delta P(z_i + \Delta z/2)^2 = \sum_{j=i+1}^n (g(z_j) \delta \rho(z_j) \Delta z)^2 + (\delta P_m(z_n + \Delta z/2))^2
\]

At the top of the profile, the uncertainty in the model fitted pressure is assumed to be around 15%. The effect of model fitted pressure, on the temperature uncertainty, decreases rapidly with altitude, and is less than 1% at 10-12 km from the top of the height range [Hauchecorne and Chanin, 1980; Ferrare et al., 1995]. Sivakumar et al., [2003] have also shown that the standard error associated with the temperature measurement at Gadanki is \(\sim 15\) K at the top reference level of 90 km and decreases exponentially to \(\sim 1\) K at 50 km.

The accuracy of the density and temperature measurements depends upon the number of photons \(N(z)\) received from the height range \(\Delta z\) during the time \(\Delta t\). It therefore varies as \((N(z))^{1/2}\) or \((\Delta t \Delta z)^{1/2}\), and will depend on the time and space resolutions required; these will vary with the problem to be studied. For long period and large scale phenomena, \(\Delta t\) and \(\Delta z\) can be large, although for smaller scale rapidly varying features, these should be as small as possible. A study was
made on the errors in derived density and temperature as a function of data length and bin width. The performance of the system for different integration times is shown in Figure 2.8, derived from the observed data on 21 October 2001. These data correspond to a vertical resolution of ~ 480 m. Temperature profiles were obtained from this data set using different data lengths corresponding to 10, 30, 60, 90, 120, 180, and 240 minutes. As the integration time is increased, the errors are seen to decrease. For a 10 minute data, typical uncertainties in the derived densities (temperatures) are 0.7% (~ 2.0 K) at 40 km, 1.6% (~ 5.0 K) at 50 km, 4.2% (~ 12 K) at 60 km, and 15% (~ 35 K) at 70 km. These are significantly reduced as the duration of the observation session is increased. The values for the total observation session (of about 240 minutes) are 0.1% (~ 0.26 K), 0.3% (~ 1.0 K), 0.8% (~ 2.0 K) and 2.3% (~ 7.0 K) for heights of 40, 50, 60, and 70 km, respectively. A detailed estimate of errors is also given in Table 2.4.
Table 2.4: Error variation in temperature derivation with altitude and different integration times.

<table>
<thead>
<tr>
<th>Height (km)</th>
<th>1 Hour Integration</th>
<th>2 Hour Integration</th>
<th>4 Hour Integration</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>0.5</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>40</td>
<td>0.8</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>45</td>
<td>1.2</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>50</td>
<td>2.1</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>55</td>
<td>4.3</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>60</td>
<td>5.8</td>
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</tr>
<tr>
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<td>12.0</td>
<td>4.5</td>
<td>3.2</td>
</tr>
<tr>
<td>75</td>
<td>27.0</td>
<td>21.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>

2.8 Satellite Based, NCEP and ERA-40 Data Sets

In addition to the lidar data, satellite based temperature, total column ozone measurements and National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP - NCAR), and European Center for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) data sets have also been used in the present study.

2.8.1 Temperature Data from HALOE onboard UARS

Upper Atmosphere Research Satellite (UARS) equipped with 10 instruments onboard for the Earth’s atmospheric probing was launched using space shuttle Discovery in 1991 [e.g., Reber et al., 1993]. It orbited at an altitude of 576 km with an orbital inclination of 57° and was in operation till 2005. It measured temperature, ozone, chemical compounds which affect ozone chemistry and processes along with the winds and the energy input from the Sun in the stratosphere-mesosphere and in the lower thermosphere. One of the important instruments onboard UARS was the Halogen Occultation Experiment (HALOE). The basic scientific goal of
HALOE was to provide global scale data on temperature, odd chlorine (ClOy), odd nitrogen (NOy), odd hydrogen (HOy) etc., compounds needed to study the chemistry and dynamics of the middle atmosphere [Russell et al., 1993]. It employs the principle of satellite solar occultation and a technique of absorption of solar energy in selected spectral bands. The HALOE instrument includes broadband and gas filter channels covering the spectral range from 2.45 micrometer to 10.04 micrometer as described by Russell et al., [1993]. All together, these measurements are very useful for unraveling the role of the upper atmosphere in the Earth's climate and in its variability. Detailed discussions related to the validity of HALOE data can be found in a number of papers [e.g., Russell et al., 1993; Hervig et al., 1996; Singh et al., 1996].

In the present study, HALOE temperature data from 1991-2005 have been used for the satellite passes near (±5°) to the lidar site at Mt. Abu.

2.8.2 Ozone Data from TOMS

Total Ozone Mapping Spectrometer (TOMS) onboard Nimbus-7 and Meteor-3 provided global measurements of total column ozone on a daily basis and together provide a complete data set of daily ozone from November 1978-December 1994. After an eighteen month period when the program had no on-orbit capability, ADEOS TOMS was launched on August 17, 1996 and provided data until June 29, 1997. Earth Probe TOMS was launched on July 2, 1996 to provide supplemental measurements, but was boosted to a higher orbit to replace the failed ADEOS. Earth Probe continues to provide near real-time data. Total column ozone data over Mt. Abu during 1997-2001 are utilized to investigate a possible association between observed temperature and ozone.

2.8.3 NCEP and ERA-40 Data Sets

The National Center for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis data set providing the temperature and wind information from ground to lower stratosphere at intervals of about 2.5 × 2.5 latitude and longitude resolution [e.g., Kistler, et al., 2001]. Along with NCEP data,
European Center for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) data sets [Kallberg, et al., 2004, Uppala et al., 2005] have also been used in characterizing the event based phenomena double stratopause, stratospheric sudden warming. NCEP wind at different pressure levels have also been used in interpretation of the observed temperature features.