

Pratham satellite: Faraday rotation based TEC measurement

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Pratham, the student satellite of Indian Institute of Technology Bombay is a landmark project undertaken by the students of the institute in collaboration with ISRO. The project is in its environment testing phase now. Total electron content (TEC) measurement was chosen as the payload for the satellite keeping in mind the current scientific atmosphere in India with the Indian Regional Navigational Satellite System (IRNSS) and GPS-Aided Geo-Augmented Navigation (GAGAN) system in the process of development. This paper describes the use of Faraday rotation method for TEC measurements. The key features of the method, n-pi ambiguity resolution, possible sources of error and simulations carried out to get the initial estimates of the TEC values are also discussed. The on-board and on-ground hardware implementation are briefly explained.

Keywords: Student satellite; Total electron count (TEC), Faraday rotation, GPS error correction

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1 Introduction

Total electron count (TEC) is defined as the number of electrons present in a column of unit cross sectional area, extending from the ground all the way up to the end of the ionosphere. TEC values (electrons m^{-2}) are a prominent source of information for understanding the structure and the dynamic behaviour of the ionosphere. But since the ionosphere virtually extends to large distances from the earth, it can be stated that only 95% of the ionosphere is covered between the earth and Pratham satellite's orbit.

1.1 TEC for error correction for GPS systems

During recent times, GPS satellites are used on many fronts and their use for position determination has proven 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. After integrating the group and phase delays along the GPS signal path, one can obtain a range between satellite and receiver that is different from geometrical distance between them. This difference is mainly due to the ionospheric error. If one has a dual frequency GPS receiver, then

one can deal with this error by taking into account ionosphere's dispersive nature. But if one is using a single frequency GPS receiver, then one needs some other method for getting rid of this error. Most GPS receiver manufacturers provide an in-built error model that predicts TEC values on the basis of previous history sheets. But it becomes difficult if one is situated near the equator 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. The performance can only be worse if one takes into account the potential effect of a solar or geomagnetic storm during medium or high solar activity periods. So these models fail to deliver a satisfactory performance¹. An increase in data points in this region can be used by GPS manufacturers for correcting this ionospheric error. Through Pratham, an attempt has been made to supplement the current database and the other ongoing Indian projects for TEC measurement with inhouse available TEC data, which will be available in the open source domain.

The currently used global ionospheric models can only model the monthly mean total electron content (TEC) to about ± 10 percent. These models cannot tell

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 about 22-27 percent root mean squared (RMS) of the ionospheric delay. The performance can only be worse if one takes into account the potential effect of a solar or geomagnetic storm during medium or high solar activity times. One may do it by supplementing the current database and the ongoing Indian projects for TEC measurement with Pratham's TEC data.

1.2 Equatorial ionization anomaly (Appleton anomaly)

Equatorial ionization anomaly (EIA) is characterized by a depression in ionization densities (or trough) at the geomagnetic equator and two peaks on either side of the equator at about 15° magnetic latitudes. It may be noted 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 (Fig. 1).

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. As Mumbai falls in this region, one can easily get involved with this experiment.

1.3 Equatorial spread-F (ESF)

Equatorial spread-F (ESF) can be defined as the spread F/plasma bubble irregularity phenomenon resulting 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 (i.e. pre reversal 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 development².

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.

1.3.1 Location

Usually ESF is not observed at higher latitudes. Its presence is felt at lower latitudes during late evening. It happens between 20° South and 20° 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 (termed as plasma bubbles). These plasma bubbles can be observed with the help of Radars operating in the VHF range.

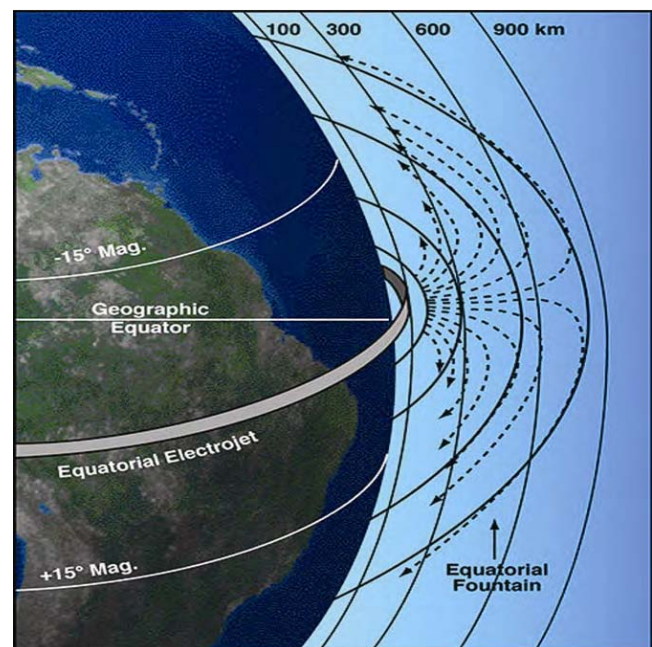


Fig. 1 — Equatorial electrojet

1.3.2 Link between ESF and EIA

EIA is intensification of ionization crests in the late afternoon near $\pm 20^\circ$ 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 one can get very steep plasma gradients in the equatorial region, which are conducive to Rayleigh Taylor instability and this explains the relationship between EIA and ESF. The variations of ESF 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 Dynamics of TEC variation

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.

2.1 Diurnal variations

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.

2.2 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 hrs LT, while at the equator, the peak is broad, i.e. it occurs for a longer duration of time and occurs around 16:00 hrs LT. A short-lived day minimum occurs between 05:00 and 06:00 hrs 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. The day minimum in TEC is flat during most of the nighttime hours, i.e. from 22:00 to 06:00 hrs LT. 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.

2.3 Climatic variations in TEC

Talking about the seasonal variations, 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.

Having looked at the complicated dynamics of TEC variations, one must realize that the lack of complete understanding of the above phenomena often leads to navigational errors and communication losses. TEC measurements are necessary to improve the 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 the capability for forecasting space weather events. The data from Pratham will shed some light on some of the complex phenomena occurring in space.

3 Orbit and lifetime

The efficacy of the endeavour depends entirely on the orbit of the satellite. Most of the ionospheric phenomena occur at specific times of the day and the satellite needs to have a pass over the ground stations at those times to obtain the relevant TEC values.

A circular orbit with an inclination of approximately 24° would 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. However, this will end up mixing temporal and spatial variations since the passes will be nearly perpendicular to the longitudes. Hence, keeping tomography in mind, this orbit is not ideal for the present mission.

A polar sun synchronous orbit would only allow 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 to measure the TEC values at a time when the EIA is at its peak.

Literature survey reports that TEC measurements would require a period of around a couple of months for validation of data. Hence, the satellite would have a minimum lifetime of 3 months. However, the data generated would be comprehensive if the satellite operates for an entire year, so that the seasonal variations in TEC values can be captured.

4 Other methods for measurement of TEC

4.1 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:

$$n_g = 1 + \frac{40.3N_e}{f^2} \quad \dots(1)$$

where, n_g is group refractive index; N_e , electron density (el m^{-3}); f , frequency of the wave (Hz). Now, the time delay in modulation phase is given by:

$$\Delta t = \frac{1}{c} \int_{h_1}^{h_2} (n_g - 1) dl \quad \dots(2)$$

Thus, this delay is directly proportional to the TEC from the satellite to the ground station. Now, suppose two carrier waves are sent 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, one can detect the TEC.

4.2 Doppler shift due to electron density fluctuations

The phase refractive index is known as:

$$n_p = 1 - \frac{40.3N_e}{f^2} \quad \dots(3)$$

Thus, the phase of the carrier wave will depend upon the TEC as:

$$= \phi_0 + \Delta \quad \dots(4)$$

$$\text{where } 10\text{mm}\Delta = \int_{h_1}^{h_2} N_e dl \quad \dots(5)$$

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

$$f = \frac{d}{dt} = \frac{d}{dt} \phi_0 + \frac{40.3}{cf_0} \frac{d(\text{TEC})}{dt} = f_0 + \frac{40.3}{cf_0} \frac{d(\text{TEC})}{dt} \quad \dots(6)$$

Thus, there will be a shift in the frequency proportional to the change in the TEC. However, this technique is useful for Geosynchronous (GEO) satellites only. In case of Low Earth Orbit (LEO) satellites, the term consists of two parts: (i) due to the fast motion of the satellite relative to the ground station; and (ii) 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 later. 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.

4.3 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 electromagnetic 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 some noisy picture is obtained. These can then be used to determine the scale of the irregularities.

5 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 TEC is given by:

$$\Delta = 2.36 \times 10^4 f^{-2} \int_{h_1}^{h_2} N B \cos \theta dl \quad \dots(7)$$

where, N , is electron density; B , magnetic field of earth; θ , angle between the radio wave and line of sight; Δ , angle of rotation; and f , frequency of the wave.

5.1 Measurement process

In order to radiate linearly polarized waves from the satellite, it is planned to use a monopole antenna. The angle of polarization is measured at the ground station by using a crossed Yagi antenna and measuring the intensities of the signals at the two feeds. The ratio of these intensities give the polarization angle.

5.2 Measurement of phase angle by AD8302

The relative intensities of the radio waves is measured by an Analog Devices chip AD8302. This chip takes two inputs: input A (INPA) and input B (INPB) and gives a voltage output proportional to the

level ratio of these signals in dB. In addition, the phase output pin (VPHS) gives the phase difference between the signals at the INPA and INPB. The output of the AD8302 is given by:

$$V = 20 \log_{10} |\tan \theta| \quad \dots(8)$$

where, θ , is the plane of polarization. Hence,

$$= \tan^{-1}(10^{V/20}) \quad \text{or} \quad \dots(9a)$$

$$= -\tan^{-1}(10^{V/20}) \quad \dots(9b)$$

To resolve this ambiguity, one needs to use the phase difference information. If the output is close to 30 mV then Eq. (9a) is true. If the output is close to 1.8 V then Eq. (9b) is true. This chip gives ± 0.3 dB error for magnitude ratios within ± 20 dB. The output graphs of this chip are shown in Figs 2 and 3 at two different frequencies.

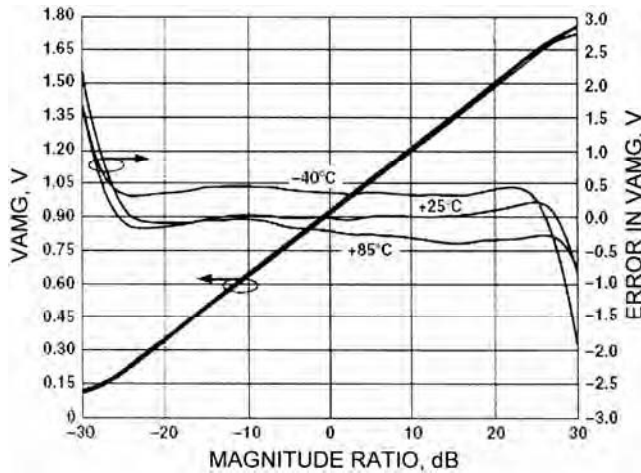


Fig. 2 — Voltage magnitude output and log conformance vs input level ratio at frequency of 900 MHz, reference level = -30 dB

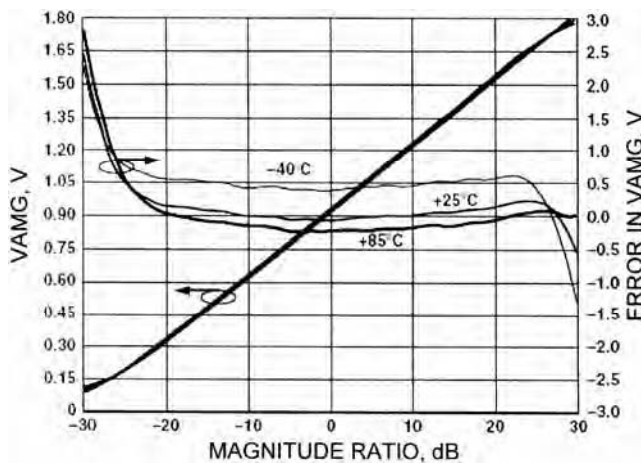


Fig. 3 — Voltage magnitude output and log conformance vs input level ratio at frequency of 100 MHz, reference level = -30 dB

Thus, the maximum error in angle corresponding to this dB error will be 1° , which can give a signal to noise ratio (SNR) of about 100 which will be quite good for measurements.

5.3 Resolution of the n ambiguity, use of two stations

The two-station or the Leightenjeir method is used in order to resolve the n ambiguity in the measurement of the polarization angle at the ground stations. This method involves the use of readings at two ground stations simultaneously in order to determine the n ambiguity at both the stations. Here, the approximation, that the ionospheric electron distribution is in a thin shell of uniform density, is used. Obviously, this is a very bad approximation, but it is enough to determine the n ambiguity to the nearest integer. Under this approximation, one can write with several values of $T_{i,1}$ and $T_{j,2}$, one can fit a straight line to Eq. (9a) for all values of i, j and can then get least squares estimates of n_1 and n_2 .

5.4 Resolution of initial attitude ambiguity

Measuring the angle of rotation without any attitude data on ground will be impossible as the signals will have some initial polarization angle which will depend upon the yaw of the satellite. It is, hence, proposed to use two monopole antennae operating at two different frequencies. If the initial angle of polarization for the two monopoles is kept same (by keeping their orientation), one can eliminate the effect of the initial polarization angle by taking the difference of the polarization angles measured at the two frequencies at the ground station. To achieve this, one requires the yaw angle of the satellite to be $90^\circ \pm 5^\circ$ and the monopoles to remain parallel within 1° angle. These values come from the following analysis.

5.4.1 Misalignment of antennae

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 one can't know unless one knows 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 graph shown in Fig. 4. Even if, one initially places the monopoles within one degree of parallelism, severe distortions can occur in the shape and position of the monopoles at the time of deployment and during

launch. As seen from the graph, the error is minimum if the satellite has a yaw angle of 90° .

5.5 Polarization impurities and Faraday ellipticisation 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 is not perfectly linearly polarized because the monopoles have a finite radius. This introduces a circularly polarized component into the waves and thus, the measurements made at the ground station are faulty. Considering the requirement of measuring polarization angle at the ground station upto an accuracy of 1° , one would require the monopoles on the satellite to transmit radio waves with a polarization purity of 99.9%

(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 under consideration, this effect is not so important. For a frequency of 433 MHz, the minimum length needed to traverse in order to get an axial ratio of even 20 dB (very weakly elliptically polarized) is of the order of 10000 km, which is far greater than what is experienced (817 km).

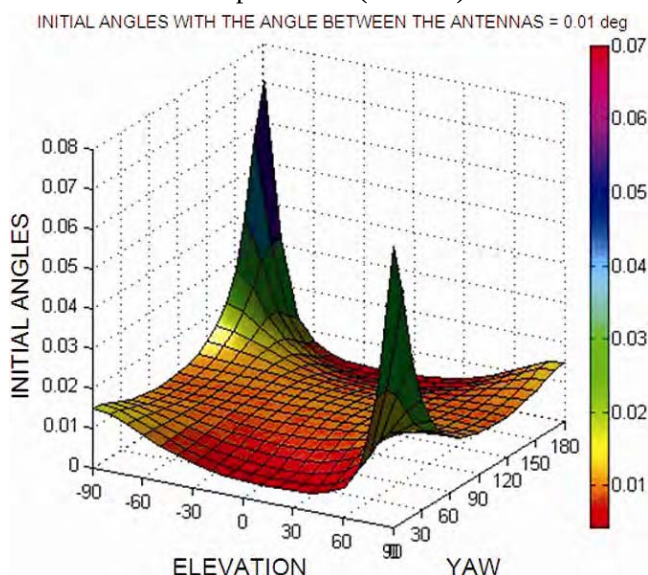


Fig. 4 — Initial polarization angle variation with satellite attitude

5.6 Advantages and disadvantages of Faraday rotation

The first advantage of this process is that it needs comparatively less hardware on-board the satellite. This in continuation reduces complexity of the entire system. Also, 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.

On the other hand, the signal transmitted from the satellite must have a high degree of polarization purity, which is not so easy. The final result is not directly proportional to the TEC but depends upon the magnetic field along the path as well. Thus, this dependence has to be accounted for by some other way. To attain high values of accuracies, the angle between the antennae has to be very small.

5.7 Simulations

To model this rotation given by Eq. (7), a standard model of the ionosphere available from http://ccmc.gsfc.nasa.gov/modelweb/models/iri_vitmo.hphere is assumed. The magnetic field values were obtained from <http://www.ngdc.noaa.gov/geomagmodels/IGRFWMM.jsphere>. The magnetic field is assumed to be constant in magnitude and direction at all the places. This is not a good approximation but can give 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). Simulations of this method performed with a standard model of the ionosphere yield values of n_1 and n_2 which are close to the actual values. Some typical results are presented in Table 1.

Also, the vertical profile of electron density is also assumed to be the same over all the places. This gave the graphs of rotation angles vs elevation angle and angle with the east direction, respectively as shown in Figs 5 and 6. Taking the variation with height and latitude into consideration, the plot obtained is shown in Fig. 7.

Table 1 — Integer ambiguity calculations

Actual value		Simulated value	
N1	N2	N1	N2
0	1	-0.19	0.87
2	2	2.18	2.08

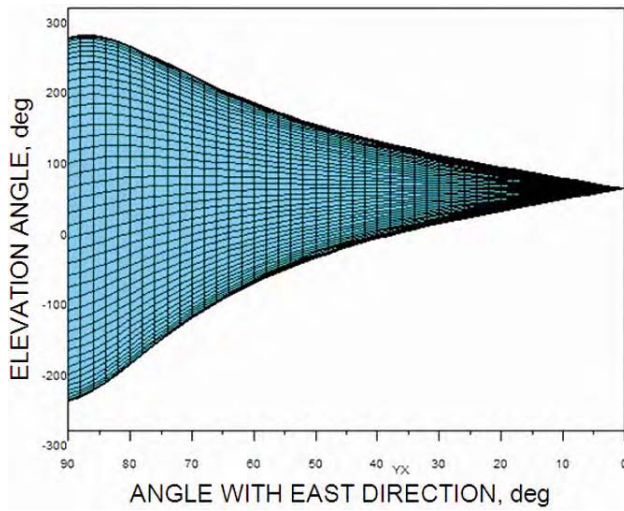


Fig. 5 — Constant phi plots (Phi contours)

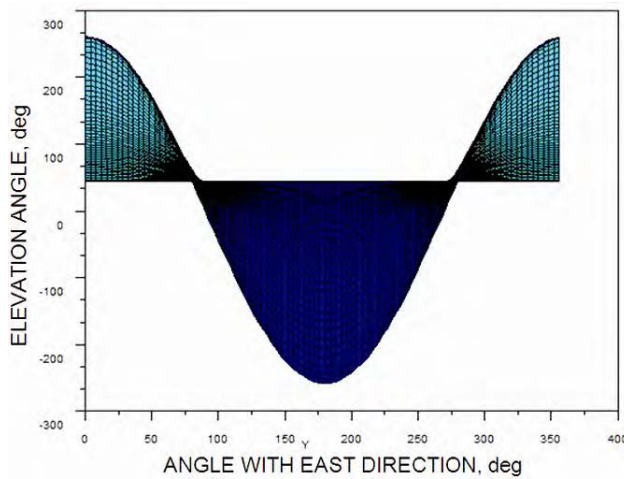


Fig. 6 — Constant theta plots (Theta contours)

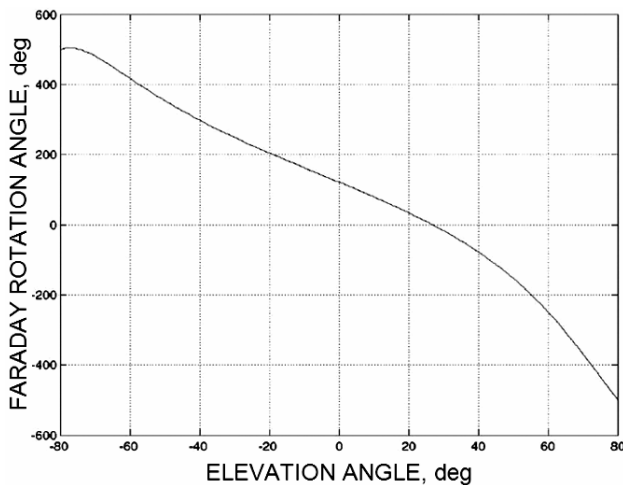


Fig. 7 — Plot at constant azimuth taking into consideration the variable electron density completely

6 Conclusion

There are other methods available to measure ionospheric TEC, but Faraday rotation has not yet been put to use. As discussed, this method is low cost and simple to implement, since the on-board complexity is significantly low. If this attempt is successful, then in future satellites, one can try out other methods to measure TEC and then actually there will be a plethora of values from various methods, which will give a much more clear understanding of the data. The variation of TEC over India is of great interest to all scientists studying the atmosphere and in particular, the ionosphere. This mission, if successful, will provide additional data with a yet unexplored method and give a fresh angle to the study.

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