CHAPTER II

EXPERIMENTAL TECHNIQUES AND DATA PROCESSING
2.1 Introduction

Radar has increasingly been used to observe horizontal winds and convective systems during monsoon. This chapter will focus on pulsed Doppler radar widely known as the wind profiler. Section 2.2 will discuss the development of radar and its use in observing clear air. A discussion of radar operating principles including the wavelength, scattering of electromagnetic waves in the atmosphere and the general components of a radar system will follow this in section 2.3. The review will conclude with a discussion of the signal processing used in wind profiler Doppler measurements and the parameters that can be estimated (Section 2.4). The wind profiler however, uses fixed beam directions close to vertical and therefore only observes atmospheric properties directly over the radar (Section 2.5). The wind profiler provides a higher temporal and vertical spatial resolution view of the atmosphere. The 1.3 GHz boundary layer wind profiler used in this study can provide continuous clear air observations up to about 3-4 km (Section 2.6).

The wind profiler can utilize the vertical structure of the precipitating systems whereas the Doppler weather radar must use the horizontal spatial characteristics. Radar found its first regular use during the Second World War. This was also the time when the major hardware developments were made. Later, radar found a significant use in
meteorology and has now become an essential part of research and operational forecasting.

2.2 History of radar remote sensing

Atlas (1990) gives a good review of the history of radar use in meteorology. Radar was originally developed to detect and determine the range of aircraft. Observations of the atmosphere using radio waves can be traced back to 1924 where reflections from the ionosphere were first detected. The invention of the resonant magnetron in 1940 gave the ability to transmit power at centimeter wavelengths. Before the magnetron radar generally operated at frequencies of around 200 MHz (wavelength of about 1.5 m). Shorter wavelengths allowed the detection of precipitation. Originally, echos from precipitation were considered clutter, as they masked targets such as aircraft. The ability to observe precipitation and the movement of storm systems was, however, the beginning of radar meteorology. Radar meteorology had its greatest advance during World War II. The US military recognised the importance of weather radar and began a significant development programme at the Fort Mammouth labs in 1945. The early weather radar systems were adapted from military radar systems. Watson and Watt developed the first 10 cm weather radar in 1940 at the General Electric Labs. A convective storm was tracked in 1941 using 10 cm wavelength radar in England, and multicellular storms were first looked at by Byers and Battan (1949), when
they studied vertical wind shear and showed that a new cell grew upshear of an old one. Most early radars were continuous-wave (CW), relying on the interference between the direct signal received from the transmitter and the Doppler-shifted signal from the moving target for detection. The CW radar determined the velocity of a target using its range and angle in successive illuminations. A pulsed Doppler radar is essentially continuous wave radar where the wave is also amplitude modulated. It allows the measurement of radial velocity through the determination of a Doppler spectrum. Pulses are used to remove range ambiguity and the principles of pulsed Doppler radars are discussed in the next section.

2.3 Wind profiling radar

Meteorological radar originally relied on the presence of precipitation for useful observations. The observation of clear air echos was a major development in radar meteorology, giving the ability to observe atmospheric properties such as wind speed in the absence of precipitation. The ability to make observations in clear air also gave rise to the development of wind profiling radars. Hardy and Gage (1990) broke the development of clear air observing radar into four main stages. From 1935 to 1949 several types of clear air echos were observed and reported. Friend (1949) showed that the reflections observed by the ionospheric radars in the troposphere were regions of temperature
inversion with large gradients of refractive index. Also the first observations of insects and birds made which were previously unknown causes of “Angle Echos” on radar screens. Work on propagation beyond the radio horizon (over the horizon) by scattering of radio waves by turbulent tropospheric structures marked the second period. This work was important as it is also a factor in the radar back scattered energy. In this period, the importance of isotropic scattering and reflection were discussed. For vertically pointing radar beams, echos from horizontal structures with large refractivity gradients would be important. However, for off vertical beams, isotropic scattering is important.

The third period from 1963 to 1972 showed increased activity in observing atmospheric structures. The first radar observations of convective processes in the boundary layer were made, and evidence that clear air echos from insects and birds occurred at wavelengths of 10 cm or less (Hardy et al. 1966(a)) was found during this period. At longer wavelengths, reflection occurs from refractive index gradients rather than from particles (Hardy et al. 1966(b)). Radars operating at wavelengths of 3 cm or less predominantly observe clear air echos from insects and birds. At wavelengths greater than 10 cm the echos result from strong refractive index gradients. Konrad and Kropfli (1968) observed clear air convection over the sea and reported that the radar echo pattern moves with the mean wind in the convective layer.
From 1973 to 1982, there was increasing use of VHF wavelength radars which were constructed mainly as large phased array antennas that operated unattended (e.g., Woodman and Guillen 1974). The Sunset radar operated in Boulder, Colorado was the first VHF radar built for observation of the lower atmosphere. It was operated at a frequency of 40 MHz, with the first results published by Green et al. (1975). By the 1980's several VHF and UHF radars designed specifically for the troposphere (wind profilers) were being designed and deployed as networks (Strauch et al. 1984). The NOAA Aeronomy laboratories were pioneering this work (Gage and Balsley 1978). The UHF and VHF radars have shown capabilities for measuring, horizontal and vertical velocities, turbulence, momentum flux and precipitation (Gage 1990). The wind profilers have fixed beam directions which can be switched rapidly. By using three beam directions, one vertical and two inclined from the vertical orthogonal to each other, profiles of the horizontal wind can be determined. The Colorado wind profiler network, described by Strauch et al. (1984), was a first step towards making the transition from the research to the operational sector. The first wind profiler observations routinely incorporated in analysis were from Christmas Island in the central Pacific Ocean. These wind profilers were developed for probing the free Mesosphere, Stratosphere and Troposphere and hence were called MST radar. They have been used for investigating measurements included momentum fluxes, phase velocities and modes and energy associated with internal gravity waves (e.g., Clifford et al. 1994; Larsen and Röttger...
Work on the tropospheric wind profilers led to the development of the boundary layer wind profiler (Ecklund et al. 1988). The boundary layer wind profiler has become an important tool for the measurement of atmospheric boundary layer parameters. Measurements can be made at high temporal resolution and with greater height coverage than meteorological towers or clear air measurements with Doppler weather radar. In the mid 1980's a 915 MHz wind profiler was developed by NOAA Aeronomy Laboratories specifically for measurements within the ABL (Ecklund et al. 1988). The boundary layer wind profiler (BLWP) was designed to compliment the existing 50 MHz wind profiler network in the tropics by providing high resolution wind measurements in the boundary layer (Ecklund et al. 1988). It was shown by Balsley and Gage (1982) that to obtain a height resolution of 100 m or better, with fast system recovery (providing measurements at least as low as 100 m), a frequency near 1000 MHz is required. The original wind profiler antenna developed by Ecklund et al. (1988) was mechanically steered to four beam positions. The newer antennas are electronically steered, using phase-shifted antenna elements.

Boundary layer wind profilers have been developed to operate at various frequencies including 1357.5 MHz radar that has been in operation since 1992 (Hashiguchi et al. 1995; Reddy et al. 2002). Doppler radar studies of the ABL have included observation of momentum fluxes (e.g., Rabin and Doviak 1982); wind velocities and temperature profiles...
associated with ABL development (e.g., May and Wilczak 1993; Angevine 1994a; 1994b) the sea breeze (e.g., Banta et al. 1993) the nocturnal jet (e.g., May 1995) and cold fronts (e.g., Shapiro et al. 1984; May et al. 1990a).

2.4 Operating principles for pulsed Doppler radar

With a pulsed Doppler radar, a high power amplifier is turned on and off by a pulse modulator to transmit a train of pulses which have a set duration $t$ and a pulse repetition time (PRT) of $T_s$ and angular frequency $\omega$. Part of the pulse power is scattered back towards the radar by fluctuations in the refractive index. If the transmitter and receiver antennas are co-located, a transmit/receive switch modulates between a transmit time and receive time. When the signal is received, it is mixed to base band (i.e., frequency about DC) with known relative phase (Doviak and Zrnic, 1993). A quadrature detector converts the signal to an in phase component and a component 90 degrees (quadrature) out of phase.

The phase angle of the returned signal can be determined, and the time evolution shows whether the radial velocity is towards or away from the radar. The phase change between pulses resulting from a moving target is extremely small. As a result, pulses that are close to each other in time (a period over which phase change is assumed negligible) can be averaged to increase the signal by reducing the random noise. A block diagram of a typical wind profiler is shown in Figure 2.1. The antenna and
VHF/UHF transmit/receive unit are located in the field. A computer located in the field laboratory controls the radar operating parameters, processes the returned signal, and displays and stores the resulting data.

![Block diagram of wind profiler radar](image)

**Figure 2.1 Block diagram of wind profiler radar**

A wind profiler antenna usually consists of a number of antenna elements in an array. In the case of Doppler weather radar this is usually replaced by a parabolic dish. The wind profiler antenna designed by Ecklund et al. (1988) consisted of 16 radiating elements. As coherent waves are transmitted from each of these elements, the waves will constructively or destructively interfere with each other. As a result, the
power transmitted will depend on the angle from the antenna bore sight, with most of the power being transmitted in the direction of constructive interference. If the antenna elements are appropriately spaced, and the phases of the transmitted waves from these elements are varied with respect to each, then the beam can be focused in a particular direction. If we assume a linear array of elements, the superposition of waves shows that a \( \sin(\theta)/\theta \) power distribution is generated as shown in the figure 2.2.

The beam pattern shows a maximum gain in the main direction. However side lobes will also occur and in radar design it is beneficial to minimize these side lobes. Side lobes of the transmitted beam are reflected from ground targets including towers, topography and forests leading to an unwanted component in the returned signal. Characteristics of clutter and removal techniques are further discussed in Section 2.5.

Fig.2.2: Beam geometry of a linear array of radiating elements forming a \( \sin\theta/\theta \) pattern. Two alternate display methods are shown: Amplitude on a polar plot (left), and using decibels on a Cartesian plot (right).
The maximum observable height is limited by the power of the radar, as the power of the return pulse is reduced with range. It is known that for volume scattering, the return power is inversely proportional to the square of the range (Gossard 1994). The return signal ($S$) strength is related to the background noise level ($N$) through the SNR (Signal to Noise Ratio). The SNR expressed in decibels (dB) may be calculated as

$$\text{SNR} = 10 \log_{10} \left( \frac{S}{N} \right)$$

(2.1)

The noise component is spread over a greater range of frequencies than the signal and hence the signal may be detectable even at SNR down to approximately -10 dB.

The backscatter of radio waves depends on atmospheric refractive index variations which are caused by variations of air temperature and moisture. The potential refractivity gradient ($M$) can be used to model the radar return based on the moisture and temperature contributions to the refractive index and is given by

$$M = -77.6 \times 10^{-6} \frac{P}{T} \left( \frac{\delta \ln \theta}{\delta z} \right) \left[ 1 + \frac{15500q}{T} \left( 1 - \frac{1}{2} \frac{\delta \ln \frac{q}{\theta}}{\delta z} \right) \right]$$

(2.2)

here $P$ is the pressure (hPa), $T$ is the absolute temperature (K), $\theta$ is the
absolute potential temperature (K), \( q \) is the specific humidity (kg kg\(^{-1} \)), and \( z \) is the height (m) (e.g., Tsuda et al. 1988).

The echo power \( P_v \) is given by

\[
P_v = \frac{P_t \lambda^2 G^2 E(2k)M^2}{16\pi^2 r^2}
\]  

(2.3)

Where \( P_t \) is the transmitted power, \( \lambda \) is the radar wavelength, \( r \) is the range from which the signal is backscattered, \( G \) is the antenna gain, \( C \) is a constant depending on the radar wavelength and height resolution and \( E(2k) \) is the energy density of fluctuations with a vertical scale of half the radar wavelength.

Wind profilers often show horizontal bands of enhanced reflectivity within the atmosphere. These can be a result of refractive index variations associated with the vertical profiles of temperature and moisture. The top of the boundary layer is often marked by an increase in temperature and decrease in moisture. The equation for potential refractivity gradient suggests that the wind profiler should be able to observe the top of the boundary layer as a region of enhanced signal return. Enhanced signal return also occurs within clouds as a result of turbulent mixing.
2.5 A Brief Description of L-band Wind profiler at Gadanki

The first Lower atmospheric wind profiler (LAWP) system was installed at Gadanki (13.5°N, 79.2°E) near Tirupati, India with a major collaboration between Ministry of Post and Telecommunications (MPT)/Communications Research Laboratory (CRL), Japan and Indian Space Research Organization (ISRO)/National Atmospheric Research Laboratory (NARL), Gadanki, India for detailed investigation of winds, turbulence and precipitating weather systems in the tropical latitude. The Gadanki-LAWP was fabricated at Meisei Electric Co., Ltd. (MEC), Tokyo, Japan with the specifications given by the CRL, Tokyo, Japan. Gadanki-LAWP is coherent UHF phased array radar operating at 137.5 MHz with a peak power aperture product of $1.2 \times 10^4$ Wm². The system design specifications are presented in Table 2.1. Figure 2.3(a) shows the functional block diagram and 2.3(b) shows the antenna assembly of the Gadanki-LAWP. The following subsections present brief descriptions of the functioning of various subsystems.

The phased antenna array consists of 576 circular micro strip patch antenna elements arranged in a 24 X 24 matrix over an area of 3.8 m x 3.8 m. The total array is organized into four quadrants of 0.715λ spacing, λ being the wavelength at the operating frequency. A total peak power of 1000 W is delivered to the antenna array by a parallel array of four outputs from Power Amplifier (PA), each feeding 250 W to one quadrant.
(12 x12 elements) of the array. The Transmitter (TX) unit, preceded by PA, generates an output power of 175 W, which is sufficient to drive the PA. The PA generates the required final output power by a division-amplification-combining technique. The output power is fed via the beam changer (BC) switch and hybrid circulator. The power distribution across the array is tapered to obtain better side lobe suppression. The array produces a pattern having a beam width of 4° and a gain of 29 dB. The beam direction can be tilted by 15 degree towards North and East (two principal planes) from the zenith by electrical steering that is by injecting a progressive phase difference between the successive elements. Phase shifters are used to steer the beam in the North direction. For the East beam required phases are injected through the appropriate lengths of the feeder lines. The same antenna array is used for all three beams.

The power received by the antenna array from the atmosphere is delivered to the receiver via the circulators. The receiver is a phase coherent heterodyne type having Quadrature detector at the final output, and delivering the video outputs to the signal processor. The receiver has an overall gain of 50 – 120 dB depending upon the gain setting of the Automatic Gain Controller (AGC) amplifier. The dynamic range of the receiver is about 66 dB. The quadrature (I and Q) outputs of the receiver are limited to a peak-to-peak voltage of 10 volts and given to the Signal Processor Unit (SPU). The SPU consists of an A/D converter (ADC) and a coherent accumulator. The ADC has 12-bit resolution and
samples the analog input at the interval set at the Data Processing Unit (DPU). The SPU performs the coherent accumulation on the ADC output data. The constituted coherent data is then transferred to the DPU for further processing. The DPU performs an FFT on the received coherent data. The on-line computer displays the frequency spectrum (North, East and Zenith beams), signal strength, wind speed and direction. The data is further processed to compute moments before being transferred to the off-line computer via Ethernet for archival. Each data file in the archival corresponds to one cycle and contains parameter file, physical file, spectrum file and moment data file. Finally the data of incoherent, spectral moments and velocity field is archived on magneto-optical disks and eventually transferred to compact disks (CD-ROM). Assuming horizontal homogeneity of the wind field (at least for the mean wind) in the volume spanned by the radar beams, one can say that the measured radial velocities are the components of the 3-dimensional wind vector along the fixed antenna directions.

2.6 Signal processing in pulsed-Doppler radar

The following descriptions are based on parameters used for the 1.3 GHz lower atmospheric (boundary layer) wind profiler [LAWP, wind profiler or wind profiler radar] at Gadanki. The wind profiler consists of an antenna, a transmit/receive unit, a radar controller and signal processor and a recording device.

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Fig. 2.3: (a) Simplified block diagram, antenna assembly and (b) out-door unit of the Gadanki Wind profiler radar.
Table 2.1: Gadanki -LAWP system specifications

<table>
<thead>
<tr>
<th>Location</th>
<th>Gadanki (13°27'34&quot;N, 79°10'34&quot;E)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TRANSMITTER/RECEIVER</strong></td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>1357.5 MHz</td>
</tr>
<tr>
<td>Peak power</td>
<td>1 kW</td>
</tr>
<tr>
<td>Transmit Pulse width</td>
<td>0.33, 1 &amp; 2 µs</td>
</tr>
<tr>
<td>Inter pulse period (IPP)</td>
<td>20 - 999 µs</td>
</tr>
<tr>
<td>Maximum Duty ratio</td>
<td>5%</td>
</tr>
<tr>
<td>IF frequency</td>
<td>60 MHz</td>
</tr>
<tr>
<td>IF bandwidth</td>
<td>3.75 MHz, 1.25 MHz, 0.65 MHz (for the above 3 pulse width)</td>
</tr>
</tbody>
</table>

| **ANTENNA** | |
| Antenna type | Phased arrays |
| Antenna aperture | 3.8 x 3.8 m². Planar phased array |
| Beamwidth | 4° |
| Number of beams for automatic scan | Electrical steering 3 directions |
| Beam switching | Zenith, North 15°, East 15° |

| **DATA PROCESSING** | |
| Data sampling interval | 0.33, 1, 2 µs |
| Number of sample points | 1 to 64 |
| Number of Coherent integration | 1 to 256 |
| Number of incoherent Integration | 1 to 128 |
| Number of FFT points | 64 to 2048 (2ⁿ where n = 6 to 11) |

| **OTHERS** | |
| Electric power consumption | 4 kw maximum |
| Electric power voltage | AC 100 V ± 10% 47-63 Hz (stepped down from AC 200 V ± 10%) |
| Recording media | Hard disk or Magneto-Optical disk |
| Data items recorded | (1) System parameters |
| | (2) Doppler spectrum |
| | (3) Moments |
| | (4) Physical quantities. |

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For a typical measurement, a 0.7 µs pulse is transmitted by the radar with a peak power of 400 W. As the pulse travels through the atmosphere, it is scattered due to refractive index gradients and turbulence (Reddy et al., 2001). Scattering occurs most strongly from turbulence on scales of half the radar wave length ($\lambda/2 = 23$ cm for the 1.3 GHz profiler). This process is known as Bragg scatter. Since turbulent parcels are advected by the wind, the wave scattered back towards the radar will have a Doppler shift related to the mean radial wind component. If the radial wind direction is towards the radar, there will be an increase in frequency (a positive Doppler shift). If the wind direction is away from the radar, there will be a decrease in frequency (a negative Doppler shift). The range ($r$) from which the pulse arrived is determined by the return time ($t$) as

$$r = \frac{ct}{2} \tag{2.4}$$

Where, $c$ is the velocity of light. The radar pulse undergoes back-scatter throughout its propagation. By matching receiving gates on the radar to the return time of the pulse at specified ranges, a single pulse can provide data for a range of heights (Figure 2.4). A series of pulses is transmitted (e.g., 54 pulses) and these pulses are averaged to produce an average complex signal (coherent integration). Averaging pulses increases the ability to detect the signal for low SNR by reducing the noise (random errors) variance (e.g., Woodman and Guillen 1974). A Doppler spectrum is then calculated using 128 averaged points. A spectrum of Doppler
shifts is observed due to variations in the radial velocity component of the advected turbulent parcels within a pulse volume. The pulse volume is determined by the pulse length (0.7 μs; which can be converted to a pulse length in meters by Equation 2.4) and the beam width (9 degrees). It has been found that this return Doppler spectrum is Gaussian in shape (Woodman 1985). Sixty successive power spectra are calculated and averaged to increase the statistical stability of the Doppler and power estimates.

Fig. 2.4: Range/time diagram. In this diagram, $r_{\text{min}}$ is the minimum observable height which is equal to the pulse length $\Delta r$ or equivalently in time $\Delta t_1$. The maximum unambiguous range $r_{\text{max}}$ is such that the pulse travel time $t_1$ is less than the inter pulse period (IPP). Hence $T_1$ is the first pulse $T_2$ is the time of the second pulse a period equal to the IPP later (Rottger, 1985)
The three parameters which define the Doppler power spectrum ($S$) are (Woodman1985):

1) The total power ($P$) (zeroth moment of the Doppler spectrum) given as the integral of the power spectrum amplitude for all Doppler frequencies $\omega_d$ (area under the power spectrum):

$$P = \int S(\omega_d) \, d\omega_d$$

(2.5)

2) The average frequency shift ($\Omega$) (first moment of the Doppler power spectrum) is given by the Doppler frequency component weighted by the spectral power at that frequency:

$$\Omega = \frac{1}{P} \int \omega_d S(\omega_d) \, d\omega_d$$

(2.6)

3) The spectral width $\sigma_W$ (second moment of the Doppler spectrum) is given by the square of the frequency components deviation from the mean weighted by the spectral power at that frequency and is equivalent to the variance of the distribution:

$$\sigma^2_W = \frac{1}{P} \int (\omega_d - \Omega)^2 S(\omega_d) \, d\omega_d$$

(2.7)
If the return spectra is Gaussian in shape, these three parameters contain all the information obtainable from the radar echoes (Woodman 1985). The physical significance of the total spectral power, mean Doppler frequency and spectral width are depicted in Figure 2.6.

The three parameters contain important information on the physical properties of the medium through which the radar pulse propagates. The total power gives information on the intensity of the turbulence, the mean frequency shift corresponds to the mean radial velocity and the spectral width refers to the velocity dispersion (Woodman 1985).

The pulse pair technique is also often used in the estimation of Doppler velocity, particularly for Doppler radar. This method estimates the first two moments of the Doppler spectrum from estimates of the auto-correlation function at one sample lag. The Doppler power spectrum is a Fourier transform pair with the auto-correlation function (Wiener-Khichin Theorem). The auto-correlation at one sample lag can be estimated as

\[ R(T_s) = \frac{1}{M} \sum_{m=0}^{M-1} V^*(m) V(m+1) \]

where \( V \) is the signal at the \( m \) th sample each of which is spaced at \( T_s \), and \( M \) is the total number of samples used in the calculation (Doviak and Zrnic 1993). In the pulse pair technique, the mean change of phase over time is estimated by the argument of the auto correlation function at one lag and gives the mean Doppler shift.
N = Noise power
$\bar{N}$ = Average Noise
$f_D$ = Doppler frequency
$P_r$ = Signal Power
$W_f$ = Spectral width
$\Delta f$ = Frequency step size

Fig.2.5: (a) Elements of the Doppler power spectrum. (b) Shown are the mean noise level, the Zeroth (Power), first (mean) and second (spectral width) moments of the power spectrum. The ratio of the signal ($S$; above the noise level), to the noise underneath the signal peak ($N$) is the signal to noise ratio.

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The complex auto correlation function has an amplitude and phase. This phase angle expressed as \( \text{Arg } R(Ts) \) is the mean change in phase between two successive samples in the sample interval \( Ts \). Ground clutter generally introduces a symmetrical spectral peak close to the zero Doppler frequency. This is only an issue for targets at a distance greater than the first range gate although nearby objects may contribute to beam blockage. The effect of ground clutter is to bias radial velocity estimates towards zero.

Many techniques have been applied to reduce the impact of ground clutter both before measurement and after measurement. Ground clutter contamination can be reduced by siting the profiler in a favourable topographic environment or by using a clutter fence to block waves travelling along the surface towards the radar.

Post measurement clutter removal techniques have varied from simple n-point interpolation about the zero Doppler frequency (Strauch et al. 1984), and half plane subtraction (Passarelli et al. 1981), and DC removal, to the application of neural networks (Clothiaux et al. 1994) and wavelet analysis on the time series (Jordan et al. 1997). Intermittent clutter from airborne targets (e.g., birds or aircraft) and communications equipment also interferes with the returned signal. Techniques for
reducing this interference have been developed by researchers including Merritt (1995) and Jordan et al. (1997).

The radial velocity estimates can be used to derive horizontal and vertical velocity. The horizontal winds are calculated using the beam geometry and an assumption of statistical homogeneity between the beams (Figure 2.6). An example for a three beam system with a vertical beam and two beams inclined from the zenith by $\theta$ towards the east and north, the zonal velocity ($u$) is given by

$$u = \frac{V_E - w \cos \theta}{\sin \theta}$$  \hspace{1cm} (2.10)

where $V_E$ is the east beam radial velocity, $w$ is the vertical beam radial velocity.

The meridional component ($v$) can be derived by substituting the north beam radial velocity

$$v = \frac{V_N - w \cos \theta}{\sin \theta}$$  \hspace{1cm} (2.11)

These equations assume a spatially uniform wind field over the beam separation. Since the beam measurements are not taken simultaneously, a suitable averaging period is needed.
Fig. 2.6 Beam geometry. The Horizontal wind is determined by the vertical velocity \( w \) and the radial velocity \( V(\theta,R) \) from a beam inclined \( \theta \) from the vertical. The height of the observation is given by \( Z \) and the range by \( R \).

2.7 Experimental Techniques and Data Processing

Radar remote-sensing techniques used in the field of probing the earth’s atmosphere are discussed in brief. The scattering mechanisms such as Bragg scattering, Fresnel scattering/reflection and Rayleigh scattering in relevant to the radar remote sensing of the atmosphere and specific to the present study are outlined. A brief description of state-of-the-art- radars such as the Lower Atmospheric Wind Profiler (LAWP) also
known as Boundary Layer Radar (BLR) is used, for this study are also described briefly. The signal and data processing techniques as applied to the two radar systems are explained. The data processing applied for interpreting the radar data in terms of clear air and precipitating conditions is also discussed in details.

(ii) Computation of Zonal (U), Meridional (V) and Vertical (W) Wind:

After computing the radial velocity for different beam positions, the absolute velocity (UVW) can be calculated. To compute UVW, at least three non-coplanar beam radial velocity data are required. Least square method [Sato, 1989] will give an optimum result in estimating the three dimensional wind vector, when there are more than three non-coplanar beams data are available.

After computing the radial velocity for different beam positions, the absolute velocity (UVW) can be calculated. To compute UVW, at least three non-coplanar beam radial velocity data are required. If there exists more than three non coplanar beams data, then the computation will give an optimum result in the least square method. The line-of-sight component, V_d of the velocity vector V=(V_x, V_y, V_z) at a given height is expressed as

$$\overline{V_d} = \overline{V_i} = V_x \cos \theta_x + V_y \cos \theta_y + V_z \cos \theta_z \quad (2.12)$$

where i is the unit vector along the radar beam and X, Y and Z directions.
are aligned to East-West, North-South and Zenith respectively, $\theta_x$, $\theta_y$ and $\theta_z$ are the angles that the radar beam makes with the X, Y and Z axes.

Applying least square method [Sato, 1989].

$$
\varepsilon^2 = (V_x \cos \theta_x + V_y \cos \theta_y + V_z \cos \theta_z - V_{Di})^2
$$

(2.13)

Where, $V_{Di} = f_{Di} * \frac{\lambda}{2}$ and i represents the beam number.

To satisfy the minimum residual, $\frac{\partial \varepsilon^2}{\partial V_k} = 0$, K corresponds to X, Y and Z.

$$
\vec{V_d} = \vec{V} = V_x \cos \theta_x + V_y \cos \theta_y + V_z \cos \theta_z
$$

(2.14)

where $V_d = -f_d \frac{\lambda_R}{2}$; Thus solving equation (2.14) we can derive $V_x$, $V_y$ and $V_z$, which corresponds to U (Zonal), V (Meridional) and W(vertical) components of wind velocity.

(iii) Calculation of Horizontal wind speed ($V_h$) and Wind direction:

Horizontal wind speed or simply wind speed and wind direction can be obtained as follows

$$
V_h = \sqrt{(U^2 + V^2)}
$$

(2.15)

Wind direction = $\tan^{-1}(V/U)$

(2.16)
2.8 Atmospheric Refraction:

Refraction on the troposphere relies on the variations in space of the refractive index \( n \). Typically, the refractive index falls with increasing height. The refractive index governs the speed of propagation in a medium - which can be seen from the equation for the electric field in space and time. If the refractive index falls with height, the wave front will be progressively refracted downwards: This downward bending can compensate to more or lesser effect for the curvature of the earth - i.e. the radio waves can propagate beyond the visible horizon.

![Figure 2.7- Propagation over horizon](image)

Typically, the refractive index in the troposphere falls slowly with height and the resulting refraction causes the radio horizon to appear to be 1.33 times further away than the geometric horizon. The value of the refractive index of air is very close to unity, typically 1.0003. To make figures easy a new value is defined - the refractivity. The refractive index of air and
hence $N$ depends mainly on the atmospheric pressure $P$ (millibars), the temperature $T$ (Kelvin) and the partial pressure of water vapour $e$ (millibars) through the following relation. There are two terms, the 'dry term' which covering dry gases, mainly Nitrogen and Oxygen and the 'wet term' governed by water vapour. The atmospheric pressure falls exponentially with height, falling to $1/e$ (that is $e$ an in natural logs) of the surface value at a height of 8km. Temperature falls by about 1 degree every 100m. The behavior of water vapour is much more complex as it is governed by the weather and is limited to the saturated vapour pressure (how much water the air can hold before it condenses as rain or ice). The saturated water vapour pressure is around 40 mbar at 300K (a warm day) and 6mbar at 273K (freezing). As a result, the amount of water vapour above the zero degree isotherms is negligible.

The net result is that $N$ usually decreases by $\sim 40$ N units per km in temperate regions. This decrease is called the lapse rate of $N$. Variations in pressure; temperature and humidity do cause significant deviations in the lapse rate. Values of $N$ that are greater than $-40$/km cause sub-refraction, between $-40$ to $-75$/km cause normal refraction, between $-75$ to $-157$/km cause super-refraction, the $N$ values bellow $-157$/km cause ducting.

If the decrease of $N$ with height exceeds $\sim 157$ units per km, the radiowaves will follow the curvature of the earth in a phenomenon often termed 'ducting'. Another parameter that is useful in studying propagation
is the concept of the effective earth radius 'k' factor. Remember that radiowaves normally propagate 1.33 times the geometrical horizon distance.

For terrestrial planning, we are interested in the relative curvature of the radiowaves compared with that of the earth. By using the concept of the k-factor, calculations of the distance to the horizon can be made more easily. It is possible to model propagation over the earth by appropriately adjusting the k-factor so that the radio waves appear to travel as straight lines and the earth 'bulges' less than usual. It is then easy to check for obstructions against a path profile. When the amount of adjustment to the curvature of the radiowave paths is by the effective earth radius, the radiowaves will travel in straight lines relative to the terrain.

2.9 Anomalous Propagation:

As has already been stated, the refractive index of the atmosphere generally falls with height with a lapse rate of -40 units/km and this leads to some bending of radiowaves towards the ground allowing them to propagate beyond the geometric horizon. This is normal propagation. When there is anomalous propagation the cause is of course an abnormal change in refractive index with height as shown in Figure 2.7 above. The anomalous propagation effects that are of most interest are those that cause radiowaves to propagate much further than normal. It can be
shown using the small angles approximation (sine ≈ tan e) that the radius of curvature of a radiowave is very close to the rate of change of the refractive index n with height.

\[
\text{Radius of curvature} = -\frac{dn}{dh}
\]  

(2.17)

The curvature of the earth is the inverse of the radius of \( \frac{1}{6378} \) km. This equals \( 157 \times 10^6 \) km. Remember that the value of N is equal to \( n \times 10^6 \). Therefore if the lapse rate of N (dN/dh) is equal to 157 units/km the radiowave will follow the curvature of the earth. If the lapse rate is greater than 157 units/km radiowaves are bent down towards the earth becoming trapped near the surface and can propagate over very long distances.

The radiowaves can become trapped between a layer in the troposphere and the surface or even between layers in the troposphere depending on the refractivity profile. This is generally called a duct and is a waveguide like mode of propagation. As a result, energy is constrained into two dimensions as it can spread out horizontally but not vertically. This means the path loss increases directly with range rather than with range squared, resulting in much lower path losses and very high signal levels at long ranges.

When trapped between an elevated layer and the surface in a surface duct, extended propagation will occur if the reflection from the ground is low loss. The angles are small and low loss reflections can
occur, especially where the roughness of the terrain is small compared to the wavelength. When trapped between layers within the troposphere in an elevated duct is formed and the refraction loss depends on the roughness of the layers.

![Figure 2.8 - Surface and Elevated Ducts](image)

**Frequency Sensitivity**

There are two constraints on the ability of a duct to contain and propagate RF energy at different frequencies. The first, which places a lower bound on the frequency, is that the size of the duct has to be sufficient to propagate in a waveguide mode. The second is that the roughness of the boundary layer must be low in relation to the wavelength as otherwise; energy will leak out of the duct. This puts an upper frequency bound on the ducts ability to propagate radiowaves. Small variations in horizontal refractive index generated through turbulence...
become increasingly important at microwave frequencies. Surface ducts lower bound always follow the ground contour and the same is true to a lesser extent for the elevated boundary - radiowaves in ducts do not cross mountains.

Coupling into a duct

Ducts can only trap energy if the angle of incidence at the duct is relatively small - a value derived from Geometric Optics gives the maximum angle in comparison to the refractivity gradient:

$$\theta_{\text{max}} = 0.081(\sqrt{\Delta N}) \text{ Degrees} \quad (2.18)$$

As the refractivity gradient across the layer is unlikely to be more than 50-100 N units, the maximum coupling angle is under a degree and very often much less. That means that effectively to couple into a duct well, the elevation to the horizon should not be greater than 0.5 degrees and conversely that a fair amount of protection from long distance interference can be obtained using site shielding.

2.9.1 The causes of Anomalous Propagation:

The major cause of ducting is humidity and temperature inversion. The pressure lapse rate does not vary much as winds soon restore equilibrium. Substituting typical starting values of Pressure P of
1000mbar, Temperature T 273k and water vapour pressure e of 15mbar in equation 2.19 gives a sensitivity analysis.

\[
\delta N = 0.26 \delta P + 4.3 \delta e - 1.4 \delta T
\]  (2.19)

Ignoring the pressure we will concentrate variations in the lapse rate of N promulgated through variations in e and T.

**Temperature Inversions:**

Usually, temperature falls with height by about 1K per 100m. On clear nights the ground cools quickly and this can result in a temperature inversion, where the air temperature rises with height. If it is dry, the temperature term is dominant in Equation 2.19 and super refraction and ducting can occur. This is particularly common in desert regions.

If there is significant water vapour the relative humidity can quickly rise to 100% and vapour condenses out as fog. This condensation reduces the water vapour density near the ground leading to cold dry air near the ground, warmer moister air above and results in sub-refraction. This can lead to multipath on otherwise apparently perfectly good line of sight links.

**Subsidence:**

This is a mechanism that can lead to elevated ducts and is associated with high pressure weather systems - anticyclones.
Descending cold air forced downwards by the anticyclone heats up as it is compressed and becomes warmer than the air nearer the ground leading to an elevated temperature inversion. (Atmospheric pressure always increases closer to the ground). This all happens around 1-2km above the ground far too high to cause ducting except for very highly elevated stations as the coupling angle into the duct is too great for a ground based station. As the anticyclone evolves the air at the edges subsides and this brings the inversion layer closer to the ground. A similar descending effect happens at night. In general, the inversion layer is lowest close to the edge of the anticyclone and highest in the middle. Anticyclones and subsequent inversions often exist over large continents for long periods.

Absorption, Refraction and Anomalous Propagation:

As EM energy propagates through the atmosphere, it is attenuated (i.e., undergoes a loss in overall energy) by absorption and scattering. The major gaseous absorbers in the atmosphere are water vapor, carbon dioxide, ozone, and oxygen. Each is selective about what it absorbs, (e.g., oxygen absorbs UV energy), but for most radar, absorption is fairly negligible in terms of its effect on EM propagation. EM energy is also scattered by liquids and solids in the atmosphere. This effect is greatly dependent on the size of the particle in relation to the wavelength, but as with absorption, scattering represents a small factor in EM propagation.
Changes in temperature, moisture, and pressure in the atmospheric column cause a change in atmospheric density, which in turn causes variations in the speed of EM waves in both the vertical and horizontal. These changes in speed lead to changes in the propagation direction, or bending, of the waves. The bending of EM waves as they pass through the atmosphere is an example of refraction (see Figure 2.9).

Refraction is always such that the waves turn toward the medium in which they ravel more slowly, as they pass from a faster speed medium into a slower speed medium. This is the case shown in Figure 2.9, where medium a is the faster speed medium. Refraction causes waves to turn back toward the slower speed medium as they pass from the slower into the faster medium. You can visualize this case if you mentally reverse the arrow directions in Figure 2.9.

Refraction can cause waves to bend back toward the slower speed medium as they try to propagate into a faster speed medium. This analogous to the way a car that veers onto a soft sandy shoulder on the side of a road turns toward the sandy area in which it travels more slowly. This bending toward the slow speed medium can lead to trapping in which waves are unable to propagate out of the slow speed medium. Some amount of refraction is always present in our atmosphere, and is quite normal. However, when the structure of the atmosphere causes abnormal bending of the energy waves, anomalous propagation (AP) occurs. AP takes place when an unusual, other-than-normal vertical
distribution of temperature, moisture, and pressure exists within the atmosphere.

Figure 2.9 – A simple refraction

Figure 2.10 shows schematically some examples of normal and anomalous radar heights and ranges. The AP regions indicate the height and range effects of anomalous temperature, moisture, and pressure distributions. Note that AP can greatly extend, or reduce, the height and/or range of radar.

Figure 2.10 - Anomalous Propagation