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1. Introduction

TEC refers to the Total Electron Count of the Ionosphere. It refers to the total number of electrons in a cylinder of unit area of cross section extending from the ground station up to our satellite in space. TEC values are one of the most prominent sources of information for understanding the structure and dynamic behavior of the ionosphere. However, since there is a fraction of the ionosphere (about 5%) above the altitude of our satellite, what we wish to measure is known as the Ionophere Electron Count.

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Importance of TEC

2.1 Error correction for GPS systems

These days GPS satellites are used on many fronts and their use for position determination has proved to be important and useful for not only navigation but also several other research applications. But in order to achieve a high level of accuracy from GPS (of the order of millimetres), one must correct the carrier phase advance and pseudo range group delay that are caused when GPS signals pass through the ionosphere. If we have a dual frequency GPS receiver, we can then deal with this error by taking into account ionosphere's dispersive nature. But if we are using a single frequency GPS receiver then we need some other method for getting rid of this error.

Most GPS companies provide an inbuilt GPS model that predicts TEC values on the basis of previous history sheets. But the fact that we are situated near the equator makes life a bit difficult for us because most of these models are based on data points obtained predominantly from mid latitude regions and have very sparse data of equatorial region. Further, the equatorial region is highly susceptible to fluctuations in TEC values due to various reasons. So these models fail to deliver a satisfactory performance. An increase in data points in this region can be used by GPS manufacturers for correcting this ionospheric error. The currently used global ionospheric models can only model the monthly mean total electron content to about ± 10 percent. These models cannot tell us about the day-to-day variability of the TEC which can be 20 to 25 percent (1 sigma) of the monthly mean value. So, even if the monthly mean TEC is modelled perfectly using one of the global ionospheric models, TEC predictions can be off by 20 to 25 percent. If the bias between the monthly mean TEC and the predictions provided by these models is 10 percent of the monthly mean values, then the performances of these models are considered to be excellent. The combined effect of the error in the monthly mean predictions and the day-to-day variability of the TEC will result in an overall performance of these models to be at about 22-27 percent (RMS) of the ionospheric delay. The performance can only be worse if we take into account the potential effect of a solar or geomagnetic storm during medium or high solar activity times. This is in addition to the fact that most of these single frequency GPS receivers use data models that use values obtained from South American & African Stations. So anyways the data for equatorial region is very sparse, so to have better accuracy of GPS in India we will have to device methods that can give us additional information of day to day variability. We wish to do it by supplementing the current database and the ongoing Indian projects for TEC measurement with our TEC data.

After integrating the group and phase delay along the GPS signal path we will obtain a range between satellite and receiver that is different from geometrical distance between them. This difference is known as ionospheric error. Error is negative for carrier phase (phase is advanced, measured range is shorter than the geometrical range) and positive for pseudo ranges (i.e. phase is delayed, so measured range is greater than geometrical range).These two are equal in magnitude but opposite in sign.

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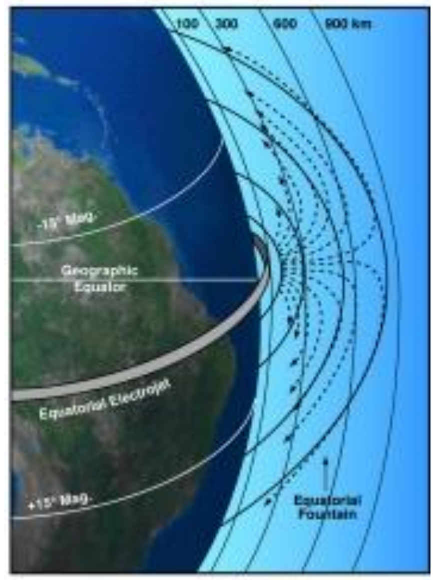
Note: The Physics behind the ionospheric delay is explained in section

2.2 Equatorial Ionization Anomaly (Appleton Anomaly):



EIA, or equatorial ionization anomaly is characterized by a depression in ionization densities (or trough) at the geomagnetic equator and two peaks (crests) on either side of the equator at about 15° magnetic latitudes.

Possible reasons:

It is suggested that the trough exists because plasma produced by photo ionization at great heights over the magnetic equator diffuses downwards and outwards to the north and south leaving depletion at the equator.

Another explanation is that the mutually perpendicular east-west electric field and north-south geomagnetic field give rise to an upward electrodynamic ($\mathbf{E} \times \mathbf{B}$) drift of plasma during the daytime. As the plasma is lifted to greater heights, it diffuses downward along geomagnetic field lines towards higher latitudes under the influence of gravity and pressure gradients and produces the anomaly. The anomaly crests in both hemispheres occur at lower altitudes and become weaker with height. The ratio of the electron density at the crest to the electron density at the trough is a measure of the intensity of the anomaly. The crest-to-trough ratio is maximum near the height of the F2 region peak and decreases both downward and upward.

The EIA is also asymmetric about the geomagnetic equator, caused by field aligned plasma flow due to factors like neutral winds.

An interesting feature in the geographic location of India is that the magnetic equator passes through the bottomside tip of the country and the northern crest of the equatorial ionization anomaly lies in the middle of the country, providing a unique opportunity for making studies on the latitudinal variation equatorial ionization anomaly (EIA) which occurs at 5 – 25 geographic latitude. So as Mumbai falls in this region, we can easily get involved with this experiment.

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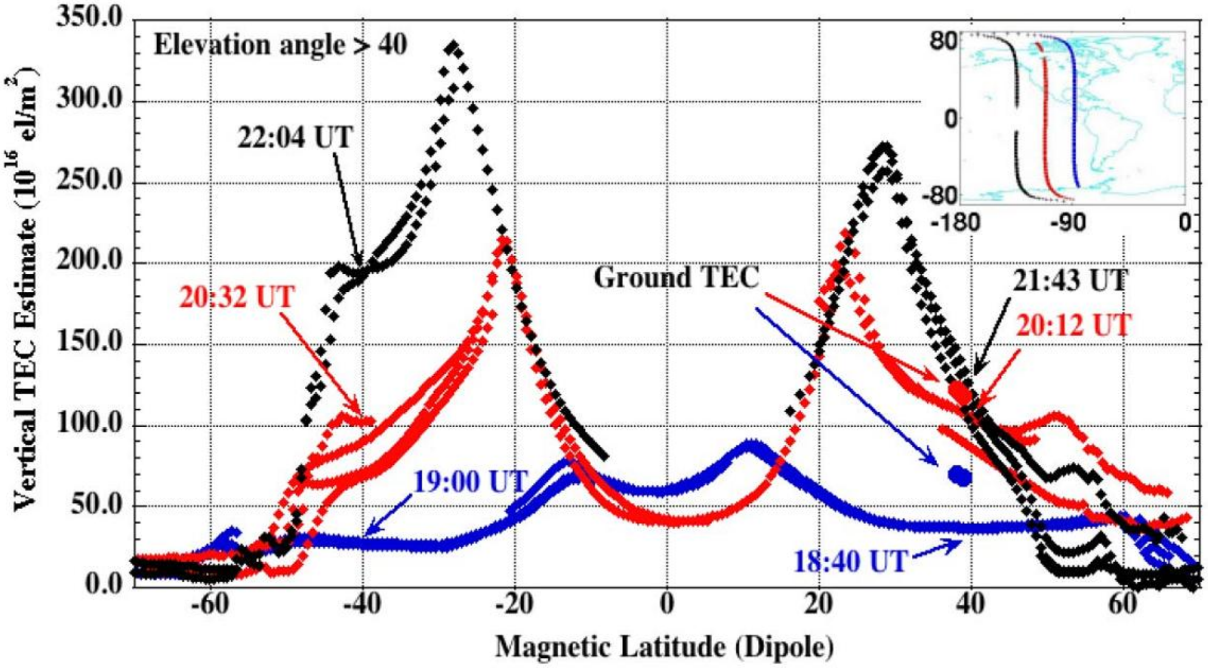

2.3 ESF - Equatorial Spread F

Technically it can be defined as,

"*The spread F/plasma bubble irregularity phenomenon results from vertical coupling process involving upward propagation of atmospheric waves (in the form of tides, gravity- and planetary waves) from the lower atmospheric regions of their origin to the dynamo region in the ionosphere where the electric fields are generated. The development of zonal (eastward) electric field enhancement in the evening hours, (that is, the prereversal electric field, PRE), by the F region dynamo is known to be the most basic requirement for the post sunset F-layer uplift as a precursor to the irregularity development.*"

On certain nights, the spread in the width of the pulses reflected from the F-layer increases abnormally, showing up as a diffuse trace, and this phenomenon is called Spread-F. ESF actually refers to formation of areas in ionosphere that have abnormally low plasma density. These bubbles are found to travel upwards in the ionosphere.

Location:

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Usually ESF is not observed at higher latitudes. Its presence is felt at lower latitudes during late evening. It happens between 20 deg South and 20 deg North belt. Usually spread F persists only for few hours and on some occasions continues throughout the night. Sometimes, after the disappearance in the pre-midnight period, spread F reappears in the post-midnight period.

On the days of ESF occurrence, the F-layer near the magnetic equator becomes unstable around evening and as a consequence of this, some irregularities develop in the electric field and plasma densities with a wide range of scale sizes. These irregularities get aligned with the Earth's magnetic field lines forming sometimes severe density depletions called 'holes' or 'bubbles' (These are termed as plasma bubbles) .These plasma bubbles can be observed with the help of Radars operating in the VHF Range.

Link between EIA & ESF:

Studies have shown that ESF is closely linked with EIA.

EIA as we know is intensification of ionization crests in the late afternoon near +/- 20deg latitude. Formation of EIA is due to flow of plasma along a fountain from the equator towards the crest, which is caused due to Electric field generated in the atmosphere. This increase in ionization comes at the expense of depletion in ionization of lower F layer (near the equator). So we get very steep plasma gradients in the equatorial region, which are conducive to Rayleigh Taylor instability and explains the relationship between EIA & ESF.

ESF is not completely understood:

As for example, the variations with longitude, season, and from day to day are not clearly understood. The altitude of ESF onset where the instability is initiated can vary over an altitude range of more than 100 km

2.4 Daily variation of TEC values:

This randomness in the day-to-day variation in TEC may be attributed to the changes in the activity of the sun itself and to the associated changes in the intensity of the incoming radiations, and the zenith angle at which they fall on the Earth’s atmosphere, in addition to the changes which take place in the Earth’s magnetic field and the equatorial electrojet (EEJ) strength, added to the effects due to the dynamics of the neutral winds.

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A logical explanation for day night variation in TEC can be given as:-

During night time, there is no solar radiation falling on the atmosphere, so there is nothing that is going to ionize the atoms present in the ionosphere. But the opposite process of recombination of ions takes place and so there is a decrease in ion density of atmosphere and hence reduced TEC is observed. During afternoon when the solar radiation is maximum, ionization increases, overtaking the process of recombination of ions and hence TEC value increases.

2.5 Variation in equatorial regions:

The daily variation in TEC at the EIA region shows its steep increase and reaches its maximum value between 13:00 and 16:00 LT, while at the equator the peak is broad i.e. it occurs for a longer duration of time and occurs around 16:00 LT. A short-lived day minimum occurs between 05:00 to 06:00 LT at all the stations from the equator to the EIA crest region. Beyond the crest region the day maximum values decrease with the increase in latitude, while the day minimum in TEC is flat during most of the nighttime hours, i.e. from 22:00 to 06:00 LT, a feature similar to that observed in the mid-latitudes. Further, the diurnal variation in TEC show a minimum to maximum variation of about 5 to 50 TEC units, respectively, at the equator and about 5 to 90 TEC units at the EIA crest region.

2.6 Climatic variations in TEC:

The seasonal variation in TEC maximizes during the equinox months (equinox is that period of time when sun passes over equator and lengths of day and night become equal , this occurs on 21st March and 22nd September) followed by winter and is minimum during the summer months.

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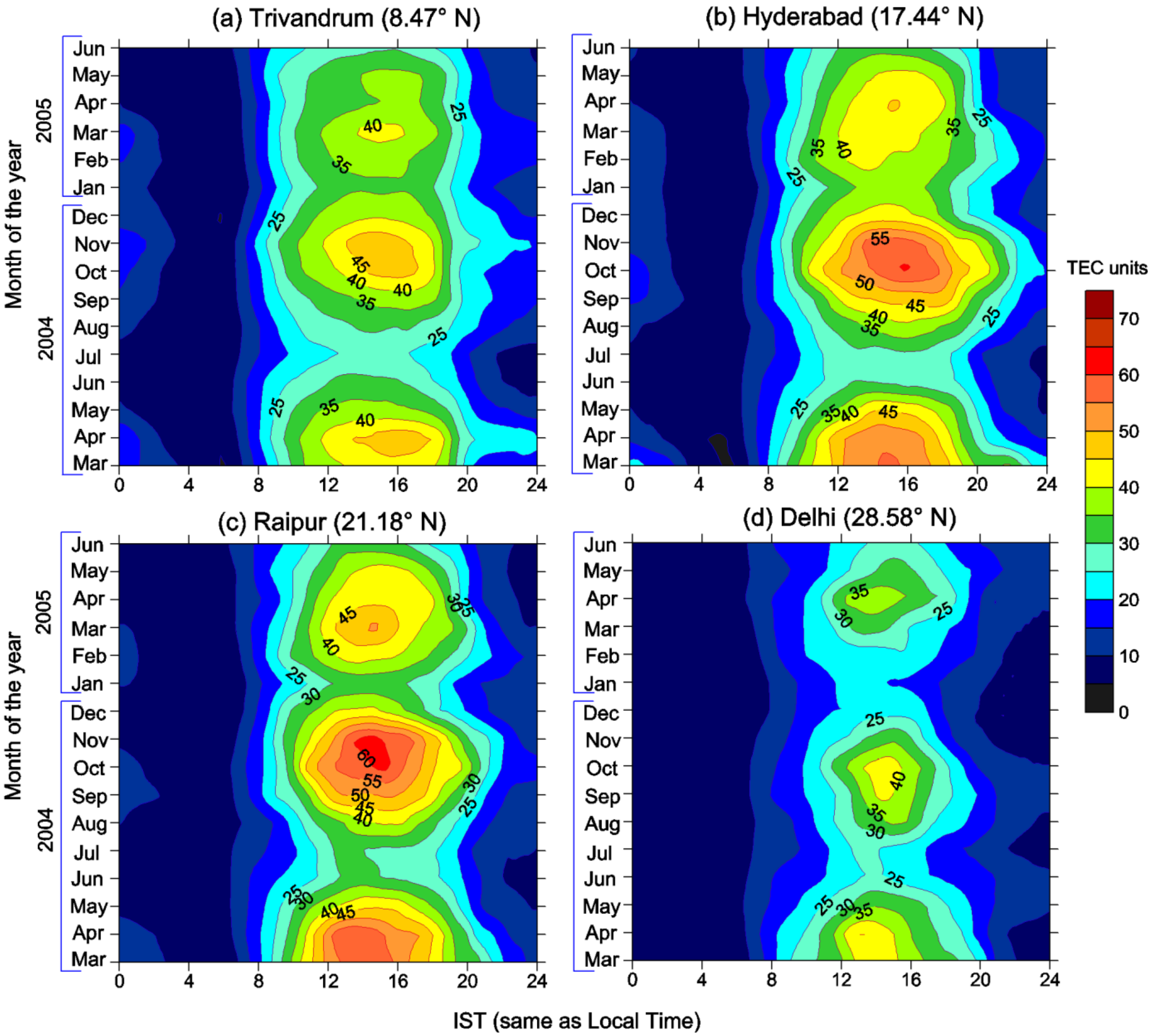

Contour plots of the monthly average diurnal variation of TEC at four stations across India (taken from the results of GPS Aided Geo Augmented Navigation (GAGAN) project of ISRO + AAI)

The lack of complete understanding of the above phenomena often leads to navigational errors and communication losses. TEC measurements are necessary to improve our understanding of the interaction between the solar wind and the earth's ionosphere, which is very crucial for the functioning of several space borne and ground based systems and also to increase our capability for forecasting space weather events. Our venture will shed some light on some of the complex phenomena occurring in space.

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3. Orbit

The efficacy of our endeavor depends entirely on the orbit we get for our satellite. Most of the ionospheric phenomena occur at specific times of the day and we need the satellite to have a pass over the ground stations at those times for us to obtain the relevant TEC values.

A circular orbit with an inclination of approximately 24 degrees would be optimum for the mission since it will render several passes at different times of the day and these passes would occur at different times of the day over the course of the lifetime of the satellite. The exact value of the actual inclination would depend on the location of the ground stations, which depends on the efficacy of the tomography algorithms, which is yet to be worked out.

However, we know that in all likelihood, we would be launched along with a mainstream satellite of ISRO which would invariably put us in a polar sun synchronous orbit. This would only allow us to measure the TEC values at the same local time. Given this limitation, a 2:30 am-pm orbit would be optimum for the satellite as it would allow us to measure the TEC values at a time when the EIA is at its peak.

4. Techniques for measurement of TEC from LEO satellite

The various techniques that can be used to measure TEC from LEO satellites are described below:

1. Measurement of Faraday rotation (our method)
2. Measurement of group delay of received signal
3. Measurement of Doppler shift of received signal due to ionospheric fluctuations
4. Measurement of amplitude scintillations of received signal.

4.1 Measurement of Faraday rotation of polarization angle:

When a linearly polarized radio wave passes through an ionized medium with a magnetic field in the direction of propagation, the plane of polarization rotates. This effect is called Faraday rotation.

The relation between the rotation angle and the TEC is given by:

$$\Delta\phi = 4.87\times10^{4}\times f^{-2}\int_{h_1}^{h_2} NB\cos\theta dl\ ,$$ where N = electron density

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B = magnetic field of earth,
Θ = angle between the radio wave and line of sight,
Δφ = angle of rotation,
f = frequency of the wave.

Measurement process:
In order to radiate linearly polarized waves from the satellite, we plan to use a monopole antenna. The radiation pattern of a monopole is such that the radiation is always polarized in the $\hat{\theta}$ direction assuming the monopole is oriented in the $\hat{z}$ direction. Thus, we know the initial polarization angle.

Measurement at the ground station:
We will be measuring the angle of polarization at the ground station by using a crossed Yagi antenna and measuring the intensities of the signals at the two feeds.

Resolution of the nπ ambiguity, use of two close frequencies:
A major problem of the process is the fact that there would always be an ambiguity of nπ in the angle measured at the ground station. The formula for Faraday rotation gives an angle of about 110° for the rotation at a frequency of 433 MHz even when the satellite is overhead. The maximum angle at this frequency comes out to be about 600° which is pretty large.
We propose to resolve this ambiguity by use of two very nearby frequencies viz. 400 and 433 MHz and then measuring the difference between the angles of polarization of the two waves. The difference between the angles is given by:

$\Delta\phi_1 - \Delta\phi_2 = 4.87 \times 10^4 \times \int_{h_1}^{h_2} NB\cos\theta dl \times \frac{f_1^2 - f_2^2}{f_1^2 f_2^2}$, where f_1, f_2 are the two frequencies.

This is not very large and can be easily measured without any ambiguity as the maximum value of this angle is only about 90°. We hence plan to use the frequencies 400 and 433 MHz. The following graphs illustrate the situation:

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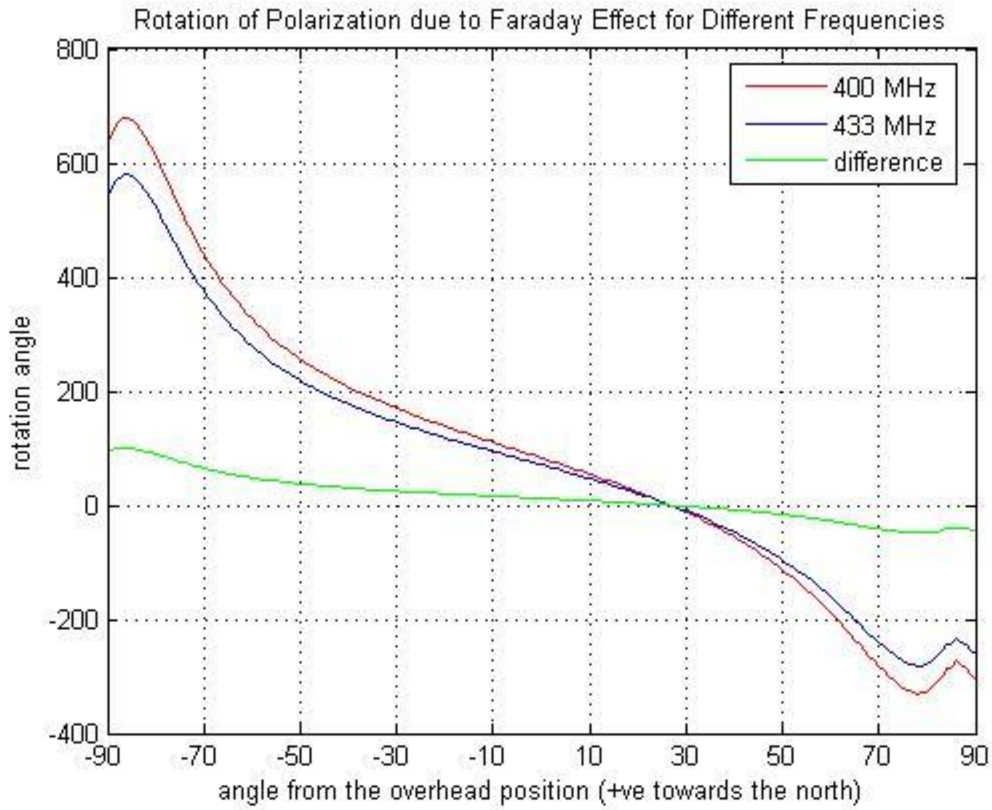

However, to measure the actual difference between the angles of rotation of the two frequencies without any attitude data on ground will be impossible as the signals will have some initial angle between them which will depend upon the yaw of the satellite and the angle between the antennae. But if we keep the antennae perfectly parallel, then this initial angle will be 0, irrespective of the yaw angle.

<u>Advantages:</u>

The advantages of this process are the following:

- Needs comparatively less hardware on board the satellite.
- Measurement is done only on carrier phase polarization angle which is an inherent property of the signal unlike a modulated signal where errors might arise.
-

<u>Disadvantages:</u>

The disadvantages of this process are as follows:

- The signal transmitted from the satellite must have a high degree of polarization purity which is not so easy.

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- The final result will not be directly proportional to the TEC but will depend upon the magnetic field along the path as well. Thus this dependence will have to be accounted for by some other way.
- The angle between the antennae will have to be very small.

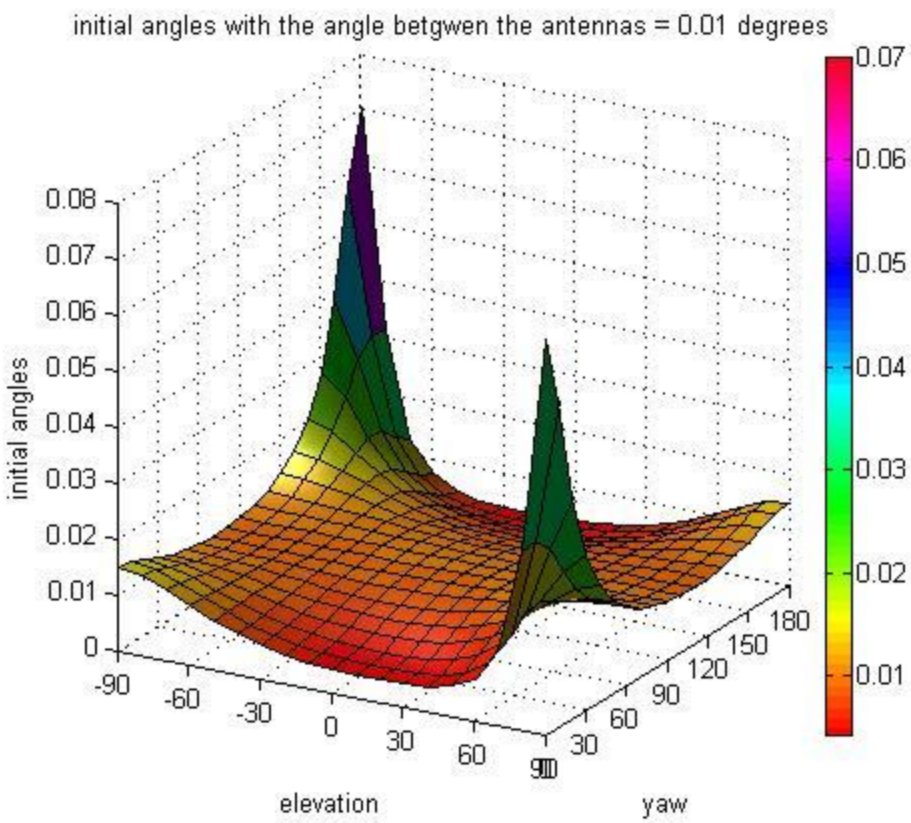
Error sources:

If we assume an SNR of about 500, the minimum error in measuring the angle comes out to be about 0.1°.

The various error sources and their contributions are discussed below.

- Misalignment of antennae:

  Now, the initial angle between the two waves depends upon the angle between the antennae and the position of the ground station relative to the antennae. Thus, if the two antennae are not parallel there will be some initial angle between the waves, which we can't know unless we know the attitude of the satellite. This initial angle depends upon the yaw angle of the satellite and the elevation of the satellite above the horizon. The relation between them is brought out in the following graph.



However this is not much important as the misalignment in angles is not expected to be more than 0.01°. This is because the error in fabrication of the antenna system can be as small as 100µm, and thus the error in the angle will not exceed 0.01°.

$$\text{error in angle} = \frac{\text{error in distance}}{\text{length of the monopole}} \text{ radians} = \frac{10\times10^{-4}\times180}{17\times\pi} = 0.003^{\circ}$$

Hence we are well within the safety limits regarding this factor.

- Polarization impurities and Faraday ellipticization of wave:
  The radio wave which will be received at the ground station will not be perfectly linearly polarized due to mainly two reasons:
  i. Polarization impurity of the monopole antenna:
     The wave emitted by the monopoles aboard the satellite will not be perfectly linearly polarized because the monopoles will have a finite radius and such factors. This will introduce a circularly polarized component into the waves and thus the measurements made at the ground station will be faulty.
  ii. Faraday ellipticization of wave:
     When a linearly polarized EM wave passes through a medium with a transverse magnetic field and plane of polarization neither parallel nor perpendicular to the magnetic field, another effect known as Faraday ellipticization also takes place, by which the EM wave becomes elliptically polarized. However, for the frequencies we are considering, this effect will not be so important. For a frequency of 433 MHz, the minimum length needed to traverse in order to get an axial ratio of even 20dB (very weakly elliptically polarized) is of the order of 10000 km, which is far greater than what we will be experiencing (670 km).

4.2 Relative Group Delay of two Different Frequency Waves:

When a radio wave passes through the ionosphere, the group velocity of the wave is decreased due to the refractive index of the ionosphere. The relation between the group refractive index and the electron content of the ionosphere is given by:

$$n_g = 1 + \frac{40.3 N_e}{f^2},$$ where N_e=electron density (in el/m^3),

f=frequency of the wave (in Hz).

Now, the time delay in modulation phase is given by:

$$\Delta t = \frac{1}{c}\int_{h_1}^{h_2}(n-1)dl = \frac{40.3}{cf^2}\int_{h_1}^{h_2} N_e dl$$

Thus this delay is directly proportional to the TEC from the satellite to the ground station. Now, suppose we send two carrier waves with the same signal upon them, the information on one will arrive faster than the other due to the $1/f^2$ dependence of this delay on the frequency. By measuring this delay between the two signals, we can detect the TEC.

Disadvantages:

- The same signal has to be imposed on two different carrier frequencies simultaneously, which is difficult
- Phase measurement at the ground station is not an easy task.

Advantages:

- The obtained reading will be directly proportional to the TEC, which is very much preferable
- There are no stringent conditions on the antennae on board the satellite

4.3 Doppler Shift due to electron density fluctuations:

We know that, phase refractive index,

$$n_p = 1 - \frac{40.3N_e}{f^2}.$$

Thus, we have that the phase of the carrier wave will depend upon the TEC as,

$$\phi = \phi_0 + \Delta\phi,$$

$$\text{where, } \Delta\phi = \frac{40.3}{cf}\int_{h_1}^{h_2} N_e dl$$

But, frequency is simply the time derivative of phase. Thus, if TEC is dependent upon time, then we will have,

$$\begin{aligned} f &= \frac{d\phi}{dt} \\ &= \frac{d\phi_0}{dt} + \frac{40.3}{cf_0}\frac{d(TEC)}{dt} \\ &= f_0 + \frac{40.3}{cf_0}\frac{d(TEC)}{dt} \end{aligned}$$

Thus, there will be a shift in the frequency proportional to the change in the TEC. However, this technique is useful for GEO satellites only. In case of LEO satellites the term $\frac{d(TEC)}{dt}$ consists of two parts:

b. Due to the fast motion of the satellite relative to the ground station,
c. Ionospheric fluctuations.

The typical magnitudes of the former are about 10 TECU/min whereas that of the latter is about 0.1 TECU/min. Thus, in case of LEO satellites the former factor always swamps out the latter. Thus, this method is of use only in case of GEO satellites where the former factor is absent due to the orbit of the satellite.

4.4 Amplitude and Phase Scintillations of Received Signal:

The electron density of the ionosphere is not homogenous but rather it has both fine scale and large scale irregularities. These irregularities cause an EM wave to face a diffraction grating type structure of the ionosphere and as a result, when they emerge from the ionosphere, they have spatial amplitude as well as phase scintillations, just like a diffraction pattern. As the satellite passes over the ground station, these scintillations sweep over the station and as a result, we get some noisy picture. These can then be used to determine the scale of the irregularities.

5. Ionospheric Tomography

5.1 Introduction:

By Faraday rotation method, we can measure the TEC (Total Electron Content) at various elevation angles of the satellite. This gives us information about the integrals of electron density in various directions from the IIT Bombay ground station. From these integrals, we can derive the values of the electron densities at various positions of the ionosphere. This technique is called ionospheric tomography.

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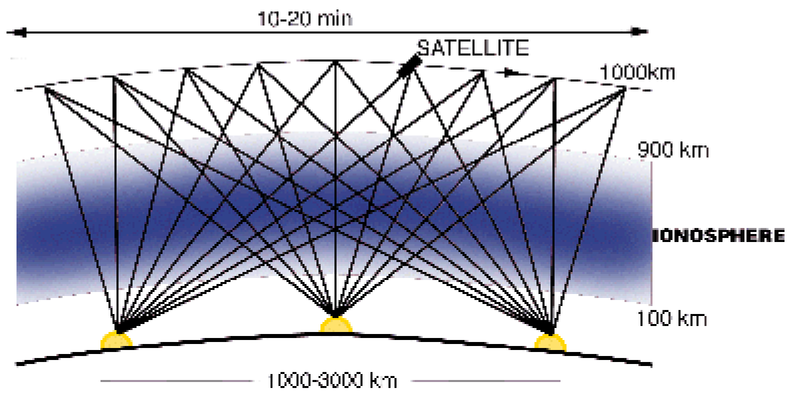

Figure 1: Geometry of the situation

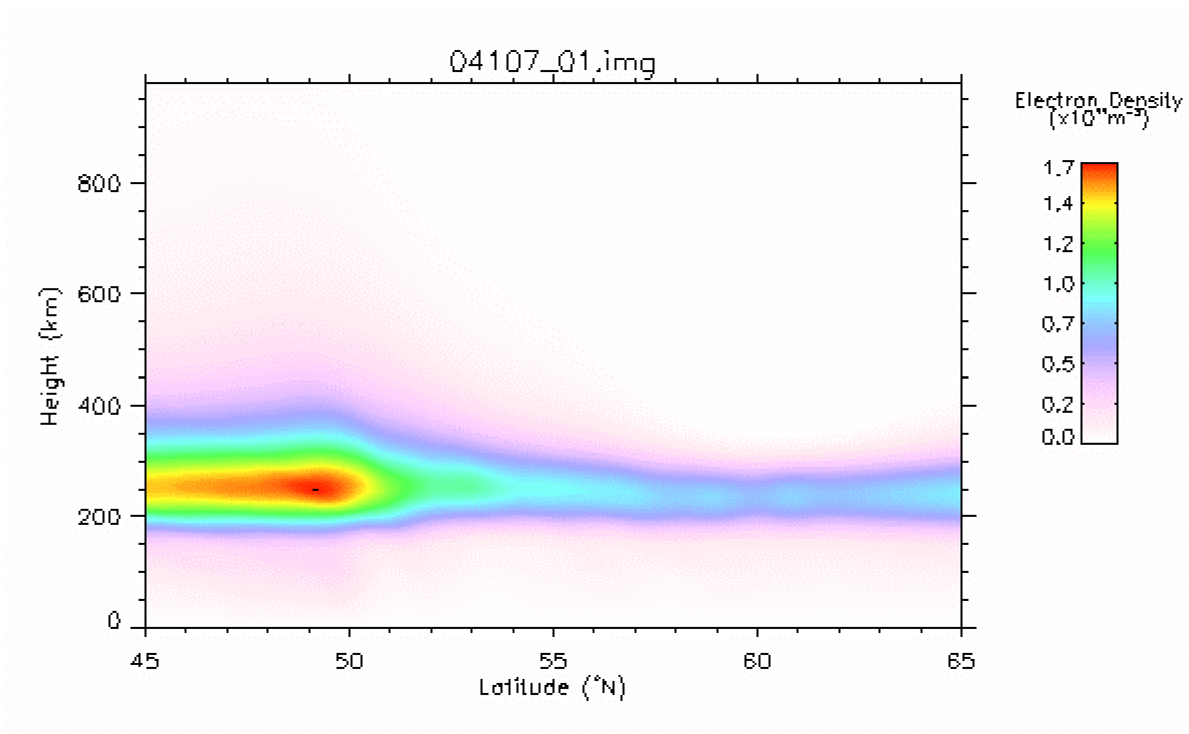

Figure 2: Tomographic image

5.2 Our technique:

There may be two different approaches to the problem.

i. <u>Continuously obtaining data at only one ground station:</u>

In case of our payload, we will be measuring the values of the total electron count at various elevation angles of the satellite at our IIT Bombay ground station. This will be used for tomography. Here we assume that the ionosphere doesn't vary more than our resolution within the time the satellite takes to pass over us.

ii. Data from several ground stations:
In this approach, we will be setting up ground stations at various centers over India, preferably over the same longitude (as we will be getting the latitudinal data from the STEC values at the ground stations only).

5.3 Algorithms:

Various algorithms are followed in tomography. These are summarized below:

- Transform methods:
  The procedure for these methods is:
  i. The derived values are transformed to a different domain (usually the frequency domain) through some transform (usually Fourier Transform).
  ii. Then some relation between the transformed variable and the transform of the required variable is used to determine the transform of the actual variable.
  iii. Upon applying an appropriate inverse transform, the required variable is generated.
  - Advantages:
    Continuity of the output variable comes automatically as the inverse Fourier transform of the obtained transform is usually continuous.
  - Disadvantages:
    i. The transforms for various geometries of the measurements can lead to very different transforms for generating the required variable. This is the reason why we could not use this method in our case, as we were unable to come up with an appropriate transform for this special case.
    ii. These methods are inherently continuous. But in case of a computer, we cannot get any continuous function. Thus, there are always some discretization errors in these methods.

- Algebraic methods:
  The procedure for these methods is:
  i. The domain of the required function is divided up into pixels, i.e. discrete zones where the function is assumed to be constant.
  ii. Then the integrals can be expressed as a linear combination of these pixel values.

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iii. Solving these systems of linear equations, we get a solution which is a picture of the required function.

Mathematically, let the column vector consisting of the components of the picture relative to some basis pictures be [x_i]. Also, let the column vector consisting of the components of the integrated electron density values at various elevation angles relative to some basis be [y_j]. Then, the relation between [x] and [y] is given by:

$\bar{y} = [R]\bar{x}$ where R_{ij} = the length of ray path of y_i which lies in the x_j pixel.

Now, in general, this set of linear equations may have infinite or even no solutions. Noise plays an important role to distort the readings. Thus, the general process of inverting [R] will not work here. Instead, we take the following approach.

Let the expected variance in the readings be μ. We also assume an a priori distribution of the pictures. We assume the pictures to be normally distributed about a central picture $\bar{x}_0$ by some variance σ. Then, we have

$$P(\bar{X} = \bar{x}) = \frac{1}{\sqrt{2\pi\sigma}} e^{-|\bar{x}-\bar{x}_0|^2/2\sigma^2} \quad \text{... (a priori)}$$

Also, let $\bar{y} - R\bar{x} = \bar{u}$. Then, we have,

$$P(\bar{U} = \bar{u}) = \frac{1}{\sqrt{2\pi\mu}} e^{-|u|^2/2\mu^2}$$

Now, the Bayesian estimate of $\bar{x}$ is obtained by minimizing $P(\bar{X} = \bar{x})\,.\,P(\bar{U} = \bar{u})$. For this condition to be satisfied, we must minimize $\frac{|\bar{x}-\bar{x}_0|^2}{2\sigma^2} + \frac{|\bar{y}-R\bar{x}|^2}{2\mu^2}$. Thus, we have,

$$r^2 R^T(\bar{y} - R\bar{x}) + (\bar{x} - \bar{x}_0) = 0 \quad \text{... where } r = \mu/\sigma$$

An iterative algorithm for obtaining this solution is given by

$$\bar{x}_{k+1} = \bar{x}_k + \lambda\big(r^2 R^T(\bar{y} - R\bar{x}_k) + (\bar{x}_k - \bar{x}_0)\big) \quad \text{where } 0 < \lambda < \frac{2}{r^2\mu_{max} + 1}, \text{ where}$$

$$\mu_{max} = \text{largest eigenvalue of } R^T R$$

Thus, we can deduce the value of the required $\bar{x}$ by following this algorithm.

- Advantages:
  i. Method works equally well for any geometry of the receiving positions.

ii. A-priori knowledge about the required distribution can be easily built into the process by means of the initial vector $\bar{x}_0$.

- <u>Disadvantages:</u>
  i. Computation intensive.
  ii. Convergence to the actual solution is generally slow.

6. Simulations for determining the value of Faraday rotation of polarization due to a typical ionosphere:

We know that the Faraday rotation of a linearly polarized wave propagating through the ionosphere is given by:

$$\Delta\varphi = 4.72\times10^4 f^{-2} B\cos\theta\int_{h_1}^{h_2} Ndl$$

(where B $\cos\theta$=magnetic field component in the direction of propagation of the wave,
N = electron density,
f=frequency of the wave) $\cdots$ (1)

To model this rotation, we assumed a standard model of the ionosphere available from http://ccmc.gsfc.nasa.gov/modelweb/models/iri_vitmo.php.

The magnetic field values were obtained from http://www.ngdc.noaa.gov/geomagmodels/IGRFWMM.jsp.

We assumed the magnetic field to be constant in magnitude and direction at all the places. This is not a good approximation but can give us a good idea about the order of magnitudes of the values. For example, the values of magnetic field components at 300 km over Mumbai are (32674.2 nT, -506.3 nT, 16230.9 nT) and those at 10° to the north are (29040.5 nT, 410.4 nT, 28548.4 nT) while those at 10° to the south are (33812.2 nT, -1509.7 nT, 2230.3 nT) where the components are in order (north, east, vertical).

At first, we assumed the vertical profile of electron density also to be the same over all the places. This gave us the following graphs of rotation angles vs. elevation angle and angle with the east direction respectively.

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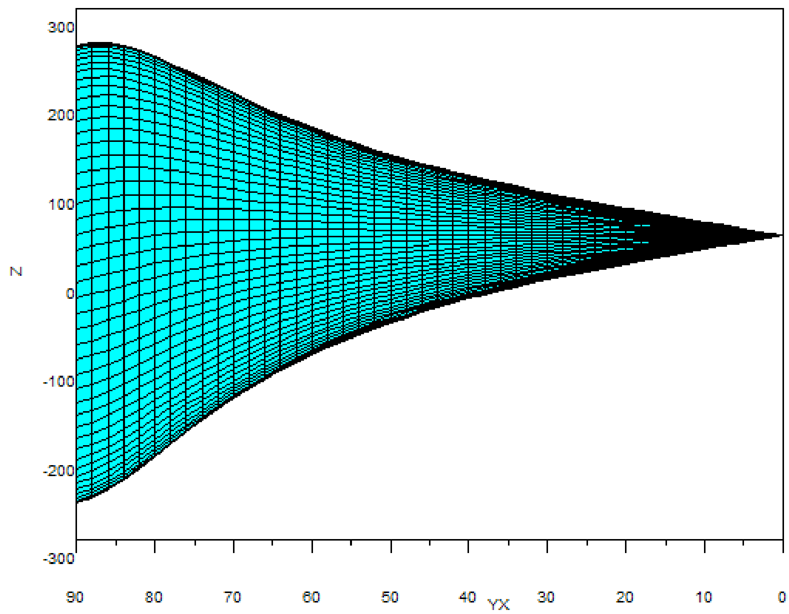

Figure 3 Constant phi plots (Phi contours)

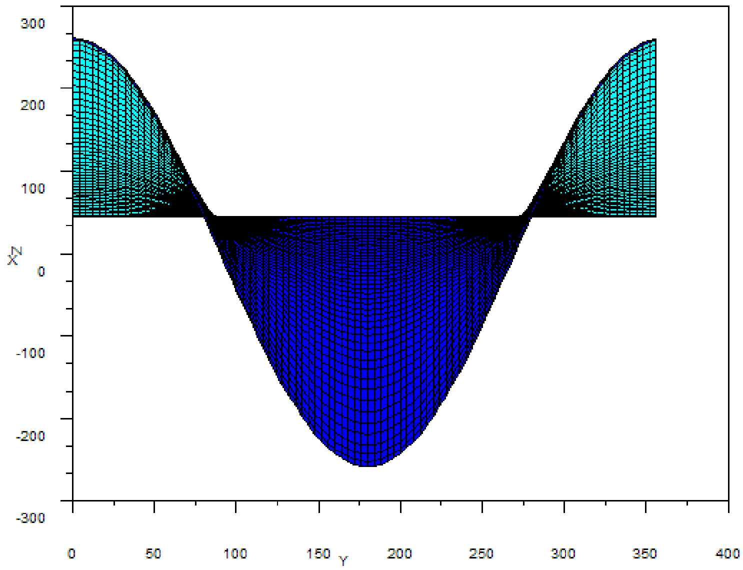

Figure 4 Constant theta plots (Theta contours)

Then we used the data for the variation of electron density vs. latitude and height. We assumed these two parameters to be acting independently on the electron density values i.e. we assumed that

$$\frac{N(h,\theta)}{N(h_0,\theta_0)} = \frac{N(h,\theta_0)}{N(h_0,\theta_0)} \cdot \frac{N(h_0,\theta)}{N(h_0,\theta_0)}$$

where $N(h,\theta)$ = electron density at latitude θ and height h,

h_0 = specific height, assumed to be 300 km,

θ_0 = specific latitude, assumed to be 19.06°, latitude of Mumbai.

Then we simulated the variation of the rotation angle vs. only the elevation angle with the angle with the east direction being constantly 0. We obtained the following graphs for 400 MHz, 433 MHz, and their difference.

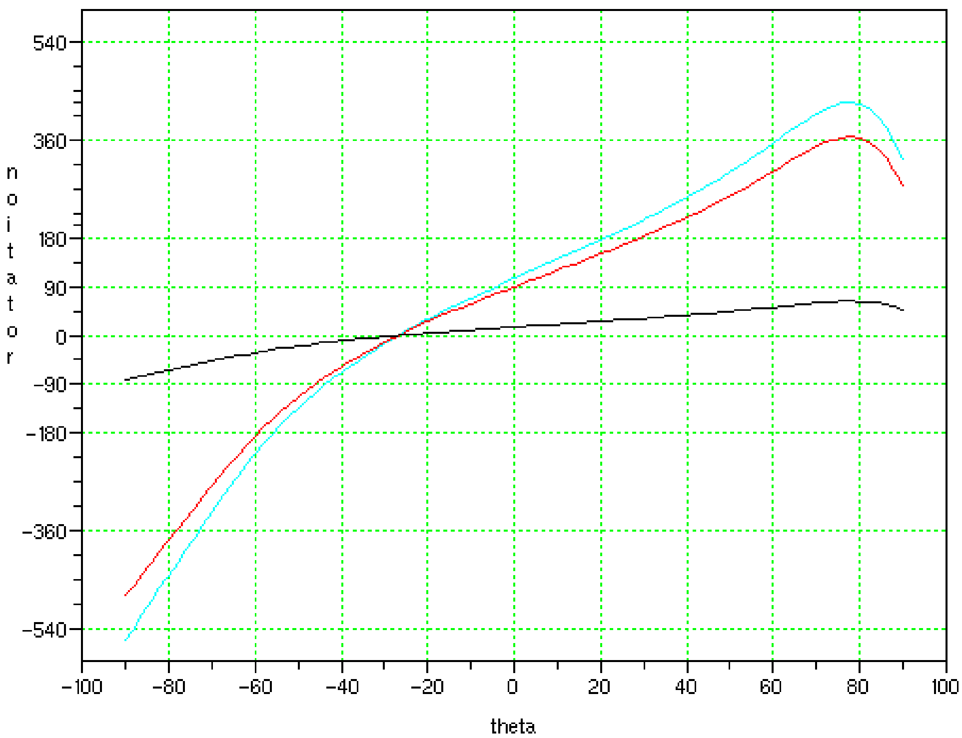

Figure 5 Red is 433 MHz, Blue is 400 MHz and black is their difference