CHAPTER II

Instrumentation and Data

2.1 Interaction of electro-magnetic waves with the atmosphere

Any type of electromagnetic wave (EM) propagating through the atmosphere is affected by air molecules or particles (aerosols) of the atmosphere because of their interaction with radiation. The interactions fall into three categories; (i) scattering, (ii) absorption, and (iii) emission.

2.1.1 Atmospheric scattering

Scattering is the redirection of electromagnetic radiation by particles suspended in the atmosphere or by large molecules of atmospheric gases. The amount of scattering depends upon the size of the particles, their abundance, the wavelength of radiation, depth of the atmosphere through which the energy is traveling and the concentration of the particles. The concentration of particulate matter varies both in time and over season. Thus the effects of scattering will be uneven spatially and will vary from time to time. Theoretically scattering can be divided into three categories depending upon the wavelength of radiation being scattered and the size of the particles causing the scattering. The three different types of scattering from particles of different sizes are described below.

2.1.1.1 Rayleigh Scattering

Rayleigh scattering predominates where electromagnetic radiation interacts with particles that are smaller than the wavelength of the incoming light. The effect of the Rayleigh scattering is inversely proportional to the fourth power of the wavelength. Shorter wavelengths are scattered more than longer wavelengths. In the context of remote sensing, Rayleigh scattering is the most important type of scattering. It causes a distortion of spectral characteristics of the reflected light when compared to measurements taken on the ground.
2.1.1.2 Mie Scattering

Mie scattering occurs when the wavelength of the incoming radiation is similar in size to the atmospheric particles. These are caused by aerosols; a mixture of gases, water vapor and dust. It is generally restricted to the lower atmosphere where the larger particles are abundant and dominates under overcast cloud conditions. It influences the entire spectral region from ultra-violet to near-infrared regions.

2.1.1.3 Non-selective Scattering

This type of scattering occurs when the particle size is much larger than the wavelength of the incoming radiation. Particles responsible for this effect are water droplets and larger dust particles. The scattering is independent of the wavelength, all the wavelength are scattered equally.

Apart from these scattering, other types of scattering also exist, which is called as clear-air scattering. A brief description about these is given below.

2.1.1.4 Bragg Scattering

Bragg scatter or turbulent scatter is the primary source for UHF/VHF echoes from clear air atmosphere. The basic theory of radio wave scattering by turbulent fluctuations of the atmosphere was developed originally by Booker and Gordon (1950) to explain ‘Over The Horizon’ (OTH) troposphere radio propagation. According to the theory, radar backscatter signal arises from irregularities in the refractive index of length scale equal to one half of the radar wavelength. Hence in order to have coherent backscatter, the condition to be satisfied is

$$\lambda_{\text{min}} < \frac{\lambda}{2} < \lambda_{\text{max}}$$

where, $\lambda_{\text{min}}$ and $\lambda_{\text{max}}$ are related to the inner or Kolmogorov Scale ($\xi$) and outer scale (Lo) of the turbulence and $\lambda$ is radar probing wave length. Kolmogorov’s theory describes how energy is transferred from larger to smaller eddies, how much energy is contained by eddies of a given size and how much energy is dissipated by eddies of each size. In the inertial subrange, energy is neither produced nor dissipated but handed down to smaller and smaller scales. Coherent backscatter occurs from the refractive index fluctuations with scale sizes $\sim \lambda/2$. Hence we get a strong signal as the scale size dominantly exists in the inertial subrange.
2.1.1.5 Fresnel (partial reflection) Scattering

The echoing process that involves spatial coherence of fluctuations transverse to the radar beam is referred to as Fresnel reflection or scattering. This process is mainly due to sharp gradients in radio refractive index. Fresnel reflection/scattering occurs from horizontally stratified refractive index gradients in the neutral atmosphere of troposphere and stratosphere (Gage and Green, 1978; Röttger and Liu, 1978) and electron density stratification in the mesosphere (Fukao et al., 1980). At any particular height whether the echoing mechanism is reflection or scattering depends on the horizontal layer structure. "Fresnel reflection" (Röttger and Larsen, 1990) is observed if a signal arises from prominent discontinuity of the refractive index in vertical direction whereas "Fresnel scattering" (Gage et al., 1981; Hocking and Röttger, 1983) occurs from randomly distributed refractive index discontinuities in vertical direction, which exist in a range gate. It means that Fresnel reflection is a single layer concept whereas Fresnel scattering is a multi layer concept and it is a kind of volume scattering that leads to specular echoes.

Fresnel reflection process is also sometimes referred to as "Partial reflection" because only a very small fraction of the incident power gets reflected. Occurrence of Fresnel reflection/scattering is more likely for longer radar wavelengths, i.e. in the lower VHF range. The concepts of Fresnel reflection and scattering have been introduced to indicate that the horizontal correlation distance of the discontinuities is of the order of the first Fresnel zone dimension \( \left( \frac{R \lambda}{2} \right)^{1/2} \), where \( R \) is the distance between the radar and the radar backscatter volume and \( \lambda \) is the radar wavelength. The spectral width is narrow due to sharp vertical gradient in the radio refractive index. This particular feature can be utilized to distinguish these echoes from those arising due to the refractive index irregularities associated with turbulence.

2.2 Radar probing of the atmosphere

RADAR (Radio Detection And Ranging) proved to be a potential instrument to study the atmosphere. In atmospheric studies using radar, the targets are the refractive index irregularities and particles such as hydrometeors present in the Earth's atmosphere.
The clear air echoes are extremely weak in nature and other echoes which are due to scattering by dust and biota (largely insects and birds feeding on these insects) can sometime mask these. Radar used for lower atmospheric studies can be classified as clear air radars or weather radars depending upon the echoing mechanism and probing frequency. Clear air radars are operated in VHF and UHF frequency bands and receive echoes mainly from the refractive index irregularities in the atmosphere, which depend on variations in temperature, pressure and humidity. These irregularities could be generated due to atmospheric turbulence and/or stable layers in the atmosphere (Balsley and Gage, 1980; Gage and Balsley, 1980; Röttger and Larsen, 1988; Doviak and Zrnic, 1993). This turbulence is referred to as Clear Air Turbulence (CAT). Weather radar which is normally operated at 3 or 5 GHz frequencies receive echoes from hydrometeors and are useful to study precipitation, clouds, thunderstorms, cyclones etc. There are a number of clear air radars around the world which are operated in the VHF frequency band near 50 MHz. These radars are high power VHF radars known as MST radars since they detect clear air echoes all the way from Troposphere to Stratosphere to Mesosphere (e.g., Jicamarca radar (49.9 MHz) in Peru, MU radar (46.5 MHz) in Japan, MST radar (53 MHz) in India, Chung-Li radar (52 MHz) in Taiwan, Poker flat MST radar (49.9 MHz), Soucy radar (53.5 MHz) in Germany, EAR (47 MHz) in Indonesia).

Ultra High Frequency (UHF) radars are extremely sensitive to Rayleigh scattering from birds, insects and precipitation. In the presence of these targets in the lower troposphere, interpretation of UHF radar data becomes complex. In the presence of precipitation which often occurs in the lower troposphere, determination of clear air parameters viz., winds and turbulence become difficult due to the presence of strong hydrometeor echoes. In such scenario, the role of VHF radars becomes significant, since, the VHF radars are much less sensitive to the hydrometeors.

The use of UHF wind profilers to observe boundary layer and lower troposphere has accelerated in the past two decades. The earlier profilers typically operated at frequencies around 915 MHz (Strauch et al., 1984) with height coverage from 350 m to less than 10 km. Concurrent development of a 404 MHz profiler by NOAA, for use in a demonstration network occurred during the same period. The coverage of the 404 MHz profiler is from about 500 m to 16.2 km (Frisch et al., 1986). In India UHF wind profiler
operating at 404.37 MHz installed at the tropical station Pune is having typical height coverage from 1.05 km to 6-10 km depending upon the atmospheric conditions (Pant et al., 2005).

2.2.1 Radar equation for meteorological targets

A pulsed radar consists of a high power RF transmitter, an antenna to radiate the transmitter signal and a sensitive receiver with its signal processor. Normally the antenna is used for transmission and reception by the use of a duplexer device; the latter connects the transmitter to the antenna and then switches the antenna to receive port when the high power transmit pulse has passed.

The basic radar equation is a relation between the received backscattered signal level and the Radar parameters such as transmit peak power, antenna gain (or aperture) and the distance to the scatterer and the scattering parameter of the medium denoted by the scattering cross section.

If a transmitter power $P_t$ is radiated by an isotropic antenna into space, the diverging radio wave would have a power density of $(P_t / 4\pi R^2)$ at a distance $R$ from the antenna. In practice one uses a radiating antenna with some forward gain $G_t$ and hence the power density at a distance $R$ would be $(P_t G_t / 4\pi R^2)$ in the forward direction. If the scatterer's scattering area is $\sigma$ and it is assumed that the scattering is isotropic, the radar return signal density may be written as

$$\frac{P G_t}{4\pi R^2} \cdot \frac{\sigma}{4\pi R^2}$$

(2.1)

The receiving antenna aperture (area) $A_e$ intercepts this power density and thus the return signal power $P_r$ may be written as

$$\frac{P_t G_t}{4\pi R^2} \cdot \frac{\sigma}{4\pi R^2} A_e$$

(2.2)

Equation (2.1) is the classical radar equation for a point target; the latter phrase
means that the scatterer is small in dimension compared to the spatial width of the antenna transmit beam at the distant height R.

In meteorological situations the scatterer is the atmospheric medium and it may consist of swarm of cloud borne water droplets or a myriad of refractive index irregularities caused by turbulence or humidity or temperature gradients. In such situations, the scattering is a volume phenomenon and hence the atmospheric target is called a volume target. Radar equation for volume target is given by

$$\text{Pr} = \frac{\alpha_r \alpha_i A_t P_t}{R^2 64 \ln 2} (c \tau) \eta \quad (2.3)$$

Where $\alpha_r, \alpha_i$ transmitter and receiver path losses, $\tau$ is the radar transmitter pulse width and $\eta$ is the volume reflectivity given as $\eta = \sum N_i \sigma_i$ per unit volume, where $N_i$ is number of scattering centers per unit volume of the medium with a scattering cross section $\sigma_i$.

### 2.3 UHF (404.37 MHz) wind profiler radar at Pune

In India the only 404 MHz wind profiler system now available at Pune was developed by Society for Applied Microwave Electronics Engineering & Research (SAMEER) in 2001 under sponsorship of Department of Science and Technology, Government of India. The system has been commissioned in Pashan (Pune) campus of India Meteorology Department and was being regularly operated up to 2008.

The system consists of a dual polarized coaxial collinear antenna array made out of low loss dielectric RF coaxial cable of 7/8” size, operating at 404.37 MHz with a peak power aperture product of $3.6 \times 10^4$ Watt-m$^2$ (Pant et al., 2005). A parallel feed arrangement of two way/five way power dividers/combiners is made in slab line structures which feed the two polarization arrays. The two arrays are aligned along true N-S and E-W directions respectively. A set of high power coaxial configuration RF relays are used in conjunction with the five sets of four way power dividers to suitably phase the arrays to produce three beams, two tilted beams; one along the east, the other along south and the third looking at zenith. A high power solid state diode duplexer is used to switch the antenna array to transmitter port during transmission and to receiver.
port during inter pulse period. The exciter subsystem generates 404.37 MHz signal (phase locked to 10 MHz reference) which then pulse modulated and coded in pulse modulator coder unit. This signal is amplified using a chain of solid state driver amplifiers and high power triode amplifiers. The power is boosted to about 16KW (+72dBm) at the last stage. The output of power amplifier is routed through Transmit/Receive switch and fed to antenna through feed power dividers and beam switching units. Antenna subsystem comprising of coaxial collinear sub arrays radiates the total 16 KW power in a narrow pencil beam of about 5 degrees. Weak backscatter echoes from different layers of the atmosphere are received through the same antenna and directed to receiver through a T/R switch.

The receiver is a heterodyne type and consists of a blanking switch, Low Noise Amplifier (LNA), RF amplifier chain, Mixer and band pass filters. Local Oscillator (LO) signals required for the receiver operation are derived from exciter subsystem. During first stage the LO frequency (404.37-IF) is mixed to get IF output which is filtered and amplified using IF amplifier. In second stage a quadrature mixer is used to recover the base band in I and Q channels. This is subsequently passed through a low pass filter and Video amplified and then fed to two independent ADC channels. Output of ADC goes to processor where time domain processing takes place. Coded signal is first decoded in the processor and then subjected to coherent integrations. The pre-processed data is then given to FFT processor and the host computer for further frequency domain analysis. More details of the hardware components of this Pune wind profiler are described by Chande et al. (2000). Figure 2.1 shows the Antenna array and Figure 2.2, the receiver-transmitter assembly of the Pune wind profiler. System specifications are given in Table 2.1.
Figure 2.1: Photograph of the Pune wind profiler antenna system

Figure 2.2: Photograph of Transmitter, Duplexer and Receiver assembly
<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-Co Antenna (Phased Array)</td>
<td>13m × 13m</td>
</tr>
<tr>
<td>Frequency (f)</td>
<td>404.37 MHz</td>
</tr>
<tr>
<td>Radar wave length (λ)</td>
<td>74 cm or .74m</td>
</tr>
<tr>
<td>Transmitted peak power (Pt)</td>
<td>16 K Watts</td>
</tr>
<tr>
<td>Effective aperture (Ae)</td>
<td>80 m²</td>
</tr>
<tr>
<td>3 dB beam width</td>
<td>≤ 5°</td>
</tr>
<tr>
<td>No. of beams</td>
<td>3 (NS, EW and Zenith)</td>
</tr>
<tr>
<td>Off Zenith Angle or Elevation</td>
<td>16.3° or 73.7°</td>
</tr>
<tr>
<td>Gain (G)</td>
<td>~ 36 dB</td>
</tr>
<tr>
<td>Receiver band width (B_N in KHz)</td>
<td>IF 500 &amp; Video ~ 300</td>
</tr>
<tr>
<td>Receiver path loss (α_r)</td>
<td>2.2 dB</td>
</tr>
<tr>
<td>Transmitter path loss (α_t)</td>
<td>0.8 dB</td>
</tr>
<tr>
<td>Cosmic temperature (T_B)</td>
<td>~ 200 K</td>
</tr>
<tr>
<td>System temperature (T_s)</td>
<td>800 K</td>
</tr>
<tr>
<td>Maximum duty ratio (LH/HH)</td>
<td>3.3 % in LH &amp; 10 % in HH</td>
</tr>
<tr>
<td>Pulse width</td>
<td>2μs (uncoded) / 16μs (8-bit-coded of 2μs baud length)</td>
</tr>
<tr>
<td>Inter Pulse Period (IPP) LH/HH</td>
<td>60μs/160μs</td>
</tr>
<tr>
<td>Range resolution (ΔR)</td>
<td>300 m</td>
</tr>
<tr>
<td>Coherent Integrations (N_c)</td>
<td>76 (selectable)</td>
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<tr>
<td>No. of FFT points</td>
<td>512 (selectable)</td>
</tr>
<tr>
<td><strong>Observational window:</strong></td>
<td></td>
</tr>
<tr>
<td>Lowest range bin (km)</td>
<td>1.05</td>
</tr>
<tr>
<td>Highest range bin (km)</td>
<td>10.35 (selectable)</td>
</tr>
<tr>
<td>Incoherent integrations</td>
<td>10</td>
</tr>
<tr>
<td>Beam dwell time (sec.) LH &amp; HH</td>
<td>32.3 &amp; 85.5</td>
</tr>
</tbody>
</table>

Table 2.1: Wind profiler experimental specifications and data processing parameters
2.3.1 *Data processing and moment estimations*

Wind profiler data processing is basically done in two stages, partly online and partly offline. The on-line processing significantly compresses the data volume by time averages and usually produces power spectra and the off-line calculations for parameter extraction. The online processing steps are given below in detail.

2.3.1.1 *Coding/pulse compression technique*

Since the radar backscattered power depends directly on the pulse width of the radar pulse, one may think therefore that the radar range could be increased by increasing the pulse width of the transmit pulse. However the range resolution of the radar is better if the radar transmits a narrow (width) pulse. The other way is by increasing the transmit power of the radar and transmit a narrow pulse to maintain a fine range resolution. However this latter option is rather costly and much more technically involved. The way out of the situation, that of maintaining a high average transmit power and yet obtaining fine enough range resolution is to use the technique of a pulse compression. In time domain pulse compression can be implemented by way of phase coding, especially binary phase coding, which lends itself conveniently for digital processing of the signal.

2.3.1.2 *Coherent integration*

The Bragg scattering coefficient/cross section is normally defined in terms of volume reflectivity ($m^2/m^3$) (Gossard et al., 1983; Doviak and Zernic, 1984). For a typical Bragg scatter this ranges from values of $10^{-13}$ to $10^{-17}$ $m^2/m^3$ in the troposphere (Doviak and Zernic, 1984). The single pulse returned from clear air is very weak and hence certain number of range gated returns is integrated to improve the (S/N) ratio before evolution of spectra and detection. Although atmospheric clear air signal has relatively long coherence time and such integration is feasible, higher coherent integration time automatically narrows the unambiguous measurement range of the Doppler shift frequency which in turn limits the unambiguous measurement range of the radial velocity.

If the range to a scattering volume is $R$ and the operating wave length of the radar is $\lambda$, the number of waves in the two way (return) path is $2R/\lambda$; since a wave comprises of $2\pi$ radian, the phase $\Phi$ of the return signal can be written as

$$\Phi = 2\pi \cdot 2R/\lambda = 4\pi R/\lambda$$
The Doppler shift

\[ W_d = 2\pi f_d = d\Phi/dt \]

and hence

\[ 2\pi f_d = d\Phi/dt = 4\pi/\lambda \cdot dR/dt = 4\pi v/\lambda \]

or

\[ f_d = 2v/\lambda \]  \hspace{1cm} (2.4)

where \( v \) is the radial velocity of the echoing centre or the mean radial wind velocity.

### 2.3.1.3 Incoherent spectral integration

The Doppler spectrum obtained from time series of the decoded and coherently integrated signal is invariably noisy. It is therefore the usual practice to average several signal spectra for a given range gate before further processing of the spectra for the moment estimation. This is known as incoherent spectral integration. If a total of \( n_i \) spectra are integrated/averaged for a every range gate, the noise variance in the spectral domain reduces by a factor of \( \sqrt{n_i} \) and this can be thus considered as improvement in S/N ratio for the signal detection.

### 2.3.1.4 Moment Estimation

Moment estimation is done through offline processing. After the preprocessed data is archived in the spectral form, the spectra are further subjected to offline processing through the offline-software. This software converts spectral binary data into the ASCII form. During offline processing lot of intermediate procedures are involved, the noise level estimation is done using Hildebrand and Shekhon (1974) method, a valid signal is tracked within the signal window to maintain the signal continuity for each range bin. Spectral values above noise threshold are separated in different signal domains for identification. The detection of the multiple spectral peaks is accomplished by searching for the maxima. Each maximum is searched on left or right for signal levels upto the threshold or any local minimum as the case may be and finally the spectral moments (zeroeth, 1\(^{st}\) and 2\(^{nd}\)) are estimated using the centroid method for all the identified peaks. These three moments represent signal strength (back scattered power), the Doppler shift and spectral width. Expressions for moment estimations are given below.

The 0\(^{th}\) moment represents the total signal power or total signal strength in the Doppler spectrum.

\[ M_0 = \sum_{i=m}^{n} P_i \]  \hspace{1cm} (2.5)
The 1\textsuperscript{st} moment represents the weighted mean Doppler shift.

\[
M_1 = \left( \frac{1}{M_0} \right) \sum_{i=m}^{n} P_i f_i
\]  \hspace{1cm} (2.6)

The 2\textsuperscript{nd} moment represents the variance (\(\sigma^2\)), a measure of dispersion from central frequency.

\[
M_2 = \left( \frac{1}{M_0} \right) \sum_{i=m}^{n} P_i (f_i - M_1)^2
\]  \hspace{1cm} (2.7)

where \(m\) and \(n\) are the lower and upper limits of the Doppler bin of the spectral window, \(P_i\) and \(f_i\) are the power and frequency corresponding to the Doppler bin within the spectral window.

Signal to noise ratio (SNR) is calculated as,

\[
SNR(dB) = 10 \log_{10} \left[ \frac{M_0}{N \cdot L} \right]
\]  \hspace{1cm} (2.8)

where \(N\) and \(L\) are the total number of Doppler bins and average noise level respectively. The product \(N\) and \(L\) gives the total noise power over the whole signal spectral window. Doppler width, which is taken to be the full width of the Doppler spectrum, is calculated as,

Doppler width (2\(\sigma\)) = \(2\sqrt{M_2}\) Hz

\subsection{2.3.2 \textit{Radial wind measurements and quality control checks}}

\subsubsection{2.3.2.1 Doppler beam swinging technique}

Any horizontal wind velocity and direction can be decomposed into orthogonal
Cartesian components $u$ and $v$. If the average vertical motion is zero, then only two wind positions are needed to be provided for profiler to measure the horizontal velocity. However when the vertical motion does not average to zero, one must provide a third (zenith) beam. The profiler radar thus has normally three antenna beam positions— one zenith beam and two orthogonal beams say along E-W & N-S. The profiler measures the radial velocities along the three beams by analyzing the observed Doppler shifted signals. This technique is called DBS (Doppler Beam Swinging) technique and tacitly assumes that wind field is spatially homogeneous over the antenna beam divergence in the three directions. This assumption may not be true under extreme convective conditions at higher atmospheric altitudes.

A profiler radar would only measure (through signal Doppler shift analysis) radial velocity along the beam. Thus in a three beam radar configuration say E-W tilted beam, N-S tilted beam and zenith beam, for the measured radial velocities, we may write

$$V_{\text{radial (east)}} = u \cos \theta + w \sin \theta$$

$$V_{\text{radial (north)}} = v \cos \theta + w \sin \theta$$

$$W (\text{zenith}) = w$$

where $u$, $v$, $w$ are the three components (zonal, meridional and vertical) of the wind and $\theta$ is the elevation angle of the beam. The beam tilt angle ($90^\circ - \theta$) away from zenith is chosen as a compromise between the desired accuracy and the loss of signal along the tilted beam direction. A beam tilt angle ($90^\circ - \theta$) is therefore chosen between 15° to 20° in a practical design.

2.3.2.2 Consensus averaging

The beam dwell time for each of the three, one vertical and two off zenith beams is typically 1.5 to 2 minutes. One set of the radial velocity profiles are thus measured every 5 to 6 minutes. Hence each profile is obtained in 6 minutes and over an hour of operation we get 10 profiles of wind. In order to test the measured radial velocities (over a period of one hour) for the presence of any outliers because of scattering from, say aircraft or birds transiting the beam or any intermittent EMI, a statistical algorithm is devised through which the data set is passed which are further subjected to consensus averaging as outlined by Fischer and Bolles (1981) and Barth (1995), in order to get the high quality data. The consensus averaged radial velocities are then used to calculate
wind components namely the zonal (u), meridional (v) and vertical wind (w) velocities representative of the mean wind in the hour of the observation.

2.4 Lidar probing of the atmosphere

Presently there are two main types of Lidar (Light Detection and Ranging) in use for probing of the atmosphere. They are Continuous Wave (CW) Lidar and Pulsed Lidar. In CW lidars, light is continuously transmitted to the atmosphere. Assuming atmospheric parameters do not vary, the backscattered signal average power is constant, coming from all distances at the same time. In pulsed lidars, short pulses are sent to the atmosphere, illuminating at each instant only a limited part of the line of sight. Therefore, backscattered signal arriving onto the detector at a time only comes from a given range of distance. The time delay between the pulse start and the measurement time informs on the distance of the analyzed zone. The range gate length is always the same, at short and long range.

2.4.1 Pulsed Lidar components

Figure 2.3 represents the general set up of pulsed lidar. Description regarding the major components is given in the subsequent paragraphs.

![Pulsed Lidar components diagram](image)

**Figure 2.3:** General set up of pulsed lidar
2.4.1.1 Laser source

A pulsed lidar needs a continuous wave laser, called Master Oscillator (MO) to generate the Local Oscillator (LO) beam and a pulsed laser to generate the powerful transmitted pulse. The frequency offset between the two sources need to be stable with time to allow an unbiased measurement of the Doppler shift. The master oscillator provides the laser wavelength, the laser linewidth, the laser intensity noise and the state of polarization. Each of these parameters has to be well known and stable to guarantee the lidar performance. The CW power is at least some milliwatts. The pulsed laser delivers cyclic pulses of high energy. The pulse duration $\tau$ is some hundreds of nanoseconds, that determines the length of the pulse in the atmosphere and so the spatial resolution. The Pulse Repetition Frequency (PRF) is as high as possible, but cannot exceed a maximum value $\text{PRF}_{\text{max}}$. To avoid ambiguity between return signals, the time between pulses ($1/\text{PRF}$) must be longer than the round trip time of flight of the pulse to the greatest height to be measured.

$$\text{PRF}_{\text{max}} = \frac{C}{2Z_{\text{max}}} \quad (2.9)$$

2.4.1.2 Circulator

The function of the circulator is to transmit the laser pulse from the laser (1) to the telescope (2) and to direct the backscattered light from the telescope (2) to the receiver (3). Power handling, transmission efficiency and isolation between (1) and (3) ports are critical parameters. In coherent pulsed lidars, most circulators use polarization to perform this function.

2.4.1.3 Telescope

The telescope magnifies the laser beam in order to reduce its divergence in the far field, and focuses the beam at any distance. The larger the beam, the smaller the divergence and the better the SNR at long range. Since the lidar signal/noise ratio is inversely proportional to the beam area, beam diameter must be minimized on the global measurement range to ensure maximum efficiency. The telescope can use reflective or refractive optics, perfectly corrected from geometrical aberrations. In order to lose less than 3dB on the detection efficiency, wavefront distortion on the global optical path has
to be less than \( \lambda/4 \) RMS, including components and atmospheric distortion. Atmospheric turbulence creates wave distortion that degrades heterodyne efficiency. To keep this distortion negligible, the telescope aperture has to be smaller than the coherence diameter of the beam expressed by

\[
d_0 = 2.4 \times 10^{-8} \lambda^{6/5} Z^{-3/5} Cn^{-6/5}
\]

2.4.1.4 Scanner

Coherent lidar measures the radial component of the wind, i.e. the projection of the wind vector on the Line of Sight (LOS). To provide two or three components of the vector, the beam has to be directed in two or three independent different directions. The scanner can move the entire telescope or only the beam.

2.4.2 Signal processing

After the pulse has left the laser, the detector starts to collect the backscattered signal from the successive range gates. It first crosses the telescope optics as a marker for the zero distance. Even if the stray light is small, due to optimized coatings (10 order) this signal is always larger than the light backscattered by the atmosphere. The power is proportional to the backscattering atmospheric coefficient velocity. For each pulse, the collected signal contains the total wind speed information on the LOS. However, both the signal and the noise fluctuate from pulse to pulse and it is necessary to average signals to get a good estimation of the spectral content. SNR increases as the square root of the number of averaged pulses N. This computation is performed for all range gates.

2.4.3 Coherent detection

The return signal mixes with local-oscillator creating the beat signal. The electronic signal on the detector contains the same amplitude, frequency and phase information as the optical signal, but is frequency downshifted to allow detection with conventional high speed detectors. So the Doppler shift, which is small in comparison to the optical frequency can be measured in base band. To allow both negative and positive shifts to be measured, an offset frequency \( F_i \) (Intermediate frequency) is added on one arm of the interferometer.

\[
F_{dop} = (\nu + F_i) - (\nu + F_{dop}) = F_i + F_{dop}
\]

LO Signal
An important advantage of coherent detection is that it can be limited by signal photon noise, if some conditions are fulfilled. First condition is that the amplitude and phase match between signal beam and the LO beam must be perfect. The second condition is that temporal coherence is optimum, i.e. the spectral width of the main oscillator must be narrower than the spectral width of the electronic signal. The third condition is that polarization state must be the same on the LO and the signal. System and component limitations lead however to a loss in heterodyne efficiency.

2.4.4 Lidar Equation

The lidar equation gives the expected signal power coming back from the atmosphere within the range gate to be analyzed. The signal power can then be compared to the noise power in order to determine the range of the lidar. The total optical power \( P_r(Z) \) reflected back in the receiver telescope from the range gate at \( Z \) is

\[
P_r(Z) = P_{peak}.T_{inst}.T_{atm}.\beta\pi(Z).\frac{c\tau}{2}.\Omega
\]

Where \( P_{peak} \) is the transmitted pulse peak power, \( T_{inst} \) is the instrumental round trip transmission and \( T_{atm} \) is the atmospheric round trip transmission and is given by

\[
\text{Figure 2.4} : \text{Radial wind velocity retrieval process}
\]
\[ T_{atm} = \exp \left( -2 \int_{0}^{z} a(x) \, dx \right) \]  

(2.12)

where \( B_a(Z) \) is the backscattering coefficient of the atmosphere at a distance \( Z \), \( \tau \) is Full Width Half Maximum (FWHM) and \( \Omega \) is the reception solid angle.

2.5 Doppler Wind lidar at Pune

‘Windcube’ is a new generation Doppler wind lidar developed by M/s Leosphere, France for meteorological applications in cooperation with the French Aerospace Agency (ONERA). Windcube-200 is the latest version of such wind lidars and is installed in IITM, Pune, India in July 2010 for studying the high resolution wind structure both in time and space in the tropical monsoon region. Figure 2.5 shows Windcube-200 system on the terrace of the Institute building.

Windcube-200 operates in near-IR wavelength (1.54 µm), and its pulse energy is 100 µJ, scanning cone angle is 15°, and speed and direction accuracy are 0.5 m/s and 1.5° respectively. It is having many advantages like constant accuracy for all heights, ready to use data (automatic data filter), portability etc. The main advantage is that it can be operated in any weather conditions. In clear sky conditions it employs aerosols as tracers and in cloudy environment it detects the motion of cloud particles. The Windcube is a pulsed lidar with a fixed focus. It has a 15° prism to deflect the beam from the vertical.

The prism holds still while the lidar sends a stream of pulses (~36000) in a given direction, recording the backscatter in a number of range gates (fixed time delays) triggered by the end of each pulse. Having sent the required number of pulses, the prism rotates to the next azimuth angle to be scanned, each separated by 90°. Wind lidar uses 0.3 µs or 50 m pulse length (so 50 m height resolution in line-of-site) with first range gate at 100 m onwards with 36000 pulses/shots for each beam consuming around 12 seconds accumulation cum processing time to get profile in each beam direction. Thus a full rotation of 360° (to four cardinal directions of North, East, South, and West) takes about 50 seconds. The schematic of the beam position in the four directions is shown in Figure 2.6. During the rotation and before the next stream of pulses can be sent, the
Figure 2.5: WindCube-200 installed at IITM, Pune

Figure 2.6: Orthogonal frame of Windcube for retrieving wind
recorded data are processed. For each range gate, the time series from each pulse are Fourier transformed to power spectra which are block-averaged. Due to the short recording duration (200 ns), the resulting spectra have poor frequency resolution. Instead of using a centroid to obtain the frequency of the peak, a mathematical model including the most important parameters affecting the shape of the expected Doppler spectrum has been adopted in the current system. This model is fitted to each block-averaged power spectrum in order to obtain the Doppler shift to a much higher resolution than could otherwise be expected. At each direction step, the Windcube combines the four most recent radial speeds at each height in order to obtain the horizontal and vertical speed and wind direction. To reconstruct the 3D components of the wind vector, some assumptions made are, horizontal homogeneity, temporal variations are slower than the inter-beam distance divided by the horizontal wind speed, and that wind slowly varies within a range gate.

In contrast to other systems, the Windcube uses an acousto-optic modulator to add a precise frequency offset to the local oscillator which is mixed to and beats with the returning Doppler shifted backscatter. Backscatter from a fixed target, introducing no Doppler shift, appears shifted in the resulting power spectrum. Thus the polarity of the radial velocity is available and there is no ambiguity regarding the wind direction.

The measurement hypothesis of this Lidar is that, it uses aerosols as ‘tracers’ along the line of sight, basically assuming that the movement of aerosols is along with the mean wind. The moving aerosols in the atmosphere induce a change in frequency of the backscattered light which is the Doppler shift. The sign of this shift will depend ultimately on the aerosols which move either towards or away from the instrument. The frequency difference between the emitted and backscattered light is measured. This difference in frequency is directly proportional to radial wind speed. The Doppler shift ($\Delta f$) can be used to find the radial velocity from the following equation.

$$V_r = \frac{\Delta f \lambda}{2} \quad (2.13)$$
This instrument measures the radial wind speeds sequentially along the 4 cardinal geographical directions and reconstructs the wind vector. Initially the wind lidar system is perfectly leveled on a plane surface and oriented in the geographical north-south direction to ensure accurate speed and direction computations.

Relations connecting different wind components (u-zonal, v-meridional, w-vertical wind velocities) and radial velocities (Vrn, Vrs, Vre, Vrw - corresponding radial velocities in north, south, east and west directions) are given below.

\[ u = \frac{(Vrn - Vrs)}{2.\sin\theta} \]  \hspace{1cm} (2.14)

\[ v = \frac{(Vre - Vrw)}{2.\sin\theta} \]  \hspace{1cm} (2.15)

\[ w = \frac{(Vrn + Vrs + Vre + Vrw)}{4.\cos\theta} \]  \hspace{1cm} (2.16)

Here \( \theta \) corresponds to the tilt of the laser beam with respect to the vertical. Horizontal wind speed and wind direction are then computed from the zonal and meridional components obtained from equations (2.14) and (2.15).

Doppler principle is the simplest and the more accurate way to measure the speed of a target (http://www.leosphere.com/lidar-technology-pulsed-doppler-laser). Doppler shift at optical/light wavelength/frequency is directly proportional to radial wind speed. Heterodyne detection downshifts light frequency to radiofrequency where it can be easily measured by a detector. Moreover, it is the more sensitive of all detections, allowing use of low power and reliable lasers. Pulsed operation of the system provides long range probing because of the high peak power and good spatial resolution by the short pulse duration.

Doppler lidar system of the type used for current studies (Windcube-200) needs no speed calibration, since the lidar uses the speed of light (constant and universal) to process the wind speed (http://www.leosphere.com/lidar-technology-pulsed-doppler-laser). However, it needs a zero-distance calibration to define the output of the laser beam. This is done by the supplier during the manufacturing process once and for all.
before installing the system in field. For a physical range resolution about 50 m
Windcube-200 uses a 200 ns pulse with a PRF = 20 kHz and a FFT windows width of
128 pts. The CNR is the carrier-to-noise ratio measured on the time series. Noise is
measured on the full bandwidth, about half of the sampling frequency. The CNR is also
measured on the spectrum, as the Doppler peak energy divided by the noise energy
integrated on the full bandwidth.

The current lidar system strictly underwent certain quality tests at the
manufacturing site before being installed at the observation site
(http://www.leosphere.com/lidar-technology-pulsed-doppler-laser). These include
environmental tests (vibration, waterproofness), functional tests (quality & performance
of all sub electronic, opto electronic and mechanical sub modules), and an endurance test
by continuously operating the system for nearly 10 days to identify aging of any
components. Also as per the lidar supplier, the performance of every new lidar system is
compared with a reference lidar system which itself is certified by a reference institute
every year. Due care is taken at the installation site by providing a stable, plane,
vibration-free platform. Adjustable (screw-type) mounting legs and bubble leveling are
provided to ensure these. From time to time the quality and performance of the sub
systems are checked by trained engineers at the site to ensure data quality.

2.5.1 Wind lidar products acquired online – some typical examples

As mentioned above, the wind lidar is capable of giving measurements of three
components of winds (u, v, w), horizontal wind, wind direction and Carrier-to-Noise
Ratio (CNR) in the height range 100-12000 meters. Figure 2.7 shows the screen shot
image of wind lidar measured vertical profile of horizontal wind (on left) and wind
direction (on right). After one full rotation of the beam, height profiles of real-time
(black), average of previous 10 minutes (green), maximum (red) and minimum (blue)
horizontal velocity are displayed on the computer screen. Further on the right-side the
real-time (black) and 10 min average (green) wind direction are also displayed. Typical
time-height variation of lidar-derived real-time (screen shot) signal-to-noise ratio (CNR)
Figure 2.7: Screen shot of wind profile on 15 June 2011

Figure 2.8: Screen shot showing time-height evolution of Signal-to-Noise Ratio (CNR) on 30 December 2010 during 0714-1342 hrs LT
up to 3000 m during the period 0714 – 1342 hrs LT on 30 December 2010 is shown in Figure 2.8. Strong backscatter signal (red) seen from surface layers starts evolving after local sunrise hours and lifts up to a height of 1000 m above ground level indicating the evolution of daytime convective boundary layer.

Screen shot images of time-height variation of signal-to-noise ratio (upper panel) and horizontal wind speed (lower panel) on 15 June 2011 during daytime is shown in Figure 2.9a. Strong backscatter echoes between 1500 m and 5000 m indicates the presence of thin low level monsoon clouds. Stronger winds (~ 15 ms\(^{-1}\)) are seen in the atmospheric layer below 2000 m and winds are relatively weaker (< 10 ms\(^{-1}\)) inside the cloud layers. Figure 2.9b shows the screen shot images of the corresponding time-height variation of wind direction (upper panel) and vertical wind (lower panel) on the same day (15 June 2011). Winds are predominantly south-westerly in direction in the entire height region. Vertical winds show both upward motions (red) and downward motions (blue) in the surface layers during daytime.

Windcube-200 is operated on continuous basis round the clock. Two types of data files are generated for further offline analysis and investigation. The 12-sec data file (RTD file) contains CNR, horizontal wind speed, wind direction, zonal (u), meridional (v), vertical (w) winds at all available height levels in 50-m height interval from 100 m above ground level. The 5-min average data file (STA file) consists of horizontal wind speed (V), standard deviation of V (dV), \(V_{\text{max}}\), \(V_{\text{min}}\), wind direction, zonal wind (u), du, meridional wind (v), dv, vertical wind (w), dw, CNR, dCNR, CNR\(_{\text{max}}\), CNR\(_{\text{min}}\), spectral width (sigmafreq), d sigmafreq, and availability of data (%) during the period.

The Doppler wind lidar derived data thus collected during the period July 2010 to May 2014 is used for various studies in the present thesis.
Figure 2.9a: Screenshots of time-height variations of CNR at 0° (upper panel) and horizontal wind (lower panel) on 15 June 2011
Figure 2.9b: Screenshots of time-height variations of wind direction (upper panel) and vertical wind (lower panel) on 15 June 2011