Chapter 2
Experimental Techniques

2.1 Introduction

Ionosphere is one of the regions of the terrestrial atmosphere, in which photo-ionization creates plasma of sufficient density to have significant influence on dynamics of the region [Louise and Keith, 2004]. The temporal (with time of the day, seasons, solar cycle etc.) and spatial (with the latitude and longitude on the earth) variations of ionosphere have significant effect on radio waves propagating through it. Thus it becomes important to study the ionosphere on day to day basis under different geophysical conditions at different geographical locations. In-situ measurements using rockets give inclusive database of state and conditions of the ionosphere. The ground based remote sensing techniques like radars help to study the temporal variability of the ionosphere, but addressing spatial variability with this is impractical. Conversely, the study of ionosphere using orbiting satellites resolves the problem of spatial variability moderately well.

Remote sensing by radio waves includes some of the major techniques for studying the ionosphere. These techniques are generally classified in three groups [Hargreaves, 1992]. (1) The radio wave may be totally reflected within the medium, ionosonde works on this principle, (2) Most of the energy may travel through the medium and a small fraction being scattered or partially reflected by constituents of the medium or by irregular structures, incoherent and coherent radar works on this principle, (3) It may pass through the medium but emerge altered, for e.g. passage of satellite signals from the ionosphere.

The techniques in first and second groups involve a transmitter and receiver both sited below or above the ionosphere. Greater sensitivity is needed for techniques in second because the returned echoes are very weaker. Techniques in third group generally require a source or a receiver above the ionosphere.
The multi-technique studies of ionosphere provides diagnostic tool to understand the ionospheric variability and various ionospheric phenomena with better clarity. The present thesis work has been carried out using some of the techniques which fall under the above groups. The following sections describe these techniques in detail.

2.2 Radio wave propagation from the ionosphere

Propagation of radio waves through the ionosphere depends on the radio refractive index of the medium. The radio refractive index for an ionized medium can be expressed by the Appleton – Hartree equation [Rishbeth and Garriott, 1969]. This equation is based on a simple explanation of the cold plasma considering the electron motions only. In addition to this it is also assumed that the electromagnetic wave induced disturbances in the plasma are small and do not affect the propagation itself, i.e. the problem is linearized.

The Appleton – Hartree equation for the complex index of refraction is given by

\[
\eta = 1 - \frac{X}{1 - jZ - \left( \frac{Y_T^2}{2(1 - X - jZ)} \right) \pm \left( \frac{Y_T^4}{4(1 - X - jZ)^2 + Y_L^2} \right)^{1/2}}
\]

(2.1)

In general \( \eta \) is complex. \( X, Y \) and \( Z \) are dimensionless quantities defined as

\[
X = \frac{\omega_p^2}{\omega^2} \\
Y = \frac{\omega_B}{\omega} \\
Y_L = \frac{\omega_L}{\omega} \\
Y_T = \frac{\omega_T}{\omega} \\
Z = \frac{\nu}{\omega}
\]

Here \( \omega_p \) is the angular plasma frequency, \( \omega_B \) is the electron gyrofrequency, and \( \omega_L \) and \( \omega_T \) are respectively the longitudinal and transverse components of \( \omega_B \).
with respect to the direction of propagation. Here \( \nu \) is the electron collision plasma frequency and \( \omega \) is the angular wave frequency.

If \( \theta \) is the angle between the propagation direction and the geomagnetic field than

\[
\begin{align*}
\omega_L &= \omega_B \cos \theta \\
\omega_T &= \omega_B \sin \theta
\end{align*}
\]  

Neglecting the collisions \( Z = 0 \) and the geomagnetic field \( Y = 0 \). Under this condition equation can be expressed as

\[
\eta^2 = 1 - X
\]

Where \( X = \frac{\omega_p^2}{\omega^2} \) and \( \omega_p = \left( \frac{N_e e^2}{m_e \varepsilon_0} \right)^{1/2} \)

Where \( N_e \) is the plasma density in cm\(^{-3}\), \( m \) is the mass of the electron and \( e \) is the electron charge. \( \varepsilon_0 \) is the permittivity of a vacuum.

\[
\eta^2 = 1 - \left( \frac{\omega_p^2}{\omega^2} \right)
\]  

At the reflection level, radio refractive index \( \eta = 0 \) therefore

\[
\omega_p = \omega \text{ or } f_p = f
\]

\[\text{(2.4)}\]
Here, $f_p$ is the local plasma frequency and $f$ is the transmitted wave frequency. Therefore at the reflection level the local plasma frequency in the ionosphere is equal to the transmitted wave frequency.

The ionosphere consists of different regions. The maximum plasma frequency of a given region is called the critical frequency of that region. For vertical incidence, the maximum critical frequency of the whole ionosphere is called the penetration frequency. Thus, the waves whose frequency is greater than the penetration frequency can be received from a source in the space by a ground based receiver. The source may be satellite onboard transmitter, or an ascending rockets or the natural radio emission from the moon or galaxy. This is known as the trans-ionospheric propagation.

The total electron content (TEC, which is the line integral of electron density along the line-of sight between the satellite and the receiver) measurements techniques are based on the trans-ionospheric radio wave propagation. When a radio waves travel through the ionosphere, it experiences a group delay and a phase advance proportional to the TEC between the transmitter and the receiver. As the ray passes through the ionosphere, phase speeds up and the ray bends in accordance with Snell’s law, as a result of the changing index of refraction of the ionosphere. If we ignore the bending and other higher order effects, we can get the TEC along the straight line between the transmitter and the receiver because the change in a phase is directly proportional to the TEC along the line of sight.

From equation 2.3

\[
\eta = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}
\]

\[
\eta \approx 1 - \frac{e^2 N_e}{2m_\text{e} \varepsilon_0 \omega^2}
\]

\[
\eta \approx 1 - 40.3 \frac{N_e}{f^2}
\]  \hspace{1cm} (2.5)
Since the mid-1950s, the TEC measurements have been made, beginning with the Faraday rotation of the lunar reflected VHF waves. These techniques became popular to study the spatial variability of the ionosphere with the advent of artificial satellites. The following section describes the different TEC measurements techniques.

2.3 TEC measurement techniques

The conventional ground based techniques like ionosonde and radar can be used to investigate the various aspects of ionosphere up to F region peak and up to ~1000 km respectively. But with the advent of satellite orbiting round the earth it became possible to study the ionosphere beyond the F region peak due to the altitude of respective satellite in the orbits. For example geostationary satellite (altitude from the ground ~ 36,000 km) provides an opportunity to study the ionosphere as well as the plasmasphere also. By measuring some of the characteristics of the coherent transmissions from satellites, such as polarization, amplitude, phase, frequency etc., it becomes possible to study the ionospheric variability on short and long time scales.

The measured parameter for such studies is TEC of the ionosphere which is comprehensively defined as the total number of free electrons in a column of unit cross section area along the path of the electromagnetic wave between the satellite and the receiver [Browne et al., 1956]. The satellite could be in low earth orbiting satellites, middle earth orbiting satellites for e.g. GPS etc. or Geostationary satellites for e.g. FLEETSAT (73°E), MARSAT 1, ETS-II etc.

The study of TEC is important at different geographical locations on short and long time scale, as it throws light on the physical process at work in the ionosphere. TEC measurements have been made by simple recording of the Farady rotation (Plane of polarization) or by the recording of differential phase or group delay. An excellent review of these different techniques is provided by Davies [1980]. The Faraday rotation measurement technique was extensively used to measure TEC till the advent of Navy Navigation Satellite System (NNSS) and
later from Applications Technology Satellite – 6 (ATS-6). The differential phase or group delay which are directly proportional to TEC that require two coherent beacon frequencies. By measuring this delay using a dual frequency GPS receiver, properties of the ionosphere can be inferred, and these properties can be used to even monitor space-weather events. Therefore, GPS is a predominant technique for TEC measurement.

In view of the fact, that the ionosphere is characterized by large gradients, intense irregularities and equatorial anomaly conditions etc. These irregularities in the ionosphere produce short-time signal variations termed as scintillations. These scintillations affect the reliability of radio transmission between earth and spacecraft. Plasma irregularities in the ionosphere (like ESF, plasma bubbles etc.) are known to cause scintillation in VHF, UHF and L-band frequency range. The fluctuations of GPS signals during scintillation event can cause degradation in range measurements and in severe circumstances, cause discontinuity in phase of the signal. This discontinuity of phase can lead to loss of lock at receiver tracking circuitry. Due to loss of lock, cycle slips occur in phase measurements of GPS data. Thus in the present age of satellite based communication and navigation, it becomes important to study the characteristics morphology of scintillation to correct these errors.

2.3.1 GPS technique for TEC and scintillation measurements

The NAVSTAR GPS (Navigation Satellite Timing and Ranging Global Positioning System) is all weather, space based navigation system established by US Dept. of Defense. GPS system consists of three segments. (a) space segment (b) control segment and (c) user segment. Space segment consists of the GPS satellite constellation. Table 2.1 represents the salient features of GPS. Control segment consists of the master station (near Colorado Springs) which takes care of all data processing, worldwide network of monitor stations (Ascension Island, Diego Garcia, Kwajalein, Colorado Springs and Hawaii) and ground antennas. User segment includes the five main modules namely antennas, receiver, signal processing and data processing capabilities input/output device such as a control
display unit and a power supply. Figure 2.1 (a) shows the space segment of GPS system. Figure 2.1 (b), (c) and (d) are user segments of GPS system.

GPS satellite transmits two radio signals. These signals consist of a C/A (coarse acquisition) code at 1.023 MHz and a P (precision) code at 10.23 MHz bandwidths. The signals are transmitted at two carrier frequencies L1 (1576.42 MHz) wavelength ~ 19 cm and L2 (1227.60 MHz) wavelength ~24 cm. All the GPS users can access the C/A code. The P-code is accessible to only authorized users. Both C/A and P-codes are transmitted on the L1 frequency, either C/A or P-code is transmitted on the L2 frequency depending on the ground command [Ananda, 1988].

The user at the ground estimates the range to each satellite by measuring the transit time of the signal. This range is called the pseudorange, because the biases in the receiver clock prevent the actual range measurements. These pseudoranges are used to estimate the user’s position in terms of latitude, longitude and height from the mean sea level and also the time offset between the transmitter and receiver clock.

The radio transmissions from GPS satellites are being used by worldwide ionospheric scientists groups to monitor the ionosphere. It is known that the ionosphere is a dispersive medium with respect to the GPS radio signal. As mentioned earlier, GPS radio signals when propagate through the ionosphere, the carrier experiences a phase advance and the codes experience a group delay. When the GPS code information is delayed, the measured pseudorange is quiet long as compared to the geometric range to the satellite [Hofmann et al., 1992]. The group delay in the GPS code depends on the TEC along the signal path. The group delay due to the ionosphere is the most deleterious error in GPS applications.
The TEC can be given as

\[
\text{TEC} = \int_{\text{receiver}}^{\text{satellite}} N \, ds
\]

(2.6)

Where, \( N \) is the electron density. The unit of the TEC is TEC Unit (TECU). 1 TECU = \( 10^{16} \) electrons / m\(^2\).

The TEC is proportional to the ionospheric differential delay between L1 and L2 signals and can be written as

\[
I_\rho = -I_\varphi = \frac{40.3 \times \text{TEC}}{f^2}
\]

(2.7)

Here \( I_\rho \) represent the ionospheric delay term in measurements of pseudorange and \( I_\varphi \) represents the ionospheric delay term in measurements of carrier phase. The differential phase and group delay methods for TEC measurements are explained in later in the chapter.

GPS receiver computes the TEC from combined L1 and L2 pseudorange and carrier phase measurements. The carrier to noise (C/No) measurements can be used to calculate the amplitude scintillation. In the present wrok, the ionospheric TEC and S4 measurements have been carried out with the GSV 4000B GPS ionospheric scintillation and TEC monitor (GISTM). The detail description of GISTM receiver is given in the next section.
### Features Specifications

<table>
<thead>
<tr>
<th>Features</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Satellites</td>
<td>30 satellites</td>
</tr>
<tr>
<td>Orbital planes</td>
<td>6 circular orbital planes</td>
</tr>
<tr>
<td>Orbit inclination</td>
<td>(55^\circ)</td>
</tr>
<tr>
<td>Orbital Period</td>
<td>11 hrs. 58 min.</td>
</tr>
<tr>
<td>Altitude</td>
<td>(~20,150) km</td>
</tr>
<tr>
<td>Velocity</td>
<td>(~3.9) km/sec</td>
</tr>
</tbody>
</table>
| GPS satellites transmit on two L-band frequencies | L1 (1576.42 MHz)  
L2 (1227.60 MHz)  
[As the ionosphere is a dispersive medium, there is a time delay at receiving end of both these frequencies. This time delay is directly proportional to the total number of free electrons encountered to the signals during their passage through the ionosphere] |
| Ionospheric Parameters derived from the GPS measurements | (i) Total Electron Content (TEC)  
(ii) Scintillation Indices (S4)  
(iii) TEC rate |

Table 2.1: Specifications of Satellite Navigation System – GPS

2.3.2 GISTM GSV4004B receiver

The GISTM system provides the true amplitude, single frequency carrier phase measurements and dual frequency TEC measurements from 8 to 11 GPS satellites in view. The receiver and recording system estimate phase and amplitude scintillation parameters and compute TEC from the combined L1 and L2 pseudo ranges and carrier phases. The receiver uses wide band-width tracking loops and an internal phase stable, crystal oscillator to compare the phase measurements with the actual carrier phase GPS observations. Thus the real time values of the amplitude scintillation index, S4, and the phase scintillations index computed over periods of 1, 3, 10, 15, 30 and 60s are obtained.
In addition to that, 4 pairs of TEC and TEC rate computed every 15s are also obtained. Thus the equipment is ideally suited for studies of TEC, TEC rate and S4 index simultaneously. While TEC represents the total number of electrons along the signal path, the TEC rate and S4 represent the plasma irregularity structures weighted by F region.

In practice, STEC is obtained from the dual frequency code measurements, given by

\[
\text{STEC} = \frac{1}{40.3} \left( \frac{1}{L_1^2} - \frac{1}{L_2^2} \right)^{-1} \left( P_1 - P_2 \right) + \text{TEC}_{\text{CAL}} \tag{2.8}
\]

where

- \( P_1 = \) Pseudo range at L1 in meters
- \( P_2 = \) Pseudo range at L2 in meters

For our purpose we use STEC measured by the receiver at every 30 seconds. The parameter \( \text{TEC}_{\text{CAL}} \) in equation 2.8 represents the bias error correction and is different for different satellite–receiver pairs. In the present study, the receiver part of the above bias is corrected by taking the value of 0.793 TECU supplied by the manufacturer by calibrating the receiver against Wide Area augmentation system (WAAS). As we are mainly concerned with variations of TEC, the above approach is satisfactory. This procedure gives the corrected slant TEC. As slant TEC is dependent on the ray path geometry through the ionosphere, it is desirable to calculate an equivalent vertical value of TEC which is independent of the elevation of the ray path.
Figure 2.1: GPS includes (a) NAVSTAR Satellites Orbits Arrangement (b) L1/L2 GPS Antenna (NovAtel’s Model GPS702) (c) GPS Ionospheric Scintillation and TEC Monitor (GISTM) GSV4004B (d) GPS setup at Rajkot
The Vertical TEC (VTEC) is obtained by taking the projection from the slant to vertical using the thin shell model assuming a height of 350 km, following the technique given by [Klobuchar, 1986]

\[
\text{VTEC} = \text{STEC} \times \cos \left( \arcsin \left( \frac{R_e \cos \theta}{R_e + h_{\text{max}}} \right) \right)
\]  

(2.9)

Where \( R_e = 6378 \) km, \( h_{\text{max}} = 350 \) km and \( \theta \) = satellite elevation angle at the ground station.

The amplitude scintillation index (S4) is defined as the normalized standard deviation of the received signal strength. The receiver collects the C/No measurements at 50 Hz rate to compute the S4 index. The formula for S4 calculation can be written as,

\[
S4 = \frac{\text{Standard deviation of } C/N_{L1} \text{ or } C/N_{L2}}{\text{Mean of } C/N_{L1} \text{ or } C/N_{L2}}
\]

(2.10)

Here, \( C/N_{L1} \) is the carrier to Noise ratio at L1

\( C/N_{L2} \) is the carrier to Noise ratio at L2

Here, \( <> \) denotes the average values of the detrended signal intensities over a 60 second period. In our study we have considered only amplitude scintillation. The signal intensities C/No are detrended with a 6th order Butterworth low pass filter (with a cutoff frequency specified by user). If the cutoff frequency is zero or not specified then the signal intensities C/No are detrended with the measurement, averaged over the 60-second interval. This is the total S4 which also includes the effects of ambient noise as well as multipath. This is recorded every minute by the receiver for further analysis [GSV 4004/GISTM User’s Manual].
The phase scintillation can be derived from dual frequency carrier phase measurements by calculating \cite{Doherty et al., 2000}

\begin{equation}
\Delta \phi(t) = \phi_{L1,L2(t)} - \phi_{L1,L2(t-1)} \\
\phi_{L1,L2(t)} = C(\phi_{L2(t)} - \phi_{L1(t)})
\end{equation}

Here \(\phi_{L1(t)}\), \(\phi_{L2(t)}\) represents the L1 and L2 carrier phase measurements respectively. \(C\) is a constant and it is used to calculate ionospheric phase delay. \(\Delta \phi(t)\) at L1 and L2 are calculated using the 50 Hz raw carrier phase measurements at L1 and L2. The raw phase measurements are detrended with a 6th order Butterworth high pass filter (with a cutoff frequency specified by user). Then, for every minute on the minute, the statistics of the residuals called phase sigma (of the previous 3000 detrended phase measurements) are computed over periods of 1 second, 3 seconds, 10 seconds, 30 seconds and 60 seconds. Thus for every 60 seconds, 5 values (1-sec, 3-sec, 10-sec and 60-sec phase sigma’s) are recorded by the receiver \cite{GSV 4004/GISTM User’s Manual}.

A MATLAB programme is developed to perform the data sorting and analysis for the long term study. To obtain the VTEC at any place we restrict to longitude grid of ±2° and latitude grid of ±2° from the observing station. Figure 2.2 represents GPS observations measured by PRN 8 at Rajkot on 01 June 2007.

The two subplots at the top reveal the elevation of the satellite from the GPS observational site and the variations in the amplitude scintillation given by scintillation index S4. The first subplot in the lower panel shows the temporal variations of the VTEC corrected from the slant-path values of the line-of-sight electron content for the GPS satellites in view. The second subplot in the lower panel reveals latitudinal/longitudinal coverage of the satellite. The VTEC will be denoted as TEC in rest of the thesis. The detail account of GPS observations will be dealt in detail in following chapters.
2.3.3 Other TEC measurement techniques

(i) Faraday Rotation

When a plane polarised radio wave travels through the magnetoionic medium like ionosphere, polarisation angle of it rotates depending approximately on the average magnetic field component in the direction of propagation and on the total number of free electrons along the ray path. This angular rotation of the plane of polarization is known as the Faraday rotation. The value of the earth’s magnetic field is known. Therefore, the measurements of the angle of rotation of the plane of polarisation of a wave of known frequency gives direct measure of total number of free electrons in a unit column along the ray path from the satellite to a receiver at the ground. From this the vertical columnar electron content can be derived.
(ii) **Differential Phase**

When the radio waves propagate through the ionosphere their phase refractive index decreases due to the presence of plasma density in their propagation path. As a result of this, there is an increase in phase velocity of radio waves. If a radio wave travels a distance $s$ in an ionized medium, its phase changes by phase $\phi$ of the carrier frequency $f$ at the receiver can be expressed as

\[
\phi = -2\pi f \int \frac{1}{v_\phi} ds \\
\phi = -2\pi f \int \frac{\eta}{c} ds
\]

(2.12)

Here, $v_\phi$ is the phase velocity and $\eta_\phi$ is the phase refractive index. From equation (2.3), in the absence of collision and magnetic field the refractive index for a radio frequency $f$ much higher than the plasma frequency $f_p$ is given by

\[
\eta^2 = 1 - \left[ \frac{f_p^2}{f^2} \right]
\]

(2.13)

Thus

\[
\eta = \left[ 1 - \frac{f_p^2}{f^2} \right]^{1/2}
\]

\[
= \left[ 1 - \frac{f_p^2}{2f^2} \right]
\]

\[
= \left[ 1 - \frac{1}{2f^2} \left( \frac{ne^2}{4\pi^2 \varepsilon_0 m} \right) \right]
\]

(2.14)

Here, $n$ is the electron density in m$^{-3}$, $f$ is in cycles/s. Now, from equation (2.8),

\[
\phi = -2\pi f \int \frac{1}{c} \left[ 1 - \frac{40.3n}{f^2} \right] ds
\]
\[
\begin{align*}
\Delta \phi &= \phi_1 - \phi_2 \\
\Delta \phi &= \left[ -2\pi f \int \frac{1}{c} ds + 2\pi \int \frac{40.3n}{cf} ds \right] - \frac{1}{\eta} \left[ -2\pi \eta f \int \frac{1}{c} ds + 2\pi \int \frac{40.3n}{c\eta f} ds \right] \\
\Delta \phi &= \left[ \frac{\eta^2 - 1}{\eta^2} \right] \frac{2 \times 40.3}{cf} \int nds \text{ radians} \quad (2.16)
\end{align*}
\]

Here, \( \eta \) is known, the measurement of \( \Delta \phi \) gives the value of TEC in a unit column along the line of propagation. It can be said that the differential phase changes are proportional to the TEC. The TEC values derived from the differential phase measurements are relative and need calibration.

(iii) Group Delay

The presence of electron density in the propagation path of radio waves from satellite to receiver at ground also results in to the decrease of group velocity of radio waves. The group delay from satellite to receiver is

\[
\begin{align*}
t &= \int \frac{ds}{v_g} \\
&= \int \frac{\eta_s}{c} ds \\
&= \left\{ \frac{\eta_s}{c} \right\} \quad (2.17)
\end{align*}
\]
Here, $v_g$ is the group velocity and $\eta_g$ is the group refractive index. Following the same procedure as is done in the differential phase method, if there are two phase coherent signals transmitted from satellite at two different frequencies, then the differential group delay is proportional to TEC. This method gives absolute measurements of TEC.

### 2.4 VHF coherent back scatter radar technique

Ionosonde works on the principle of total reflection of radio frequency signals which occurs when transmitted frequency ($f$) is equal to the local plasma frequency ($f_p$). For $f \gg f_p$, the waves almost pass through the ionosphere with a small amount of energy being scattered by random thermal motions of ionospheric plasma and this is incoherent in nature. This small amount of scattered energy is used by the incoherent scatter radar (ISR) technique. The total power in returned echo is proportional to the number density of electrons in the volume irradiated. As the electrons are consistently in thermal motion, the radiation is Doppler shifted from the incident frequency. The result is a spread in the returned echo spectrum which gives substantial information about the velocities in the medium. In addition to this, the returned echo spectrum contains the information of electron temperature and ion temperature also.

ISR technique sounds the ionosphere up to ~1000 km. As of now the lowest frequency used in ISR technique is ~50 MHz [Kelley, 1989]. These frequencies are almost unattenuated by the ionosphere and small amount of energy is scattered by the ionospheric electrons which is received back and used by the ISR.

This technique can be applied to the neutral atmosphere also because the turbulence within the homosphere – below about 100 km is able to scatter the radio wave signals. But in the case of neutral atmosphere the scattering mechanism is different from that of ionosphere, which gives incoherent scatter echoes. The radar primarily designed to study the echoes from the neutral air, in
other words to investigate the Mesosphere, Stratosphere and Troposphere is known as the MST radar.

The major disadvantage of ISR is that it has to work with a very weak signal. Therefore, it requires a transmitter of high power, a large antenna, and the most sensitive receiver and sophisticated data processing available, all of which add up to major technique and considerable expense.

If there is plasma irregularities present in the ionosphere, the electron density fluctuations in the medium can grow to values much greater than the thermal fluctuations. Radio signals backscattered from plasma irregularities with a spacing of half a radar wavelength will reinforce by constructive interference in the direction back to the radar and can produce signal strong enough to detect by smaller radar system. This phenomenon is known as the coherent backscatter and can be detected by coherent backscatter radar. Coherent backscatter radar is actually designed to receive echoes from physical structures within the ionosphere.

In last three decades, the high power VHF and UHF backscatter radars have been emerged to probe the ionosphere in order to provide better understanding of basic plasma processes associated with the ionosphere and to study the generation and dynamics of the small scale ionospheric irregularities. The observations at VHF and UHF frequencies correspond to irregularities with scale sizes of few meters to few centimeters. The investigations using Jicamarca radar (operating at 50 MHz), Altair and Tradex radars (155.5 MHz, 415 MHz, 1320 MHz) at Kwajalein, high power VHF radar (53 MHz) at Gadanki, India, HF and VHF radar (54.95 MHz) at Trivandrum, India, Portable Radar Interferometer (50 MHz) at Cornell University have contributed significant information to understand the low latitude ionospheric plasma processes.
2.4.1 Principle of Coherent backscatter

The atmosphere either ionized or not, contains irregularities of various scale sizes. It is to be believed that at each edge a small fraction of the incident energy scatters in all directions. If the numbers of field aligned irregularities are present, with spacing between them of, half of the transmitted wavelength then the resulting scattered signals will reinforce in the direction back to the radar. Thus, even the scattered energy is very weak, they can add up and the resulted signals will be strong enough to be detected by small radar system. Figure 2.3 represents the principle of volume scattering. It is not necessary for the electron density irregularities to be regularly spaced. The radar of wavelength \( \lambda_T \) will effectively select the spatial component of period \( \lambda_T/2 \), ignoring the others. Scatter in other directions will select some other spatial period. The signals from two scattering planes reinforce when their path difference is \( \lambda_T \).

When the scattering is from structures within the medium then the coherence time is high, because the structures tend to vary more slowly in comparison to radar’s ability to resolve those changes. Due to the high coherence, echoes will have the same amplitude and phase, as a result are added coherently.

The radar scatters from the irregularities in the medium, \( K_{MED} \), according to the relationship

\[
K_T = K_S + K_{MED}
\]  

(2.20)

Here, \( K_T \) is the transmitted wave and \( K_S \) is the scattered wave. For backscatter, \( K_S = - K_T \).

\[
K_{MED} = 2K_T
\]  

(2.21)
Equation 2.21 represents the conservation of momentum. Where $|K_T| = |K_S| = 2\pi/\lambda_T$, $|K_{MED}| = 2\pi/\lambda_{IRR}$. The backscattered wave vector will follow the Bragg condition i.e.

$$\lambda_T = 2\lambda_{IRR} \sin (\theta/2)$$  \hspace{1cm} (2.22)

From the above equation it also follows that the transmitted wavelength or radar wavelength determines the scale size of the irregularities that can be observed by this radar. For monostatic backscatter ($\theta = 180^\circ$), which is usually applicable for ionospheric experiments, $\lambda_{IRR} = \lambda_T/2$. Thus, the scattering wavelength is one half of the transmitted wavelength.

In backscatter radar, the scattering volume is determined by the antenna beamwidth, the transmitted pulse width as well as the vertical extent of the
echoing region under study. The mobility of the electrons is much higher along the magnetic field than perpendicular to it therefore the irregularities are elongated along the geomagnetic field lines. This fact leads to high aspect sensitivity in the backscatter. Thus, the radar line of sight has to be close to a direction normal to the field line. The radar power spectra provide information on the signal strength, mean Doppler shift and Doppler spectral width which correspond to the strength of the irregularities, line of sight phase velocity, and its variance respectively [Patra, 1997].

2.4.2 VHF coherent back scatter radar at Gadanki, India

Indian MST radar, situated at Gadanki (13.5°N, 79.2°E, dip latitude 6.3°N) in India, can be operated in ionospheric mode to study the ionospheric E and F region plasma irregularities. This high power VHF coherent backscatter radar has been established as MST (Mesosphere–Stratosphere–Troposphere) radar, primarily to study the lower and middle atmospheric dynamics. In addition to these studies, it was also meant for the coherent backscatter studies of the ionospheric irregularities. Accordingly, the phased antenna array has been aligned along the geomagnetic axis, 20° away from the geographic axis in anticlockwise direction [Patra, 1997]. The radar is highly sensitive, pulse coded, coherent VHF phased array radar operating at 53 MHz with a peak power aperture product of \(3 \times 10^{10} \text{ Wm}^2\).

To detect the backscatter from ionospheric field aligned irregularities, the radar beam has to be made transverse to the magnetic field lines. Thus the tilt of 14.8° N from the zenith has been given to the radar beam to satisfy the perpendicularity condition at 350 km. Since it is possible to orient the radar beam anywhere within 20° zenith angle, this condition can be satisfied easily. The radar beam geometry at Gadanki for the study of F region irregularities is shown in Figure 2.4. The beamwidth of radar is 2.8° in both east-west and north-south planes. Table 2.2 represents the main specifications of the MST radar [Patra, 1997].
The major subsystems of the MST radar can be listed as (i) the antenna and feeder network (ii) transmitters (iii) exciter and radar controller and (iv) the receiver and signal processor. The details of the radar and its subsystems are discussed by Rao et al., [1995] and Patra, [1997].

The radar power spectra provide information on the signal strength, mean Doppler shift and Doppler spectral width which corresponds to the strength of the irregularities, line of sight phase velocity and its variance respectively.

Figure 2.4: Geometry of the MST radar beam located at Gadanki for studying the ionospheric F region irregularities [reproduced after Patra, 1997]
<table>
<thead>
<tr>
<th>Features</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Gadanki (13.5°N, 79.2°E, Geomagnetic Latitude 6.3°N)</td>
</tr>
<tr>
<td>Frequency</td>
<td>53 MHz</td>
</tr>
<tr>
<td>Peak Power</td>
<td>2.5 MW</td>
</tr>
<tr>
<td>Peak Power-aperture Product</td>
<td>$3 \times 10^{10}$ Wm$^2$</td>
</tr>
<tr>
<td>Maximum duty ratio</td>
<td>2.5%</td>
</tr>
<tr>
<td>Number of Yagi antennas</td>
<td>$32 \times 32$, 3-element orthogonal Yagi arrays</td>
</tr>
<tr>
<td>Beam width</td>
<td>2.8°</td>
</tr>
<tr>
<td>Beam position (zenith angle)</td>
<td>$\pm 20^0$ in both E-W and N-S planes in steps 1°, 13.2° N and 14.8° N for ionospheric application</td>
</tr>
<tr>
<td>Receiver bandwidth</td>
<td>1.7 MHz</td>
</tr>
<tr>
<td>Receiver gain</td>
<td>120 dB</td>
</tr>
<tr>
<td>Receiver dynamic range</td>
<td>70 dB</td>
</tr>
<tr>
<td>Pulse width</td>
<td>1,2,4,8,16,31 μs uncoded; 16,32 μs coded with 1 μs baud</td>
</tr>
<tr>
<td>Pulse repetition frequency</td>
<td>62.5 Hz – 8 KHz</td>
</tr>
<tr>
<td>Maximum number of coherent integrations</td>
<td>512</td>
</tr>
<tr>
<td>Maximum number of range bins</td>
<td>512</td>
</tr>
<tr>
<td>Maximum number of FFT points</td>
<td>1024</td>
</tr>
<tr>
<td>Radar Controller</td>
<td>PC-AT Pentium – IV featuring programmable experiment specification file</td>
</tr>
<tr>
<td>Computer System</td>
<td>PC-AT Pentium – IV system with ADSP 21060 DSP processors for data acquisition and processing</td>
</tr>
</tbody>
</table>

Table 2.2: Main specifications of the Indian MST radar
The direction of arrival of the echoes being close to vertical, the line of sight phase velocity of the irregularities represents mostly the vertical component. The Range Time Intensity (RTI) map of ESF irregularities observed by VHF radar, Gadaki on 07 February 2008 is shown in Figure 2.5. The color code in the plot represents the strength of the irregularities in dB. The detail account of radar ESF observations will be dealt in Chapter 4.

![Figure 2.5: RTI map observed on 07 Feb 2008 using Indian MST radar. The color code in the plot represents the strength of the irregularities in dB](image)

### 2.5 Ionosonde

An ionospheric sounder or ionosonde is the oldest ground based experimental technique for investigating the terrestrial ionosphere by means of radio waves. Ionosonde is basically variable frequency radar which transmits a signal vertically whose frequency varies from 1 to 22 MHz and measures the time delay between the transmission of radio frequency pulse and echo from a reflecting layer in the ionosphere. The limitation of the ionosonde is it can sound
the ionosphere only up to hpF2 (peak of the F region) height only. Thus there is a lack of information above the hpF2 height. The satellite based miniature ionosonde can provide the information above the F2 peak. This is called the topside sounding in contrast to the previous one which is known as the bottomside sounding. In topside sounding also the information will be up to hpF2 only from topside. Thus, the combined observations, topside and bottomside, can give complete profile of the terrestrial ionosphere.

The topside sounding helps to study spatial variability but temporal variability is not visible with this. The bottomside sounding helps to study temporal variability but in general unable to address the spatial variability. Ionosonde operates on the principal of total reflection of radio signals from a reflecting level in the ionosphere.

### 2.5.1 Principle of ionosonde

The basic principle of the ionosonde is the reflection of radio signals by the ionospheric plasma when transmitted radio frequency \( f \) is equal to the local plasma frequency \( f_p \). At the occasion of reflection the transmitted frequency is known as the critical frequency. The plasma frequency \( f_p \) is related to the electron density \( N_e \) of the reflecting layer as

\[
f_p = \frac{1}{2\pi} \left( \frac{N_e e^2}{m_e \varepsilon_0} \right)^{1/2}
\]

By substituting the standard values,

\[
f_p = 9 \times (N_e)^{1/2} \text{ MHz}
\]

From this the plasma density can be given by the following expression,

\[
N_e = 1.24 \times 10^4 f_p^2
\]

As the electron density in the ionosphere increases monotonically with height, the reflection takes place for the higher values of plasma frequency \( f_p \) as
the height increases. Since the peak electron density in the ionosphere is few times $10^6 \text{ cm}^{-3}$, the plasma frequency $f_p \leq 12 \text{ MHz}$. [Kelley, 1989]. If the transmitted frequency is higher than the peak plasma frequency (frequency corresponds to the peak electron density), the radio wave signals will penetrate through the ionosphere and escape into the space. The lowest frequency which just penetrated the ionospheric layer, the penetration frequency, would provide a measure of the electron density at the peak. If there is a dense E region it can block the F region entirely by absorbing the transmitted radio frequencies as we have observed in Chapter 1-section 1.9.

The time delay measured by the ionosonde is converted into the height. As the ionosphere is not vacuumed, the velocity of the radio waves in the ionosphere is not similar to that of the velocity of light. Therefore, the height measured by the ionosonde will not be a real height but will be a virtual height. The plot of the transmitted frequency Vs virtual height is known as the ionogram. The ionograms are scaled for the different ionospheric parameters like virtual height of the ionospheric regions, critical frequency of the ionospheric regions etc. The typical ionogram recorded using CADI digisonde at Rajkot is shown in Figure 2.6. The different ionospheric regions can be observed. The E region is visible at ~100 km. F1 and F2 splitting is observed at ~325 km.

The virtual height can be converted into real height if required. The typical expression for the virtual height can be given by

$$h_v = \frac{cL}{2}$$

(2.26)

Here $t$ is the time delay of the echoes. The group velocity of the radio waves is less than the velocity of light in the ionosphere due to the presence of free electrons in their path. Hence the virtual height $h_v$ is always greater than the real height.
2.5.2 KEL IPS-42 ionosonde system

In the present study, the ionosonde data is obtained from KEL IPS-42 (Ionosphere Prediction Service) which has been in operation at Trivandrum. The instrument is a solid state, sweep frequency, pulsed ionosonde designed for routine vertical incidence sounding of the ionosphere. It employs a digital frequency synthesizer and programming control, signal processing and display technique. The main specifications of KEL ionosonde are given in Table 2.3.
### Features Specifications

<table>
<thead>
<tr>
<th>Features</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>1 to 22.5 MHz</td>
</tr>
<tr>
<td>Frequency generation</td>
<td>Digital synthesizer</td>
</tr>
<tr>
<td>Frequency sweep time</td>
<td>12s</td>
</tr>
<tr>
<td>Transmitter pulse power</td>
<td>5 kW</td>
</tr>
<tr>
<td>Transmitter pulse width</td>
<td>41.67 µs</td>
</tr>
<tr>
<td>Pulse interval</td>
<td>5.33 ms, three on each channel</td>
</tr>
<tr>
<td>Maximum virtual height</td>
<td>800 km</td>
</tr>
<tr>
<td>Height marker interval</td>
<td>100 km</td>
</tr>
</tbody>
</table>
| Programming options            | (1) Ionograms at 15, 5 or 1 minute interval  
                                | (2) 3 per minute (optional)            |
| Date/Time identification       | Recorded with each ionogram            |
| Video display                  | High resolution green phosphor (12 cm)  
                                | Video card extra 18 Kbytes of R.A.M.    |

**Table 2.3: Main specifications of KEL IPS-42 ionosonde**

### 2.6 Other techniques

#### 2.6.1 In situ measurements

Instruments have been designed for the direct measurements of many variables of the atmosphere and ionosphere. A variety of instruments are used to measure the temperature, concentration, and drift velocity of either the ambient thermal electron or the thermal ions. When instruments are mounted on satellites they are most useful for long term monitoring above about 200 km. The parameters most frequently sought are the vertical distribution of each of the electrons and the ions and neutral species. To determine the composition one requires a mass spectrometer, but much information about concentrations and temperatures can be obtained from simpler devices variously known as ‘probes’, ‘traps’ and ‘analyzer’, and many such instruments have been flown on rockets and on satellites over the years. These instruments are mounted on satellites and
rockets that are moving through the plasma at velocities between 1 and 9 km/s [Kelley, 1989].

A probe is projected into the medium and draws from it an electric current of electrons or ions depending on the sign and magnitude of the potential applied to it. A trap collects ions from the medium because the vehicle in orbit moves faster than the ions and so sweeps them up from its path. Additional electrodes are often incorporated to enable a more detailed analysis to be made in real time, the results being transmitted to a ground station by telemetry. The examples of in situ instruments are Langmuir Probes, Retarding Potential Analyzer, and Drift Meters etc.

2.6.2 TIMED satellite

The thermospheric neutral composition variations in terms of \([O]/[N_2]\) presented in the present study have been obtained from Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) onboard Global Ultraviolet Imager (GUVI) instrument. The TIMED satellite is launched by NASA under Solar Terrestrial Probes Program. The purpose is to study the sun-earth system more thoroughly. The TIMED satellite is placed in a circular orbit at an altitude of ~625 km to observe the Mesosphere and Lower Thermosphere/Ionosphere (MLTI) region. It employs advance instruments in remote sensing technology. The parameters such as temperature, pressure, wind and chemical composition, along with its energy inputs and outputs of MLTI region’s are acquired. The more details on TIMED satellite can be found on http://www.timed.jhuapl.edu/WWW/index.php

In the imaging mode the GUVI instrument of the TIMED satellite gives far ultraviolet images of thermosphere composition and temperature below about 625 km altitude. The details of the GUVI instrument, operation and example of data products are presented by Paxton et al., [1999], Christensen et al., [2003] and Paxton et al., [2004]. The atomic oxygen to molecular nitrogen vertical column density ratio (\(\sum O/N_2\)) is one of the geophysical parameter obtained from data
products of the GUVI imager. The ratio of vertical column density of atomic oxygen (135.6 nm) to that of molecular nitrogen (174.3 nm) is proportional to ratio of emission rates within the airglow layer, extending from about 140 km to 250 km [Meier et al., 2005]. A more detail on GUVI can be found on http://guvi/jhuapl.edu/.

2.6.3 Optical techniques

The study of atomic and molecular emissions in the upper atmosphere using optical techniques provides information on the chemical and physical processes going on in the atmosphere. These emissions are known as the airglow emissions. Optical investigations have a tremendous potential in inferring the behavior of the upper atmosphere. As the ionosphere is the part of the upper atmosphere, optical investigation of different emissions gives wealth of information on different chemical processes which plays a major role in sustaining the ionosphere during different time of the day. Optical techniques have been developed on different platform such as ground based, balloons, rockets and satellites.

Airglow emissions variability at any given place provides plenty of information on the behavior of the ionosphere – thermosphere system at the respective emitting altitudes. The ideal condition to study the airglow emission is the moon less clear night sky (no clouds). Dayglow study is the challenging task due to the presence of strong sunlight background. But with the development of unique Dayglow Photometer (DGP) and Multiwavelength Dayglow Photometer (MWDPM) [Narayanan et al., 1989; Sridharan et al., 1993, 1998], an investigation on various characteristics of dayglow emissions have been carried out.

The optical techniques observe fundamentally the total incoming photon flux at a particular wavelength and the variations of the photon flux with varying wavelength. The former is called the photometry while the later is called the spectrometry.
The basic parameter in the airglow study is the intensity of the emissions. The major optical instruments to study the airglow emissions at different altitude at a given place are (i) photometer (ii) imager and (iii) spectrometer. The intensity i.e. total or specific line emission of radiations is measured by photometers (with small field of view ~10° or less). The scanning photometer scans the sky at fixed angle to study the dynamics of the upper atmosphere. The schematic of night airglow photometer is shown in Figure 2.7. The different parts of the photomere are shown there.

Photometer measures integrated airglow brightness over its field of view. The photometer mainly consists of three major parts (i) front optics (ii) filter assembly (iii) detector section. The front end optics collects light from a small field of view. Collimating lens makes the light rays parallel hence a normal incidence to the filter. Narrow band interference filter is used to isolate unwanted wavelengths. Focusing lens directs all light towards the detector. Thus light is refocused on to detector (for example photomultiplier tube) which measures the intensity of incoming light. In case of scanning photometer, the scanning mirror scans the different parts of the sky at a given interval of time. The detector section has to be connected to the data acquisition system.

The bi-directional (zenith and 45° elevation towards west) measurements of night airglow emission at OI 777.4 nm are used to calculate the night time plasma drift. This drift value is used in the case study presented in section 4.4 of Chapter 4. These airglow emission measurements are done by Physical Research Laboratory group, Ahmedabad at low latitude station Gadanki. This is a multiwavelength photometer. The details of this photometer are described by Sekar et al., [2004, 2008].
2.7 Summary

In the present chapter the radio wave propagation from the ionosphere and the effects of ionosphere on it is discussed. The core part of the chapter contains the discussions on various techniques for studying the ionosphere. The GPS TEC and scintillation measurement technique is discussed in detail. The sample observations from the satellite (PRN 8) are shown and explained. The other TEC measurement techniques are also discussed. The VHF coherent back scatter radar technique for studying the F region irregularities is discussed along with the
principle. The ionosonde technique is also discussed along with its principle. The In situ techniques are highlighted. The thermospheric variation in terms of [O]/[N₂] ratio are studied using TIMED/GUVI data. The glimpse of TIMED/GUVI system is given. At the end the optical technique to study the night time ionospheric variations is also highlighted.