Chapter-III

Description of the Observational Techniques
3.1 Introduction

Waves in the atmosphere can be detected using remote sensing observational techniques. The present chapter outlines the technical characteristics and measurement methods of the ground based and space-borne instruments utilized for this study.

LIDAR (Lidar Detection and Ranging) is another powerful remote sensing techniques to probe the earth’s middle atmosphere. Lidar enables the measurement of the temperature profile in the stratosphere-mesosphere region (~30-80 km) with better accuracy. Lidar allows the measurement of the temperature profile in the stratosphere-mesosphere region (~30-80 km) with better accuracy.

SABER (Sounding of Atmosphere using Broadband Emission Radiometry) is an instrument on bound the NASA’s (National Aeronautics and Space Administration) TIMED (Thermosphere Ionosphere Mesosphere Energetics Dynamics) satellite. The primary goal of the SABER experiment is to provide the data needed to advance the understanding of the fundamental processes governing the energetics, chemistry, dynamics, and transport in the mesosphere and lower thermosphere.

3.2 Measurement Techniques

In the following sub-sections as shown in Figure 3.1, the details of the Airglow (MLTP), Rayleigh Lidar, SABER are discussed.
3.3 Ground based Techniques

As mentioned earlier, studies of the middle atmosphere (particularly the mesosphere) have been limited because of the difficulties in making observations. Weather balloons, radiosonde, reach altitudes of between 20 and 30 km before they pop, thereby preventing measurements at higher altitudes. Radar systems can only make measurements up to at most 25 km or above 60 km and, more typically, 80 km. Airglow is the one of the most important instruments for upper mesosphere measurements. Airglow measurements are confined to several layers above 80 km. For example OH layer at 85 km and O$_2$ layer at 94 km. Details of airglow are given in chapter-II. and The Lidar give full altitude information from 30-80 km.

3.3.1 LIDAR (Lidar Detection and Ranging)

Laser remote sensing of the atmosphere is referred as LIDAR, the acronym for Lidar Detection And Ranging. In Lidar, a laser pulse is sent into the atmosphere and is used as a spectroscopic probe of the atmospheric physical state and chemical composition. The emitted laser beam interacts with the atmospheric constituents causing alterations in the intensity, polarization, and wavelength of the backscattered Lidar. From the measurements of these parameters of the received backscattered Lidar, one can deduce the properties of the atmosphere and its constituents. Lidar allows range resolved
measurement that provides a vertical profile of the atmospheric parameters. The distance of the scattering medium can be deduced with high accuracy from the time delay of the return signal. Using the techniques of scattering, absorption, resonance and fluorescence, Lidar can measure solid particulates such as aerosols, species of very low concentrations such as ozone, water vapor and metal atoms such as sodium, potassium etc. Rayleigh Lidar has become increasingly useful in the study of atmospheric dynamics, allowing observation of geophysical phenomena such as atmospheric gravity waves [Gardner et al., 1989; Mitchell et al., 1991; Wilson et al., 1991a, 1991b; Meriwether et al., 1994; Whiteway et al., 1995], tidal variations [Gille et al., 1991], stratospheric warming’s and planetary waves [Hauchecorne and Chanin, 1982, 1983], mesospheric inversions [Hauchecorne et al., 1987; Whiteway et al., 1995; Ratnam et al., 2001, 2003].

3.3.1.1 Lidar Principle

The fundamental principle of probing the atmosphere by Lidar employs a laser as a source of pulsed energy of useful magnitude and suitably short duration. Typically Q-switched ruby (wavelength=0.69 µm) or Neodymium (wavelength 1.06 µm) laser systems are used to generate pulses having peak powers measured in tens of megawatts in the duration of 10-20 nsec. Pulses with such energy (i.e. of the order 1 joule) are directed in beams by suitable optical systems. Because the laser energy is virtually monochromatic and is highly coherent, such beams are highly collimated.

As the transmitted laser energy passes through the atmosphere, the gas molecules and particles or droplets cause scattering. A small fraction of this energy is backscattered in the direction of the Lidar system and is available for detection. The scattering of energy in directions other than the direction of propagation, or absorption by the gasses and particles, reduces the intensity of the beam, which is said to be attenuated. Such attenuation applies to both the paths (to and fro) of the distant backscattering region.

The Lidar backscattered energy is collected in a suitable receiver using reflective optics and transferred to a photo-detector (commonly, a photomultiplier). This produces an electrical signal, the intensity of which at any instant is proportional to the received Lidar signal power. Since the Lidar travels at a known velocity, the range of the scattering region producing the signal received at any instant can be uniquely determined from the time interval of the sampled signal from the transmitted pulse. The magnitude of the received signal is determined by the backscattering properties of the atmosphere at successive
ranges and by the two-way atmospheric attenuation. Atmospheric backscattering depends upon the wavelength of the laser energy used, and the number, size, shape and refractive properties of the particles (droplets and molecules) intercepting the incident energy. Backscattering from an assemblage of scatterers is a complicated phenomenon; in general, the backscattering increases with increasing scatterer concentrations.

The electrical signal from the photodetector thus contains information on the presence, range, and concentration of atmospheric scatterers. Various forms of presenting and analyzing such signals are available. In the simplest form, they may be presented on an oscilloscope in a coordinate system showing received signal intensity as a function of range. Since such signals are transient, (1 km of the range is represented by an interval of time of ~7 µs), it is necessary to photograph several such oscilloscope displays to obtain adequate data for presentation.

Figure 3.2 Schematic diagram showing the basic principle involved in Lidar probing of the atmosphere.

The schematic diagram of Lidar probing of the atmosphere as shown in Figure 3.2, in which \( P_0 \) represents the laser transmitted pulse energy. If one consider that the scattering...
took place at an altitude $z$, and a factor $T$ attenuates the intensity of the Lidar pulse, then
the radiation scattered in backward is $P_0 T \beta$, where $\beta$ is the backscattering coefficient (sum of Rayleigh scattering by air molecules and Mie scattering by aerosol particles). Since the backscattered radiation travels the same distance $r$ before being detected by the telescope, it further undergoes attenuation by the same factor $T$. Thus the intensity of the backscattered signal detected by the telescope becomes

$$P(r) = \frac{P_0 T^2 \beta A}{r^2} \quad (3.1)$$

where $A$ is the area of the telescope that receiving the backscattered radiation.

Lidars may be configured in two ways; (a) Mono-static configuration in which both transmitter and receiver are collocated. (b) The bi-static configuration in which both the transmitter and receiver are separated by some distance. The next section focuses on the bi-static configuration.

### 3.3.1.2 Lidar Equation

The transmitted laser beam gets scattered in all directions at all altitudes; the backscattered echoes are received by the telescope, and their intensities are measured. The field of view of the telescope is kept larger than beam divergence, to accommodate the beam completely at all altitudes. The received signal intensity is described in terms of the Lidar equation as given by [Fiocco, 1984].

$$P(r) = P_0 \eta \left( \frac{A}{r^2} \right) \left( \frac{ct}{2} \right) \beta(r) \exp \left[ -2 \int \alpha(r) dr \right] \quad (3.2)$$

Where $P(r)$ is the instantaneous power received at time $t$ from an altitude (range) $r$, $P_0$ is the transmitted power, $\eta$ is the system constant which depends on the transmitter and receiver efficiencies. $A$ is the area of primary (collecting) mirror of the receiving telescope. The term $\left( \frac{A}{r^2} \right)$ is the solid angle subtended by the primary mirror at the range $r$. This simple expression for solid angle is applicable for monostatic only because all the transmitted energy contributes to the backscattered signal from the range $r$. The term $\left( \frac{ct}{2} \right)$ gives the length of the illuminated path, which contributes to the received power, where $c$ is the velocity of Lidar and $\tau$ is the pulse duration of the laser beam.
The term \( \frac{ct}{2} \) determines the minimum spatial resolution available in the direction of the beam propagation. In the transverse direction the spatial resolution depends on the laser beam width at particular altitude. In a typical Lidar system the pulse duration of the laser beam is of the order of few nanoseconds and the beam divergence is less than a milliradian, which corresponds to a scattering volume of a few cubic meters. This is the greatest advantage of the Lidar technique which is not possible by any other atmospheric remote sensing technique.

\( \beta(r) \) is the volume backscattering coefficient of the atmosphere at range \( r \). It gives the fractional amount of the incident energy scattered per steradian in the backward direction per unit atmospheric path length and has the dimension of \( \text{m}^{-1} \text{sr}^{-1} \). \( \alpha \) is the volume attenuation coefficient of the atmosphere and has the unit of \( \text{m}^{-1} \), defined as twice the integral between the transmitter and the scattering volume to obtain the net transmission.

The term \( \alpha \) and \( \beta \) include the contribution from air molecules, aerosols, and the other atmospheric species. The problem related with the Lidar equation is that it contains two unknowns, \( \alpha \) and \( \beta \), which make it difficult to obtain the general solution. Appropriate inversion methods \cite{Fernald et al., 1984; Klett, 1981, 1985} have been developed to solve the equation. The Lidar equation, however, assumes only single scattering. Contribution arising from multiple scattering is important for high turbidity cases such as clouds and fogs.

### 3.3.1.3 Lidar Scattering or Absorption Mechanisms

As the radiant energy passes through the atmosphere, it undergoes transformations like absorption and scattering. Absorption (or emission) of radiation takes place when the atoms or molecules undergo a transition from an energy state to another. Scattering is the deflection of incoming solar radiation in all directions. Scattering of radiation depends to a large extent on particle size. If \( I_0 \) is the intensity of the incident monochromatic flux propagated through an absorbing medium and if \( I \) is the amount of flux present after traveling a distance \( l \), then

\[
I = I_0 e^{-\alpha l} \quad (3.3)
\]

\[
dI = -I\alpha dl \quad (3.4)
\]

(Or)

\[
dI = -\sigma n dl \quad (3.5)
\]
Where $\alpha$ is the extinction (absorption plus scattering) coefficient and $\sigma$ is the respective cross-section; $n$ is the concentration of particles which cause extinction. Figure 3.3 illustrates the basic processes of transmission and scattering of Lidar.

\[
I_t = I_0 e^{-\alpha nl}
\]

\[
I_s = I_0 \sigma r_0 n l \alpha
\]

Figure 3.3 Schematic diagram to explain the transmission and scattering of Lidar, the two important processes on which the Lidar principle is based.

There are several scattering or absorption mechanisms that occur when the laser energy interacts with the atmosphere. The predominant scattering is quasi-elastic scattering from aerosols (Mie scattering) or molecules (Rayleigh scattering).

3.3.1.4 Rayleigh Scattering

In 1890’s Lord Rayleigh showed that the scattering of Lidar by air molecules is responsible for the blue colour of the sky. The size of the scatterer is small compared to the wavelength of the incident radiation and a dipole is induced within the scatterer. Rayleigh scattering mainly consists of scattering from the atmospheric gasses. This type of scattering is therefore wavelength dependent. As the wavelength decreases, the amount of scattering increases. The induced dipole is in the same direction as the incident electrical vector, its moment proportional to the field and phase same as that of the incident field. Electromagnetic theory shows that the dipole radiates a polarized wave with one component of the amplitude falls off as $r^{-2}$ ($r$ being the distance from the dipole), and the other falls off as $r^{-1}$. The $r^{-2}$ dependence is valid only near the immediate vicinity of the dipole. To obtain the scattered electromagnetic field at a point $p$, is convenient to resolve the field into two components, one lying in the scattering plane ($E_i$) and the other
perpendicular (E,.) to the scattering plane. The arbitrary incident electrical vector can be written as

\[(E_{or} + E_{ol})e^{tot} \tag{3.6}\]

At point, p the dipole Eor gives a field component,

\[E_r = \left[\frac{4\pi^2}{\lambda^2 r}\right] \exp\left[i\omega\left(t - \frac{r}{c}\right)\right] E_{or} \tag{3.7}\]

and the dipole Eol gives a field component,

\[E_l = \left[\frac{4\pi^2}{\lambda^2 r}\right] \exp\left[i\omega\left(t - \frac{r}{c}\right)\right] E_{ol} \cos\theta \tag{3.8}\]

hence, the intensity of the scattered radiation becomes,

\[I_0 = |E^2| = \left[\frac{16\pi^16}{\lambda^4 r^2}\right] \Omega^2(1 + \cos^2\theta)I_0 \tag{3.9}\]

Where \(\theta\) is the scattering angle, \(\omega\) is the frequency of the incident radiation, \(c\) is the velocity of Lidar, \(\Omega\) is the polarizability of the scatterer and \(r\) is the distance between the scatterer and the point under consideration.

Addition to the fact above, the Rayleigh scattering process marked by several characteristics such as

- The intensity of scattering Lidar varies nearly as the inverse of a fourth power of interactive wavelength.
- Rayleigh scattering is directly proportional to the sixth power of the radius of the scatter and proportional to the cube of the volume of the scatter.
- The backward scattered energy equals to that of the forward direction.
- The Rayleigh scattering cross-section at 532 nm laser wavelength is \(5.235 \times 10^{-27}\) cm\(^2\).

3.3.1.5 System Description of LIDAR

The Rayleigh Lidar at the NARL (National Atmospheric Research Laboratory), Gadanki has been in operation since 1998. The system comprises the following subsystems:

1. Transmitter section,
2. Receiver section
3. Data acquisition section

The Lidar system uses the second harmonic output of the laser source at 532 nm with a maximum energy of about 550 mJ per pulse. The laser operates at a pulse width of 7
ns with a repetition rate of 50 Hz. The laser optical properties are specified as 0.45 mRad for divergence and 1 cm-l for line-width and 9 mm for beam size. A functional block diagram of Lidar system is shown in Figure 3.4.

3.3.1.5.1 Transmitter section

The laser transmitter employs a PL9050 model Nd:YAG pulsed laser (solid state laser) from Continuum, USA. The laser head is of modular design incorporating a rod, flash-lamp(s) and coupling medium. The flash lamps are surrounded by a diffuser (magnetic oxide) which results in a high pumping efficiency that minimizes thermal loading and reduces power consumption. The important specifications for the Lidar transmitter are given in Table 3.4. A detailed description of the important sub-systems of the laser transmitter is

Figure 3.4 A functional block diagram of Lidar system

3.3.1.5.1.1 Nd-YAG Laser

Neodymium (Nd) impurity ion concentration in the Yttrium Aluminum Garnet (YAG) crystal constitutes the active ingredient in the generation of the laser radiation. The system uses a four-level solid-state laser (Nd: YAG) and because of the narrow line
widths, the stimulated emission cross-section is large and the pumping threshold is low. The impurity embedded YAG crystal is optically pumped over a wide band of energy using a flash lamp. The doping levels vary from 0.9 to 1.4 %.
The YAG rod-ends have hard dielectric anti-reflective coating. The rod length is about 115 mm measured along the optical axis. Each intense flash of optical energy pumps a broad absorption band of the medium. Nd:YAG lasers operate at fixed wavelength of 1064 nm. A second and third harmonic conversions are sometimes required with Nd:YAG laser sources where the primary wavelength (1064 nm) is of limited use in the application. In such a case, the second and third harmonic generations are accomplished using suitable non-linear crystals such as Potassium (K) Di-hydrogen Phosphate (KDP). The efficiency of this conversion depends upon the quality of crystal, irradiant and coherence properties of the crystal.

3.3.1.5.1.2 Flash lamps

The linear flashlamps with a voltage polarity is used in the cavity. The discharge system of the flashlamps uses a negative critically damped pulse (-1.8 kV max) with duration of 200 µs as Full Width at Half Maximum (FWHM). The gas utilized in the flashlamps is xenon with a pressure of 1-3 atmospheres. The laser heads are designated for a beam height of 43 mm. Flashlamps and laser rods are cooled by distilled, deionised water. The resistivity of water should not fall below 500 kΩ/cm.

3.3.1.5.1.3 Q-Switch

Q-switch is used to obtain high-peak-power, short-duration laser pulses by controlling the loop gain of the optical cavity of the laser. A Q-switch is essentially a very fast shutter located between the active medium and the high reflective (HR) mirror. This shutter is closed during pumping to reduce the loop gain to zero and prevent lasing. Since there is no lasing to deplete the population inversion, energy stored in the active medium and amplifier gain both reaches to high values. The Q-switch, the shutter is then opened, producing a very high loop gain. The resulting high-intensity standing wave uses most of the energy stored in the laser active medium to produce one giant pulse. The optical components employed in Q-switch are Pockels Cell, Plate Polarizing element, and Quarter-Wave Plate.

The Pockels Cell (PC) has a longitudinal field KDP crystal with 15 mm clear aperture mounted at 43 mm beam height. A voltage of 3600 V applied to the Pockels Cell
results in a quarter wave of polarization rotation to the beam making a double pass through Pockels Cell (PC).

The thin film multilayer dielectric polarizer has an angle of incidence of 57° (Brewster angle). For this angle of incidence, the polarizer is highly transparent (> 95 %) to horizontal while being highly reflective (>99 %) to vertical. The contrast/extinction ratio is > 500:1.

The quarter wave plate is used to introduce a quarter waves (90°) of polarization rotation as the beam makes a double pass through the plate. The plate has a clear aperture of 15 mm and is mounted at a beam height of 43 mm.

The electrical components employed in Q-switch are timed pulse generated by the control unit, Marx board and Power board.

The control unit tracks the firing of the flashlamps in the laser head and then at a pre-selected delay of ~200 µs triggers the Marx board with a +15 V pulse. The signal is normally set to fire at the peak of the gain curve to the oscillator YAG rod. The Marx board charges seven capacitors in parallel and then discharges through fast switching transistors in series so that the voltage on each capacitor is summed. This generates a ~4 kV pulse with a rise time of 20 ns.

The power board generates the DC voltage (~750 V) necessary to power the Marx board. The DC voltage is adjustable by a potentiometer accessible through a hole in the top of the laser bench.

3.3.1.5.1.4 Cavity

The beam propagating within the oscillator cavity makes a double pass through the PC and quarter-wave plate. At 0 volts on the PC, it adds no rotation while the quarter-wave adds 45° with each pass, giving a total rotation of 90°. Thus, the horizontal beam that transmitted through the plate polarizer is rotated to vertical and is rejected by the polarizer and no oscillation occurs. At 3600 volts on the PC, it adds 45° rotation and the quarter wave adds 45° with each pass giving a total rotation of 180°. The plate polarizer, with a beam incident at Brewster angle, passes the horizontal polarization and reflects the vertical. The horizontal polarization rotates by either 90° or 180° when the beam makes a double pass through the combination of Pockels Cell and quarter wave plate depending on whether the Pockels Cell is activated or not. When the rotation is 90°, the polarization of the beam incident on the plate polarizer is vertical, and it is reflected away making the
Description of the Observational Techniques

laser cavity closed for lasing. When the rotation is $180^0$, the beam polarization is back to horizontal, and it passes through the plate polarizer making the cavity open for lasing.

### 3.3.1.5.1.5 Second Harmonic Generation

The technique of second harmonic generation (or frequency doubling) is a popular method of extending the normal operating frequency range of a LASER. As its name implies, it enables the output frequency to be doubled (that is, the wavelength to be halved). Thus the output of the Nd:YAG LASER at 1.064 µm can be frequency doubled to give 0.532 µm radiation. The simplest technique for second harmonic generation is to focus the output from the laser onto a suitably oriented (for phase matching purposes) nonlinear crystal. The crystals need to be of a very high optical purity to eliminate any additional cavity losses due to scattering within the crystal.

### 3.3.1.5.1.6 Beam Expander

The visible green color laser beam is made to pass through a beam expander (expand 10 times), before the laser beam is allowed to send into the sky. Hence, the transmit beam divergence is reduced from 0.45 mRad to less than 0.1 mRad. The expanded beam of 90 mm width is made to fall on a steering mirror, which is a hard coated flat type mirror with the dimensions of 154 mm diameter and 25 mm thickness oriented at 45 degrees to the beam axis. The mirror is provided with azimuth and elevation controls to align the transmit beam axis to receive beam axis.

### 3.3.1.5.1.7 Control Unit

The control unit (CU601) is a microprocessor-based system, which provides hardware interfaces and commands to and from the cabinet components and laser bench. The remote box (RB601) that plugs into the front panel of the CU601, which allows the user to enter commands on a keyboard and view responses on an alpha-numeric liquid crystal display (LCD). The user may also control the CU601 through an RS232 interface on the front panel. The CU601 initiates charging of the capacitor banks using signal exchange with the power units under control. The CU601 also provides cooling group interlocks, which sense water temperature, water level, and water flow. A cooling group interlock violation halts the laser operation and reports the interlock violation to the remote box. During a charge sequence, the charge command is sent to the power unit to charge the capacitor banks. The CU601 then locks for an End of charge (EOC) signal from the power
units. When all EOC signals are received, the CU601 then is ready to send a fire command. If the CU601 fails to receive an EOC, the CU601 reports an “EOC failure” to the remote box and halts any further fire commands.

3.3.1.5.1.8 Cooling System

The cooling system is one of the most critical subsystems in the laser. The coolant is usually refrigerated, but water-to-water or water-to-air heat exchanger may also be employed. NESLAB, USA makes water refrigerated circulator used for pumping the water through the amplifier and oscillator heads at 60 kg/cm² pressure and also for monitoring the temperature of water at 19°C. The cooling fluid circuit begins with the laser rod for maximum rod cooling. The water then flows across the lamps and the laser cavity. A flow switch is included to turn off the lamp power if the water flow is interrupted. Loss of cooling will quickly destroy seals, lamps, and the laser rod itself.

3.3.1.5.2 Receiver subsystems

The receiver subsystem employs two independent receivers to receive Rayleigh and Mie backscattered signals from the atmosphere. The Rayleigh receiver is used for collecting the backscattered Lidar from the air molecules and operates in the range of 30 to 90 km, whereas the Mie receiver is used for collecting the backscattered Lidar from the particles such as aerosols, hydrometeors, clouds etc., in the range of 4 to 40 km. The main specifications of both the receivers are given in Table 2.2. A detailed description of the two receiver sub-systems is given below.

3.3.1.5.2.1 Rayleigh Receiver

Rayleigh receiver employs a vertical Newtonian type telescope with a field of view (FOV) of 1 mrad for collecting the molecular backscattered photons. The primary mirror is a concave mirror of the effective diameter of 750 mm with a focal length of 2372 mm. This mirror has a hole at the center with a diameter of 160 mm. The thickness of the mirror is 84 mm, and the surface accuracy is better than half of the Lidar wavelength. The mirror is coated with a film of Cr+Al+Sio on a convex surface. The secondary mirror is a plane mirror of the diameter of 250 mm oriented at 45 degrees to the receive optics beam axis facing the primary mirror. The secondary mirror focuses the beam at field stop iris which, in turn, falls on a collimating lens. The collimating lens directs the beam to an interference
filter (IF), with FWHM of 1.07 nm which rejects much of the background Lidar and passes only the monochromatic spectrum at 532 nm wavelength. This band-limited Lidar is made to fall on a non-polarizing beam splitter. This beam splitter splits the beam into two equal halves and made to fall on the cathode surface of a head-on type of photomultiplier tubes (PMTs) aligned along the beam axis and fixed to the beam splitter assembly. The Rayleigh receiver employs R3234-01 model Hamatsu, Japan makes, low noise type photo multiplier operated at 25°C. As the scattered Lidar from the molecules being very small, the PMTs are operated in photon counting mode, A high gain PMT (R) (Sl. No. WA 0059) is used for collecting the molecular backscattered photons from the height range of 50 to 80 km, whereas the other PMT (Sl. No. WA0062) of low gain (U) is used for the range of 30 to 50 km. Both the PMTs work at a high-tension (HT) potential of –2 kV. These PMTs are kept in the magnetic shield enclosure to avoid the exposure to external fields.

The PMTs are delayed or gated by the duration of 80 µs; this is achieved by applying a positive pulse of +197 volts. It is being done to prevent the loading of PMTs from the large amount of back-scattered photons that arises from the lower atmosphere. The outputs drive-Philips makes pulse discriminators which contain 300 MHz pulse amplifier with a threshold adjustable compactor and a shaper circuit. These discriminators operate with no dead time for coincidence applications. It has a 15-turn potentiometer adjustment for a threshold that provides a pulse width increment from 2 ns to 50 ns for corresponding threshold adjustments from –1 mV to –100 mV. It has a veto input, which accepts a Network Interface Machine (NIM) standard level pulse that inhibits the function of the discriminator. The output of the discriminator is a current source type, which drives long cables with narrow pulse widths at –32 mAs. The output of pulse discriminators is connected to a PC-based photon counting data acquisition system operating under an EG & G Multi-Channel Software (MCS).

### 3.3.1.5.3 Data Acquisition and Signal Processing

MCS records the counting rate of events as a function of time. When a scan starts, the MCS pulse begins counting the input events in the first range bin of its digital memory. At the end of the pre-selected dwell time, the MCS advances to the next range bin 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 memory contents 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. A flow diagram showing the online processing of data is given in Figure 3.5. The MCS is a powerful software operating under windows allowing all controls and spectral manipulations to be implemented via an on-screen display. A dual port memory on the card permits quick computer access to the spectral data for display purposes, without interrupting data acquisition by MCS-plus.

The MCS plus works with dwell times ranging from 2 µs to 1800 sec and a maximum memory length of 8192 channels with input counting rates up to 100 MHz with an external trigger. With an internal trigger, the system can operate with a minimum dwell time of 1 µs. For improving the signal to noise ratio, the number of laser shots can be set to any value from 1 to 4294967295 with a memory capacity of 16777215 counts per channel. The MCS plus accepts negative NIM standard logic levels for photon counting.

![Flow diagram showing the online data processing](image)

*Figure 3.5 Schematic showing the online data processing*
The limited signal processor specifications are presented in Table 3.1. Presently the MCS-plus PC-based photon count system is working with four data acquisition channels, two from Rayleigh receiver designated as R & U photon counting with 5000 shots average (summation) with range resolution (dwell time of 2 µs) of 300 m. The MCS-plus records 5000 lasers shots integrated photon count profile as one frame with a time resolution of
250s. A sample photon count profile obtained from four different channels of Rayleigh receivers are presented in Figure 3.6 & 3.7.

### 3.3.1.5.4 Rayleigh Lidar system brief specifications

<table>
<thead>
<tr>
<th>Rayleigh Lidar Transmitter</th>
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<tbody>
<tr>
<td>Laser Source</td>
<td>Nd:YAG</td>
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<td>Software</td>
<td>4 channel PC based data acquisition system Operating with EG &amp; G ORTEC MCS software</td>
</tr>
<tr>
<td>Bin width</td>
<td>2 µsec – 1800 (*2 µsec)</td>
</tr>
<tr>
<td>Scan length</td>
<td>4-8192 channel (*1024 channel)</td>
</tr>
<tr>
<td>Maximum laser shots</td>
<td>16,77,215</td>
</tr>
<tr>
<td>Integration time</td>
<td>250 sec (corresponding to 5000 laser shots)</td>
</tr>
</tbody>
</table>

*Table 3.1 Rayleigh Lidar system specifications*
3.3.1.5.5 Method of Analysis for Rayleigh Lidar Temperature Retrieval

The method of analysis adopted for the determination of temperature profile closely follows that given by Hauchecorne and Chanin [1980]. In the height range 30-80 km, where Mie contribution is negligible, the range and atmospheric transmission corrected signal intensity is proportional to the number molecular density. Using the number density taken from an appropriate model (CIRA-1986) for the height of 50 km where the signal-to-noise ratio is fairly high, the constant of proportionality is evaluated and thereby the density profile is derived. Taking the pressure at the top of the height range (90 km) from an atmospheric model, the pressure profile is computed using the measured density profile, assuming the atmosphere to be in hydrostatic equilibrium. The model atmosphere used for the purpose is CIRA-86. Adopting the perfect gas law, the temperature profile is computed using the derived density and pressure profile.

\[ \rho(z) = \frac{C[S_L(z) - B(z)]}{t^2(z, \alpha)} \]  

(3.10)

Where \( S_L(z) \) is the range corrected signal intensity, \( B(z) \) is the signal due to dark current and sky background, \( t(z, \alpha) \) is the atmospheric transmittance between \( z \) and the top of the atmosphere and \( C \) is the normalization constant.

The air pressure \( P(z) \), density \( \rho(z) \) and temperature \( T(z) \) are related by

\[ P(z) = \frac{RT(z)\rho(z)}{M} \]  

(3.11)

Where \( \rho(z) \) density at an altitude \( z \) and \( M \) is the mean molecular weight of air. According to the hydrostatic equilibrium, the acceleration due to gravity in terms of density and pressure gradient is given by

\[ g(z) = \left[ -\frac{1}{\rho(z)} \right] \frac{dp}{dz} \]  

(3.12)

or \[ dP(z) = -\rho(z) g(z) \, dz \]

Hence

\[ \frac{dP}{P} = \left[ \frac{Mg(z) \, dz}{RT(z)} \right] \]  

(3.13)

but \[ d[\log P(z)] = \frac{dP(z)}{P(z)} \]

Hence eqn (2.9) becomes
\[ d[\log P(z)] = - \frac{[M_g(z)dz]}{RT(z)} \quad (3.14) \]

\[ \frac{P(z - \frac{dz}{2})}{P(z + \frac{dz}{2})} = \exp \left[ \frac{M_g(z)dz}{RT(z)} \right] \text{ or } \log \left( \frac{P(z - \frac{dz}{2})}{P(z + \frac{dz}{2})} \right) = \frac{M_g(z)dz}{RT(z)} \quad (3.15) \]

\[ T(z) = \left[ \frac{M_g(z)dz}{R \log(1 + X)} \right] \text{ Where } X = \left( \frac{\rho(z)g(z)dz}{P(z + \frac{dz}{2})} \right) \quad (3.16) \]

The temperature profile can be obtained using the above Equation 3.16 and the uncertainty in temperature is found to be 15% at 90 km where the pressure is assumed. The pressure contribution to the temperature uncertainty decreases rapidly with altitude, and it seems to be smaller than 2% at 15 km below the top, i.e.,

\[ \frac{\delta T(z)}{T(z)} = \frac{\delta[\log(1 + X)]}{\log(1 + X)} = \frac{\delta X}{(1 + X)\log(1 + X)} \quad (3.17) \]

With

\[ \left( \frac{\delta X}{X} \right)^2 = \left( \frac{\delta \rho(z)}{\rho(z)} \right)^2 = \left( \frac{\delta P(z + \frac{dz}{2})}{P(z + \frac{dz}{2})} \right)^2 \quad (3.18) \]

Initially, the atmospheric temperature is independently computed using the relative densities derived from the R and U channels. Then the composite temperature profile is constructed using data from low sensitive channel (U) for the altitude below 45 km, the high sensitive channel (R) above 55 km, and utilizing both channel’s data (R and U) between 45-55 km. This region of 45-55 km employs the numerical weight function with convex convergence technique. The convex convergence technique is used when two simultaneous measurements are made to converge the results and to reduce the error in measurement [James and James, 1968]. Using the weighting factors, the temperature and standard error for the transition region are expressed as:

\[ T_{(45-55)}(z) = \frac{[T_R(z) * \delta T_U(z)] + [T_U(z) * \delta T_R(z)]}{[\delta T_R(z) + \delta T_U(z)]} \quad (3.19) \]

\[ \delta T_{(45-55)}(z) = \frac{[T_R(z) * \delta T_U(z)] + [T_U(z) * \delta T_R(z)]}{[T_R(z) + T_U(z)]} \quad (3.20) \]
Where \( T_{(45-55)} (z) \) and \( \delta T_{(45-55)} (z) \) stand for the temperature and standard error for the height region of 45 to 55 km, \( T_R(z) \) and \( \delta T_R (z) \) are the temperature and standard error derived from R channel and \( T_U (z) \) and \( \delta T_U (z) \) are from the U channel. Any change in the pressure taken at the top reference level and the model density taken at the normalization level will lead to corresponding changes in the temperature determination.

3.4 Space borne Technique

One of the most important technique is space borne (satellite measurements) its technique validation for all ground-based information low and high altitudes.

3.4.1 SABER

The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) experiment was launched on the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite on 7 December 2001. SABER began routine operations in January 2002 and data available from March 2002 onwards. The primary goal of SABER has been to obtain profile measurements of parameters and species related to the thermal structure and energetics of the upper mesosphere and lower thermosphere (UMLT) region of the atmosphere. To achieve that objective, its infrared limb radiance profiles need to be free of instrument effects and registered accurately throughout the middle atmosphere (~10 to 100 km), prior to the retrieval of its primary geophysical quantities. Because the SABER measurement and retrieval concept has its heritage from the Nimbus 7 Limb Infrared Monitor of the Stratosphere. The SABER views the atmosphere \( 90^0 \) to the satellite velocity vector in a 625 km and \( 73^0 \) inclination orbit so that latitude coverage on a given daily longitude-versus-latitude coverage for the SABER tangent point locations vary along the orbit from \( 83^0 N \) to \( 53^0 S \) for the north viewing, the yaw mode of the spacecraft, as shown in Figure 3.8.

The SABER north viewing mode extends for 60 to 63 days. The spacecraft is turned to its south viewing mode for other 60+ days, and then the entire viewing sequence is repeated. The tangent track pattern of Figure 3.5 flips top to bottom for the SABER south viewing mode. Thus, there is essentially continuous coverage for the latitudes of \( 52^0 N \) to \( 52^0 S \), while the higher latitudes are viewed for alternating 60+ day periods. Yaw events occur on nearly the same dates for each succeeding year.
Vertical profiles of retrieved temperature as a function of pressure, hereinafter $T(p)$, and their derived Geopotential height and wind distributions were presented for an initial, local thermodynamic equilibrium or LTE Version 1.01 (V1.01) of the SABER data of Remsberg et al. [2003]. Climatological profiles of the minor interfering and unobserved species were obtained from the model of Garcia and Solomon [1994].

Although those early results were shown to be of good quality, some important improvements were made for the calibration and the conditioning of the observed radiances in V1.02 through V1.04 [Mertens et al., 2002, 2004]. Non-LTE (NLTE) algorithms for kinetic temperature ($T_k$) were employed in V1.03 [Lopez-Puertas et al., 2004] and in the next two public data versions, V1.04 and V1.06 [Mertens et al., 2004, 2008]. Both of those public versions made use of an iterative algorithm for the retrievals of both $T_k$ and CO$_2$ during daytime, but obtained CO$_2$ from the Thermosphere-Ionosphere-Mesosphere Electrodynamics General Circulation Model (TIME-GCM) [Roble and Ridley, 1994] for nighttime. V1.04 employed profiles of O($^3$P), O($^1$D), and other neutral molecules from TIME-GCM for its retrieval of $T_k$. V1.06 used SABER-derived values of O ($^3$P) and O ($^1$D); however, in the thermosphere those values were obtained from the Mass Spectrometer Incoherent Scatter model, MSIS-90, of Hedin [1991]. Some improvements
were made in the calculation of the forward radiances and for the registration of the observed radiances with pressure altitude for V1.06. They included the addition of line mixing for the 15-mm CO\textsubscript{2} band models and the use of an average interleave procedure for profile registration (see later). In addition, much less smoothing was employed in the calculation of the vibrational temperatures below 100 km and for the retrieval of T\textsubscript{k}.

The SABER V1.07 CO\textsubscript{2} channel radiances and its retrieved T(p) for the stratosphere and lower mesosphere (below 65 km), where the forward radiance model is based on LTE assumptions. Next, the V1.07 results from the more complex, NLTE model are evaluated in terms of the retrieval of T\textsubscript{k} above 65 km and through the UMLT region; previous assessments of the SABER NLTE algorithms and T\textsubscript{k} can be found in the work of Mertens et al. [2001, 2002, 2004] and in the work of Kutepov et al. [2006]. There were inconsistencies in the vertical structure of the diurnal temperature, tides from V1.04 and V1.06 because their daytime CO\textsubscript{2} values were retrieved while their nighttime profiles were from a model. There were also computational instabilities introduced by the NLTE forward model for the 4.3-mm CO\textsubscript{2} radiance, leading to large differences in the solutions from one retrieval interleave to the next. Attempts to screen such occurrences resulted in far too many profiles being rejected. It is noted that very little of the radiance for this channel comes from tangent layers near the mesopause. Instead, the V1.07 T\textsubscript{k} has been obtained for both day and night using monthly and diurnally averaged CO\textsubscript{2} profiles from the distributions with latitude in the Whole Atmosphere Community Climate Model (WACCM) [Garcia et al., 2007]. A detailed description of the V1.07 NLTE algorithm and estimates of the error for T\textsubscript{k} are explained elsewhere [M. Garcia-Comas et al., 2007].

The method of deriving kinetic temperatures from CO\textsubscript{2} emissions is detailed by Mertens et al. [2001]. One of the main difficulties is the determination of kinetic temperatures under conditions of nonlocal thermodynamic equilibrium (non-LTE), which pertains above about 70 km altitude. In the SABER version V1.04 temperatures analysed here, non-LTE retrievals of T\textsubscript{k} incorporate simultaneous determinations of CO\textsubscript{2} densities from the CO\textsubscript{2} 15 mm emission. This eliminates a major source of uncertainty since CO\textsubscript{2} is not well mixed above 75 km and, therefore, cannot be specified in terms of a volume mixing ratio. The CO\textsubscript{2} determinations, however, contain uncertainties connected with the knowledge of atomic oxygen densities and the rate of CO\textsubscript{2} vibrational quenching. As noted by Forbes et al. [2006], unmodeled atomic oxygen variations can also introduce errors into the retrieved temperatures, and for this reason results above 100–110 km contain
errors of unknown magnitude due to this source and should be viewed with due caution. However, we can say that no unusual or unexpected tidal behaviour is evident in any of our results up to 120 km. In the future, we hope to validate better temperatures in the region above 100 km and eventually to recover atomic oxygen densities from other SABER measurements and to eliminate nearly any associated uncertainties in the temperature retrievals.