5.1 Ionospheric Measurements

When the GPS signal travels through the ionosphere, it is delayed by the effect of free electrons. The total time delay by the ionosphere in the pseudo range (PR) is proportional to the path integral of the free electron density (Ne) in the line-of-sight (LOS) direction from the receiver to the satellite. This integral is called Total Electron Content or TEC. The delay is inversely proportional to the carrier frequency squared and can be expressed as

\[ I_{\text{LOS}} \propto \frac{1}{f^2} \int_{\text{path}} N_e \, dl \]  

(5.1.1)

where the electron density, Ne, is a function of longitude (X), latitude (0) and altitude (z) above the earth's surface. From electromagnetic theory, the resulting ionospheric delay is given by [94]

Figure 5.1 GPS Ionospheric Line-of-Sight Delay
\[ \Delta t_{\text{non}} = \frac{8.44 \times 10^{-7}}{2\pi f_{\text{corner}}^2} \times \text{TEC (seconds)}, \quad (5.1.2) \]

\[ I_{\text{LOS}} = \Delta t_{\text{non}} \cdot C = \frac{40.3}{f_{L1}^2} \times \text{TEC (meters)} \quad (5.1.3) \]

where \( f_{L1} \) is the GPS L1 frequency (1575.45 MHz), and TEC is in units of electrons/m².

The electron density, \( N_e \), is mainly affected by the activities of the sun and the variation of the geomagnetic field. A daily variation of profiles of \( N_e \) is shown in Figure 5.2. These profiles can be demonstrated by using an empirical ionospheric model (the International Reference of Ionosphere from year 1990 (IRI90) [96] was used for this figure). The profiles show the electron density distribution covers altitudes from 60 to 1000 km at a given latitude of 400 North. \( N_e \) is much higher in the day than at night and reaches its daily maximum between local noon and 2 PM local time primarily due to solar radiation. The centroids of the profiles are also shown, and are about 350 to 400 km.

Figure 5.2 Ionospheric Diurnal Variation at L1
This diurnal variation of the ionosphere is also clearly shown in the resulting ionospheric delays. Using the profiles of Ne from the IRI90 model, one can simulate a user who measures the 90° elevation angle LOS ionospheric delays for 24 hours. The delays at GPS L1 frequency can be calculated using Equation 5.2 and are shown in Figure 5.3.

In the PR measurement, as in Equation 1.2.1, the ionospheric delay is usually denoted by If for the ih receiver and ih satellite. Because the delay is inversely proportional to the square of the frequency, the delay of the GPS L2 pseudo range equals a scale factor times that of the GPS L1 frequency PR. This relation is shown in Equations (5.3)- (5.6) [1,70]:

![Figure 5.3 (a) & (b)](image_url)
\[ PR_{L1} = \tilde{\rho} + I_{L1} + \varepsilon_{L1} \] (5.1.4)

\[ PR_{L2} = \tilde{\rho} + \gamma I_{L1} + \varepsilon_{L2}, \text{ and} \] (5.1.5)

\[ \gamma = \left( \frac{L1}{L2} \right)^2 = (77/60)^2 \approx 1.647 \] (5.1.6)

where \( \tilde{\rho} \) contains the geometrical range, tropospheric delay and other errors.

For most GPS dual-frequency receiver applications, a so-called "ionosphere-free PR" measurement is calculated to eliminate the ionospheric delay to at least first order. This measurement is given by [1, 70]

\[ PR_{\text{iono-free}} = \frac{\gamma \cdot PR_{L1} - PR_{L2}}{\gamma - 1} = \tilde{\rho} + \varepsilon_{\text{iono-free}} \] (5.1.7)

Note that \( \varepsilon_{\text{iono-free}} = (\gamma \cdot \varepsilon_{L1} - \varepsilon_{L2}) / (\gamma - 1) \) and is roughly three times the error at L1. Conversely, for the purpose of observing and modeling the ionosphere, the ionospheric delay can be estimated using dual-frequency PRs by the following calculation [1, 70]:

\[ I_{L2} = \frac{PR_{L2} - PR_{L1}}{\gamma - 1} + \frac{\varepsilon_{L2} - \varepsilon_{L1}}{\gamma - 1} \] (5.1.8)

This ionospheric delay measurement has about twice the error as the basic PR measurement. WAAS uses a carrier-smoothed version of this measurement as the input for generating the ionospheric corrections.

In addition, the carrier phase will also be affected by the ionosphere. The effect is a so-called “carrier advance,” and it can be shown to be equal but opposite in sign to that experienced by the PRs. When linearly combined to form the ionospheric measurement, this low-noise measurement is usually used for carrier-aided smoothing of the PR.
5.2 Experimental set up

In the Indian Sector, which encompasses the equatorial and low latitude regions, the Indian Space Research Organization (ISRO) and the Airport Authority of India (AAI) have jointly launched a project called GPS Aided Geo Augmented Navigation (GAGAN) similar to the wide Area Augmentation System (WAAS) in United States and installed a total of 18 identical dual frequency GPS receivers at different locations in the length and breadth of the country all the way from the magnetic equator to the equatorial ionization anomaly region and beyond, with a view to study the temporal and spatial behavior of the Indian ionosphere in a greater detail by using the continuous measurement of the TEC and scintillation data (S4 index) acquired at a grid spacing of about 5 d x 5 d in latitude and longitude. In Fig. 6.1 (Page 58) is shown the locations of the GPS receiver stations installed in the Indian region, where the longitudinal coverage of these station vary from 72° E to 92° E, and the geographic latitudinal coverage vary from 8° to 32° N or a range of 1°S to 23° N geomagnetic latitudes. The TEC and scintillation data are recorded at 1 minute intervals from all the station. In the present study, the (slant) TEC and the amplitude scintillation (S4 index) data recorded at all the 18 different locations during the sixteen month period from March 2004 to June 2005 are used in this analyses.

The slant TEC measurements made are the sum of the real slant TEC, the GPS satellite differential delay bs (satellite bias) and the receiver differential delay, b (receiver bias). Therefore, the vertical TEC can be expressed as

\[
VTEC = STEC - \frac{(br + bs)}{S(E)} (5.9)
\]

Where STEC is the slant TEC measured, E is the elevation angle of the satellite in degrees, S(E) is the obliquity factor with zenith angle z at the Ionospheric Pierce Point (IPP) and VTEC is the vertical TEC at the IPP. The obliquity factor, S(E) (or the mapping function) is defined as [55, 52]

\[
SE (E) = \frac{1}{\cos (Z)} \left[ 1 - \left( \frac{R_e \times \cos (E)}{R_e + h_s} \right)^2 \right]^{-0.5} (5.10)
\]
Where $R_e$ is the mean radius of the Earth in Km, $h_s$ is the ionosphere (effective) height above the earth surface, $z$ is the zenith angle and $E$ is the elevation angle in degrees.

5.3 **TEC Station**

The equipment consists of 19" equipment rack of 30 U height with side panels, back plane doors with lock, front glass door with lock, castors, four fan tray at top, slides and angles as well as mounting plates for equipment and ten point AC power plug point board vertically mounted inside the rack at the back. The equipment consists of industrial grade Pentium - IV (1.7 GHz) PC with two 40 GB hard disks drives, 52 X CD-ROM/CD-Writer, one 1.44 MB floppy disk drive, one 250 MB ZIP DRIVE, one 56.6 kbps external modem for dialup Internet connection, Keyboard, Mouse and 15" color SVGA monitor display all mounted in the 19" rack as shown at convenient heights for easy operation.

The TEC (GPS) Receiver mounted on top bracket in the rack is a 12 channel, dual frequency, NovAtel GPS receiver with software to calculate and store TEC values in files in HDD of the PC via an RS-232C cable. A 12 volt DC supply provides power to the receiver.

A small GPS antenna with choke-ring base and dome mounted on topmost position in the airport for clear 360 degree view of the sky is connected via a 30m RF cable to the receiver. The RF cable also carries 12 volt DC to antenna Low Noise Amplifier from the receiver.