CHAPTER II
TROPOSPHERIC PROPAGATION
2.1 INTRODUCTION

An introduction to the thesis describing the background and objective of the present study are given in chapter I. In the present chapter, radiopropagation through the troposphere and effects of meteorological parameters on tropospheric propagation are described. Different models of the troposphere and various propagation mechanisms are also discussed in this chapter.

The troposphere is the region of the atmosphere extending from the surface of the earth up to a height of 8 to 10 kilometers at the polar latitudes, 10 to 12 kilometers at the moderate latitudes, and up to 16 to 18 kilometers at the equator (Dolukhanov, 1971). The troposphere is generally characterized by a positive lapse rate of temperature and is the region to which precipitation and clouds are confined. The primary effects of troposphere on radio propagation can be classified as

(i) Absorption by atmospheric gases
(ii) Attenuation due to hydrometeors
(iii) Refraction effects changing the direction of radio rays and leading to fluctuations in angle-of-arrival, de-focussing, multipath fading and ducting
(iv) Tropospheric scatter from turbulent fluctuations in the refractive index
(v) Scintillation on terrestrial and earth space-paths.

The relative importance of these factors depends upon the type of radio system involved, operating frequency and geographical location, etc. Several researchers (Stephansen, 1981; Assis, 1987; Reddy, 1988;
Olsen, 1989) have revived the progress of microwave propagation, and various propagation factors affecting the reliability of different systems.

The effects of absorption by atmospheric gases and attenuation due to hydrometeors are negligible for frequencies below 10 GHz but are limiting factors in the system design for frequencies above 10 GHz.

Nevertheless, the thrust for using ever higher frequencies continued mainly because of three factors. First, the congestion of frequency spectrum, due to crowding and sharing; secondly, the requirement for more bandwidth to accommodate the exploding requirements for information transmission; in different media such as facsimile, e-mail etc., and thirdly, the limited availability of slots in the geostationary orbit for space communication.

The use of higher frequencies has become imminent as the need for wider bandwidth is on the increase. Consequently, radio links operating in the frequency range of VHF, UHF and SHF have been developed. However, the propagation at these frequencies is subject to influence by meteorological processes in the troposphere (Reed, 1953; Ikegami, 1959; Barnett, 1972; Lin, 1977; Schiavone, 1982; Bundrock and Murphy, 1984; Claverie, 1985; Rana, 1992). The most important parameter in the troposphere which affects the radiowave propagation is the radio refractivity and its random fluctuations. In addition to radio refractivity fluctuations, precipitation and rain affect the microwave propagation especially in SHF. To understand the quality and long term variability in any communication system operating in the troposphere, it is important to determine the variability in the atmospheric parameters.
2.2 GASEOUS ABSORPTION

Oxygen and water vapour are the two main constituents of the earth's atmosphere that absorb the radio energy. Absorption takes place owing to the resonance of molecules of water vapour and oxygen. The first four well known absorption bands are centered at frequencies of 22.2 GHz \((\text{H}_2\text{O})\), 60 GHz \((\text{O}_2)\), 118.8 GHz \((\text{O}_2)\), and 180 GHz \((\text{H}_2\text{O})\). Oxygen possesses a small magnetic moment which interacts with the magnetic field of the radio wave giving rise to absorption lines around 60 GHz and 120 GHz (Van Vleck, 1947; Standberg, 1949; Artman, 1954; Stafford 1963). Similarly absorption by water vapour is due to transition between different molecular energy states with resonant frequencies at and above 22 GHz (Becker, 1948; Van Vleck, 1947).

The absorption due to oxygen is fairly constant and predictable. However, the water vapour content of atmosphere is highly variable and hence attenuation due to water vapour on a given path can not be estimated easily. Figure 2.1 shows specific attenuation \(\gamma\) at a water vapor density of 7.5g/m\(^3\) for frequencies from 10 to 350 GHz. The specific attenuation for other values of water vapor density can be calculated by the formula (Reddy, 1988)

\[
\gamma_w = \left( \frac{m}{7.5} \right) \gamma_{w7.5} \quad \ldots (2.1)
\]

where \(\gamma_{w7.5}\) is the value obtained from figure 2.1.

Generally frequencies are selected outside these absorption bands, known as atmospheric windows for radio communication systems. But frequencies in the absorption band find application in remote sensing.
FIG. 2.1: SPECIFIC ATTENUATION $\gamma_o$ AND $\gamma_w$ DUE TO OXYGEN AND WATER VAPOUR

- a) $\gamma_o + \gamma_w$ for $f$ 10 GHz
- b) $\gamma_w$ for $f$ 10 GHz
- c) $\gamma_o$ for $f$ 10 GHz
- d) $\gamma_o$ for $f$ 10 GHz

Scale 'A'
Scale 'B'

Pressure: 1 atm (1013 mb)
Temperature: 20° C
Water vapour density: 7.5 gm/m³ (i.e., $\gamma_w = 7.5$)
2.3 ATTENUATION DUE TO HYDROMETEORS

At frequencies of SHF and above rain attenuates the radiowaves considerably. Small displacement currents set up in hydrometeors interacting with radiowave give rise to re-radiation (scattering) and absorption (due to heating). The effects of fog and cloud are comparatively less severe. Snow and hail have a relatively small effect, because the complex permittivity of ice is much less than that of water. The relative contribution of scattering and absorption to attenuation by rain depends on the size of the rain drops compared to the radio wavelength (Zavody, 1974). For wavelengths which are large compared to drop size, attenuation due to absorption will be greater than that due to scattering. Conversely, for wavelengths shorter than drop sizes the attenuation due to scattering will predominate. The attenuation due to rain for a given radio frequency depends on rain rate, rain drop size and its distribution (Ippolito, 1981).

Other effects of precipitation include depolarization, rapid amplitude and phase fluctuations known as scintillations, antenna gain degradation and bandwidth coherence reduction (Ippolito, 1981). Depolarization due to non-sphericity of rain drops limits the performance of frequency re-use systems because of reduced cross polarization discrimination. Scattering from rain may also cause inter-system interference by directing unwanted signals to another RF system operating at same frequency (Crane, 1981). However rain scatter is advantageously used for tracking severe storms with radars operating at decimetric and centimetric wavelengths. More recently, radars operating at 5-10 cm wavelengths have been successfully used to measure rainfall.
rates and the importance of these is that, data can be collected in considerable detail over a large area almost instantaneously (Seliga, 1976).

2.4 RADIO REFRACTIVITY

Since the refractive index, $n$, of the atmosphere at the surface of the earth is only 0.0003 percent greater than unity, it is more convenient to refer to variations in the refractive index in $N$-units

$$N = (n-1) \times 10^{-6} \quad \ldots (2.2)$$

where $N$, is the excess index of refraction. It is the excess over the unity of the refractive index expressed in millionths. The refractivity depends on pressure, temperature and humidity and is given by an empirical formula (Smith, 1953)

$$N = 77.6 \times \frac{P}{T} + 3.73 \times 10^{-5} \frac{e}{T} \quad \ldots (2.3)$$

where $P$ is the atmospheric pressure in millibars
$T$ is the temperature in degrees Kelvin
$e$ is the water vapour pressure in millibars

The first part of equation 2.3 is known as "dry term" and the second part is known as "wet term". The error in $N$ (due to fluctuations in pressure, temperature, and humidity) is given by

$$\Delta N = 0.27 \Delta P - 1.3 \Delta T + 4.5 \Delta e \quad \ldots (2.4)$$

for $P = 1000$ mb, $T = 288$ K, and $e = 11.9$ mb
From the above expression for $\Delta N$, it is evident that inaccuracies in humidity measurements will yield more erroneous refractivity values than those in pressure and temperature.

### 2.5 TROPOSPHERIC REFRACTIVITY MODELS

Models of refractivity are usually developed for prediction of refractivity effects such as ray bending, defocusing etc., in the absence of the measured data. Various models available are effective earth's radius model, CRPL reference atmosphere, exponential model, ARDC model atmosphere etc.

#### 2.5.1 Effective Earth's Radius Model

The concept of effective earth's radius factor ($K$) is introduced to account effects of atmospheric refraction. It is given by the ratio of effective earth's radius, $a'$ to the true earth's radius, $a$.

$$K = \frac{1}{\frac{a}{dN} \left(1 + \frac{1}{\cos\theta} \right)^n}$$  \hspace{1cm} \text{... (2.5)}

$$K = \frac{1}{\frac{a}{dN} \left(1 - \frac{1}{4a} \right)^{6n}} \text{, for } \theta = 0 \hspace{1cm} \text{... (2.6)}$$

where '$\theta$' is the elevation angle of the ray, 

'h' is the height of the layer.

Further by setting $\frac{dn}{dh} = -1/4a$, we get a value of $K=4/3$, which corresponds to standard atmospheric conditions.
The distribution of refractive index implied by this method is not a very realistic representation of average refractive index structure of the atmosphere. This implies that \( n \) decreases linearly with height which is not always true.

2.5.2 Exponential Model

The average exponential atmosphere is defined by CCIR (1986)

\[
N(h) = N_s \exp(-bh)
\]  

where \( N(h) \) is the refractivity at height '\( h \)’, measured in \( \text{km} \) and \( N_s \) the mean surface refractivity which is 315 \( \text{N-units} \) and the constant \( b = -0.136 \text{ km} \). For sufficiently small heights, the decrease in refractivity is approximately linear.

2.5.3 ARDC Atmosphere

This model uses different equations for the computations of pressure, temperature, water vapour at different latitudes. For a tropical annual average atmosphere(15 \( \text{N} \)) the following expressions hold good [Brussard et al, 1983]

\[
P(h) = 1012.0306 - 109.0338h + 3.6316h^2, \quad 0 < h < 10 \quad \ldots (2.8)
\]

\[
P(h) = 10 \exp(-0.147(h-10)), \quad 10 < h < 72 \quad \ldots (2.9)
\]

\[
T(h) = 300.4222 - 6.3533h + 0.005886h^2, \quad 0 < h < 17 \quad \ldots (2.10)
\]

\[
\rho(h) = 19.6542 \exp(-0.2313h - 0.112h^3 + 0.01351h^4) - 0.0005923h^3, \quad 0 < h < 15 \quad \ldots (2.11)
\]

with \( P \) in millibars, \( T \) in degree Kelvin, \( \rho \) in \( \text{gm/m}^3 \).
2.6 CLASSIFICATION OF REFRACTIVITY GRADIENTS

The magnitude and sign of the refractivity gradient decide the nature of propagation mechanism. Various researchers (Bean and Dutton, 1966; Venkiteshwaran, 1970) have described propagation mechanisms associated with refractivity gradients and these are summarized below.

2.6.1 Sub Refraction \( (\Delta N/\Delta h > -40 ) \)

Sub-refraction occurs when \( N \) increases with height, owing to positive water vapour gradient, causing radiowaves to bend upwards, opposite in sense to the curvature of the earth's surface. Radar and other LOS ranges are significantly reduced.

2.6.2 Normal Refraction \( (-40 > \Delta N/\Delta h > -75 ) \)

Normal refraction is found when refractivity gradient lies between -40 N-units/km and -75 N-units/km, rays curve downward in the same sense as curvature of the earth's surface. This occurs in a well mixed atmosphere due to thermal convection.

2.6.3 Super Refraction \( (-75 > \Delta N/\Delta h > -157 ) \)

Super refraction prevails if the refractivity gradient is more negative than the normal, causing a greater downward bending of the radio waves. Often gradients less than -75 N-units/km are classified as super refractive gradients, occurring under the conditions of steep humidity lapse rate often associated with temperature inversions in the boundary layer.
2.6.4 Ducting ($-157 > \Delta N/\Delta h$)

Ducting is an intensified form of super refraction that may trap radio waves, causing them to propagate over extended ranges. The first necessary condition for a duct to occur is that the refractivity gradient be equal or more negative than $-157$ N-units/km. The second condition is that this gradient should be maintained over a minimum height depending on the frequencies to be trapped. The maximum wavelength that can be supported by a duct is given by the following equation (Hall, 1979)

$$A_{\text{max}} = 2.5 \times 10^{-5/2} (\Delta N/t - 0.157)^{1/2} t^{3/2}$$  \hspace{1cm} (2.12)

where $\Delta N$ is the change in refractivity across the duct and $t$, the thickness in meters. The basic transmission corresponding to propagation between two terminals immersed within the duct in dB, is

$$L = 92.4 + 20 \log f + 10 \log d + ad + L_c$$  \hspace{1cm} (2.13)

where $f$ is the transmission frequency in GHz, $d$ is the distance in km, $a$ duct attenuation coefficient, and $L_c$ an aperture to medium coupling loss (Hall, 1979; Dougherty, 1987). $L_c$ is related to the half power beam width (3dB) by the expression

$$L_c = 10 \log \left( \frac{\theta(3\text{dB})}{20} \right) \text{ dB}$$  \hspace{1cm} (2.14)

where $\theta(3\text{dB}) > 20$ and $L_c = 0 \text{ dB}$ otherwise. When one or both signal sources are exterior to the duct, the coupling losses will be considerably higher than those indicated above. Because of the unpredictability in the duct occurrence, ducting cannot be used as a
reliable mode of communication (Dolukhanov, 1971) and often duct propagation ends as a source of interference (Crane, 1981).

2.7. VARIABILITY OF REFRACTIVITY GRADIENT

Hall and Comer (1969), while reporting the refractivity gradients measured over a height interval of 75m, 150m, 500m and 1000 m in U.K, observed that gradients measured over smaller height intervals showed greater variability than those measured across larger height intervals.

Sarkar (1978) has deduced the gradients between surface and 250 m over Indian subcontinent and reported that highest gradients are observed in coastal zones in premonsoon months and lowest values in monsoon months over Srinagar region. Measurements of refractivity gradients carried out across 1 km height interval have shown inverse correlation between refractivity gradients and surface refractivity. The relation is given by

\[ \frac{dN}{dh} = -A \exp(BN) \]  ... (2.15)

where the ranges of A and B are, 2.1<A<9.3 and 0.0045<B<0.0094 (Hall, 1979).

2.8 TROPOSPHERIC PROPAGATION MECHANISMS

Three tropospheric propagation mechanisms well known are (i) Line-of-sight (ii) Diffraction (iii) Troposcatter. Line of sight is within the horizon whereas diffraction and scatter are beyond the horizon.
2.8.1 Line-of-sight propagation

Terrestrial line-of-sight microwave radio links form the backbone of telecommunications. In line-of-sight propagation the received field is a combination of direct ray, ground reflected ray with possible contributions from scatter, layer reflection etc. The interference among various rays gives rise to random fluctuations in amplitude i.e. fading, which is the main source of outage in analog and digital microwave links. The field strength on LOS link can be calculated as (Sarkar, 1987)

\[
E = E_1 + E_2 \quad \ldots \ (2.16)
\]

where \( E_1 \) = instantaneous field due to direct ray

\( E_2 \) = instantaneous field due to ground reflected ray

\[
E_2 = \frac{1}{2} \exp \left[ 1 \left( wt - \theta - \left( \frac{2\pi}{\lambda} \Delta r \right) \right) \right] \quad \ldots \ (2.17)
\]

where \( P \) = transmitted power

\( G \) = gain of the transmitting antenna

\( \lambda \) = wavelength

\( R \) = reflection coefficient

\( r \) = propagation length

\( \Delta r \) = path length difference

The field due to layer reflection is estimated by means of an expression given by (Eklund and Wickerts, 1968)

\[
E = \frac{E^{(n)}}{3} \quad \ldots \ (2.18)
\]

\[
E^{(n)} = \frac{2}{4 \varphi \left[ 1 + (\pi b \varphi / \lambda) \right]^{2.2}} \quad \ldots \ (2.18)
\]
where \( E \) = free space field
\( \phi \) = grazing angle
\( b \) = thickness of layer
\( \Delta n \) = change in refractive index through the layer. The resultant field,

\[
E = E_1 + E_2 + E_3 \quad \ldots \quad (2.19)
\]

To characterize the multipath fading on digital microwave links various propagation models have been developed (CCIR, 1986; Townsend, 1988).

2.8.1.1 Obstruction fading

Under the conditions of positive refraction, ray paths bend upward effectively, increasing the earth's bulge; the bulge reduces the clearance of ray paths at potential obstruction points and diffracts the radio waves. This phenomenon is commonly known as diffraction fading. The amount of signal attenuation due to diffraction fading depends on the nearness of ray trajectory to the terrain which can be conveniently treated in terms of Fresnel zone radii. The LOS systems can be engineered to alleviate the problem of obstruction fading by erecting towers of sufficient height so that at least grazing angle clearance is maintained under adverse conditions. The criterion of an allowance for ray paths equal to at least 0.6 of the first Fresnel zone is to be secured along the entire path for lossless propagation, since the aggregate contribution due to all the adjacent higher order zones amounts to about half of that by first Fresnel zone (Dolukhanov, 1971).
2.8.1.2 Multipath Fading

Multipath fading arises on line-of-sight radio links when there exist more than one path for rays reaching the receiver. The rays arriving from these paths interfere with each other resulting in substantial variations in the phase and amplitude of the received signal (Bullington, 1950). In analog systems, multipath fading contributes to thermal noise and intermodulation noise. In digital radio systems, multipath propagation contributes to inter-symbol and intrasymbol interference as well as a direct degradation of the signal to noise ratio. Frequency and vertically spaced antenna diversity are the two main methods used to mitigate the effect of multipath fading (Boithias, 1967; Vigants, 1975). Often a combination of these two, known as quadruple diversity system, is used to remedy effectively the problem of severe fading.

2.8.1.3 Power Fading

Power fading results from partial isolation of transmitting and receiving antennas because of:

1) Intrusion of earth's surface or atmospheric layers into propagation path (earth bulge fading or diffraction fading)
2) Antenna decoupling due to variation of refractive index gradient
3) Partial reflection from elevated layer interpositioned between terminal antenna elevations
4) Ducting formation containing only one of the terminal antennas
5) Precipitation along the propagation path
The received signal for these power fading mechanisms is characterized by marked decrease in median level below free space values and for extended period of time. These mechanisms are also basic because the most efficient fading remedies are keyed to recognizing the causative mechanisms (Mon et al., 1980; Schiavone, 1982).

The critical factor in all radio propagation models is the large scale vertical variation of radiorefractivity and the extent to which it changes with time. The height range of its significance depends on the path length viz., in LOS mode, the variation in first few hundred meters is important whereas in the scatter mode the variations upto 1 Km influence the scattered power. The large temperature changes and steep humidity gradients modify the radio refractivity index profile and lead to varied propagation conditions in the first few hundred meters.

2.8.1.4 Angle-of-arrival Variation

The variations in the angle-of-arrival are caused by changes in the mean refractivity gradients, for single path propagation. The variations in the angle-of-arrival are greater in vertical plane and are approximately proportional to the path length. The ranges of specific change in the angle-of-arrival covering 99.8% of the time may be taken as $+2 \times 10^{-3}$ deg/km for dry inland paths and $+14$ to $-5 \times 10^{-3}$ deg/km for humid coastal regions (CCIR, 1982). Angle-of-arrival discrimination using some form of adaptive array appears to show promise since the angular separation in most circumstances is a good fraction of a degree and not too dependent on layer parameters (Webster, 1982).
2.8.1.5 Ducting

While ducting significantly increases the signal levels much beyond the horizon, low level ducts have a catastrophic effect on the line-of-sight propagation. The effect of ducting is more pronounced if ducts occur close to the antenna. Several studies have been made on the problem of duct fading on terrestrial line-of-sight radio links (Ikegami, 1959, 1966). It is suggested that duct fading on LOS links can be effectively alleviated by using the quadruple diversity system.

2.8.2 Tropospheric Scattering

Small scale refractive index irregularities are produced by turbulence in the troposphere. If these refractive index irregularities are of sufficient intensity, they will scatter radio energy, and the amount of scattering in a given direction will depend on the spatial distribution of irregularities and radio wavelength (Schelling, 1933). Scattering may be divided into forward and backward scattering depending on the direction of the scattering signal. Back scattering is very weak and is mostly used for atmospheric probing, while forward scatter is used for radio communications beyond the horizon.

Large-scale spatial variation in the refractive index of the troposphere arises due to horizontal movement of one air stream over the other, vertical movement of the moist, warm air particles and any other process of entrainment where by particles of one air mass is injected into a neighbouring region of different temperature and humidity.

Tatarskii (1971), did extensive work on the influence of atmospheric turbulence on electromagnetic wave propagation and suggested
that for the homogeneous and isotropic turbulence the spectrum of refractive index fluctuations may be given by

\[ F(k) = 0.25 C_k k^{-5/3} \]  \hspace{1cm} (2.20)

for a one dimensional case, and

\[ Q(k) = 0.033 C_k k^{-1/3} \]  \hspace{1cm} (2.21)

for a three dimensional case, where \( C_k \) is the refractivity structure constant and \( k \), the wave number.

### 2.8.2.1 Scintillations

Scintillation, a direct consequence of turbulence, is a phenomenon of fluctuations in phase and amplitude of received signal caused by random fluctuations (temporal) in spatial distribution of refractive index along the path of propagation. This produces a slight focusing and defocussing of line-of-sight radio beam (Hall, 1979). In general terms, the standard deviation of logarithm of received power \( \sigma_s \) is given as (Tatarskii, 1971).

\[ \sigma_s^{-1/2} = 19.0 A \left( \frac{C(d) d^{5/6}}{dd} \right)^{1/2} \]  \hspace{1cm} (2.22)

where \( C_n^2 \) is the refractive index structure constant at distance \( d \) along the path. Both terrestrial and low elevation (<10°) earth space paths are influenced by this phenomena, particularly at frequencies greater than 10 GHz.

### 2.8.3 Knife Edge Diffraction

A propagation path with a common horizon for both terminals may be considered as having a single knife edge. The common horizon may be a
mountain ridge or similar obstacle (Kirby et al., 1955). In some cases, over relatively smooth terrain or over the sea, the common horizon may be bulging of the earth rather than an isolated ridge. This case is not covered under knife edge diffraction. The diffraction attenuation due to a single knife edge without ground reflections is given as

$$A(V,0) = 12.953 + 20 \log V$$  \hspace{1cm} \text{(2.23)}$$

while $V$ is defined by

$$V = \pm \left( \frac{2dtan\alpha_t\tan\beta_r/\lambda}{5} \right)^{-1/2}$$  \hspace{1cm} \text{(2.24)}$$

where $\lambda$ is the wavelength, $\alpha_t$, $\beta_r$, are transmitting and receiving angles and $d$ is the total path distance. In the case of line-of-sight path $V$ is negative and for transhorizon path $V$ is positive.

2.9 RAIN ATTENUATION

Attenuation can be experienced on terrestrial paths as a result of absorption and scattering by rain, snow, hail or fog. Of these, it is normally necessary to consider attenuation due to rain for very small percentage of time which are of interest in the system design. Although the rain attenuation can be ignored at frequencies below about 10 GHz, it must be included in design calculations at higher frequencies, where its importance increases rapidly.

When a passing radiowave sets up displacement currents in hydrometeors, part of the energy is absorbed (due to heating) and the remaining energy is scattered. The relative contribution of the two depends on the drop-sizes. At SHF where wavelengths are long compared
with drop size, absorption dominates the attenuation. At EHF, where dropsizes are large compared with wave lengths, scattering is responsible for the attenuation.

The total attenuation $A$ due to rain over a path length $(d)$ is given by,

$$A_R = \int_0^d \tau(r) \, dr$$

... (2.25)

where $\tau(r) = \text{specific attenuation}$.

$\tau(r)$ for a medium of sparsely distributed rain drops is given by

$$\tau = 4.343 \, Q(D)N(D)dD$$

... (2.26)

where $N(D) = \text{rain drop-size distribution}$, $Q(D)$ is the sum of absorption and scattering cross-section of a rain drop of diameter 'D' and is a function of frequency. Experiments have shown that the measured specific attenuation is related to rain rate 'R' as,

$$\tau = a \, R$$

... (2.27)

where 'R' is the rain rate in mm/hr and $a, b$ are constants which depend on the frequency and temperature. A number of prediction methods to compute attenuation from point rainfall statistics have been developed.

They are classified as:

i) Reduction coefficients are developed to convert the point rain rate to a path average rain rate $R$ from which the attenuation and its distribution can be calculated (Lin, 1977; Crane, 1980).
11) Point rain rate distributions are approximated by analytical expressions (Parametric methods, gamma, lognormal distribution) and model of spatial distribution to derive a path average rain rate distribution and hence to obtain a path attenuation distribution (Morita and Higuti, 1976).

2.10 MONITORING THE TROPOSPHERE

In-situ measurements and remote sensing are the two methods used for monitoring the tropospheric environment. The in-situ measurements give quantitative information, but they have several disadvantages like high cost and inherently limited spatial coverage, both in horizontal and vertical extents. In contrast, remote sensing using radio, optical and acoustical techniques can reveal the fine structure of the atmosphere to greater heights but often yield only qualitative information.

Instrumented towers, radiosondes, aircraft measurements, microwave refractometers, tethered balloons come under in-situ measurements category. Instrumented towers are used for measurement of meteorological parameters like pressure, temperature, humidity and wind speed and direction etc., at different heights above the ground. But the limitation for constructing high towers and number of towers restrict the use of tower measurements and limit the data. Conventional radiosonde measures the above meteorological parameters upto 20 km, but the data is available only twice a day and cannot provide continuous structure of the atmosphere. The sensitivity and rapidity of sensors used for measuring the humidity and temperature are often inadequate for radioclimatological studies. Slow rising radio-
sondes and tethered balloons (Morris et al., 1975) are developed to improve the resolution and accuracy of measurements (Hall, 1979), but the resolution is not sufficient to reveal the fine structure of the atmosphere. Consequently, microwave refractometers with a great accuracy were developed (Birnbaum, 1950; Crain, 1950) to measure refractive index directly. The disadvantage in microwave refractometer is that it requires specialized services for their operation and maintenance involving huge costs, and thus limiting the widespread usage.

The need to have a continuous structure of the atmosphere led to the development of FM-CW radar (Richter, 1969), VHF pulsed doppler radars (Dobson, 1970), MST Radar (Fukao et al., 1988; Balsley, 1988; Rao, 1990) acoustic sounder known as SODAR Mc Allister., 1968), Radio Acoustic Sounding System, RASS (Takahashi et al., 1988) and LIDAR (Anfossi., 1974). Basic principle of operation in all these techniques is to transmit electromagnetic energy of appropriate frequency (Acoustic energy in the case of SODAR and RASS, Light energy in the case of LIDAR) and to receive the echoes which are suitably processed and recorded.

In recent years the use of these systems has revolutionized the knowledge of atmospheric structure and processes in the lowest several kilometers range.