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# On the validity of the ionospheric pierce point (IPP) altitude of 350 km in the Indian equatorial and low-latitude sector

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**Abstract.** The GPS data provides an effective way to estimate the total electron content (TEC) from the differential time delay of L1 and L2 transmissions from the GPS. The spacing of the constellation of GPS satellites in orbits are such that a minimum of four GPS satellites are observed at any given point in time from any location on the ground. Since these satellites are in different parts of the sky and the electron content in the ionosphere varies both spatially and temporally, the ionospheric pierce point (IPP) altitude or the assumed altitude of the centroid of mass of the ionosphere plays an important role in converting the vertical TEC from the measured slant TEC and vice versa. In this paper efforts are made to examine the validity of the IPP altitude of 350 km in the Indian zone comprising of the ever-changing and dynamic ionosphere from the equator to the ionization anomaly crest region and beyond, using the simultaneous ionosonde data from four different locations in India. From this data it is found that the peak electron density height ($h_pF_2$) varies from about 275 to 575 km at the equatorial region, and varies marginally from 300 to 350 km at and beyond the anomaly crest regions. Determination of the effective altitude of the IPP employing the inverse method suggested by Birch et al. (2002) did not yield any consistent altitude in particular for low elevation angles, but varied from a few hundred to one thousand kilometers and beyond in the Indian region. However, the vertical TEC computed from the measured GPS slant TEC for different IPP altitudes ranging from 250 to 750 km in the Indian region has revealed that the TEC does not change significantly with the IPP altitude, as long as the elevation angle of the satellite is greater than 50 degrees. However, in the case of satellites with lower elevation angles ($<50°$), there is a significant departure in the TEC computed using different IPP altitudes from both methods. Therefore, the IPP altitude of 350 km may be taken as valid even in the Indian sector but only in the cases of satellite passes with elevation angles greater than 50°.

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## 1 Introduction

In the recent years, the measurements of total electron content (TEC) have gained importance with the increasing demand for the GPS-based navigation applications in trans-ionospheric communications with space-borne vehicles, such as satellites, aircrafts and surface transportations. The TEC measurements are necessary for making appropriate range delay corrections introduced by the ionosphere, both during quiet and disturbed periods (space weather events), such as scintillations and geomagnetic storm periods. The TEC is one of the most important quantitative parameters of the Earth's ionosphere and plasmasphere, which is defined as the height integral of electron density along the ray path from the receiver to the satellite (Leitinger, 1996).

All modern TEC measuring techniques rely on the observation of signal phase differences or on pulse travel time measurements based on geostationary and orbiting satellite signals. A standard way of measuring TEC is to use a ground-based receiver capable of processing signals from satellites in geostationary orbits, like ATS-6, SIRIO; polar orbiting satellites, like the U.S. Navy Navigation Satellite System (NNSS), the Russian Global Navigation Satellite System (GLONASS) satellites; some of which are not in use currently. The LEOS, such as the TOPEX/Poseidon's dual frequency altimeter data is used to obtain the vertical electron content of the altitude of the satellite (1336 km), but this instrument is used only to measure the ocean heights and there are data gaps over landmasses. Hence, in recent times, the TEC measurements using the Global Positioning System (GPS) are being carried out all over the world for ionospheric studies. The development of the GPS has also opened up new opportunities to investigate the ionosphere and plasmasphere on a global scale (Davies and Hartmann, 1997).

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**Table 1.** Ionosonde stations.

| Ionosonde Station | Geographic Latitude ($^o$N) | Geomagnetic Latitude ($^o$N) | Data considered |
|---|---|---|---|
| Trivandrum | 8.3 | –0.47 | Jan, March, April, June, July & Dec. 2001 |
| Waltair | 17.7 | 8.22 | Jan, March, April, June, July & Dec. 2001 |
| Ahmedabad | 23.0 | 14.46 | Jan, March, April, June & Dec. 2001 |
| Delhi | 28.5 | 19.5 | Jan, March, June, July & Dec. 2001 |

The Global Positioning System (GPS) is a satellite-based navigation system, which provides good positional accuracy of the user at any location, and at any given time. The current constellation of 29 GPS satellites (http://tycho.usno.navy.mil/gpscurr.html) orbit in six separate orbital planes with four satellites in each orbit. The orbital planes have an inclination of 55° relative to the equator. The precise spacing of the satellites in the six orbits is arranged such that a minimum of four satellites are visible to a user at any time, at any location on the Earth. The GPS signal traversing the ionosphere undergoes an additional delay proportional to the total number of electrons in the cross-sectional volume measured in TEC units. The dual frequency GPS receivers use two frequencies, L1 (1.575 GHz) and L2 (1.227 GHz), to compensate for the ionospheric delay, a measure of TEC, at least to a first order approximation, taking advantage of the dispersive nature of the ionosphere, where the refractive index is a function of frequency (Coco, 1991; Wanninger, 1993; Klobuchar, 1996). The GPS data provides an efficient way to estimate TEC with a greater spatial and temporal coverage (Davies and Hartmann, 1997; Hocke and Pavelyev, 2001). Since the frequencies used in the GPS are sufficiently high, the signals are minimally effected by the ionospheric absorption and the Earth's magnetic field, both in the short-term as well as in the long-term variations in the ionospheric structure.

The effective height of the ionosphere influences the conversion of the measured slant TEC to the vertical TEC, defined by the obliquity factor, depending on the elevation angle of the satellite. But as the GPS satellites are in different parts of the sky and the electron content varies both spatially and temporally, the ionospheric pierce point (IPP) altitude or the assumed altitude of the centroid of mass of the ionosphere plays an important role while converting the vertical TEC from the measured slant TEC and vice versa. As the northern crest of the equatorial ionization anomaly (EIA) is located over the Indian region, where the electron densities and the gradients are high, the determination of a single suitable IPP altitude is more difficult. In this paper efforts are made to examine the validity of the IPP altitude of 350 km (used in the mid latitude sector), in the Indian region where the ionosphere varies significantly from the magnetic equator to the equatorial ionization anomaly crest region and beyond.

## 2 The ionospheric effective altitude in the conversion of slant TEC

In the conversion of slant TEC to vertical TEC, it was assumed that the ionosphere and the protonosphere are horizontally stratified and are spatially uniform. Further, the ionosphere is simplified to a thin layer at an altitude of 350 km above the Earth's surface. This is called the thin shell model, and its height is the effective height or centroid of the mass of the ionosphere, which is taken as the IPP altitude or the altitude of ionospheric intersection of the user line-of-sight to the tracked satellite. This shell approximation is widely used (Coco et al., 1991; Wilson and Mannucci, 1993; Ciraolo and Spalla, 1997 and references therein), and its height is usually taken in the range of 350 to 400 km, apparently based on the maximum electron density altitudes in the ionosphere. In the equatorial and low-latitude regions, it is the spatial and temporal variations in the ionosphere that significantly effects the assumption of the effective IPP altitude and homogeneity of the ionosphere.

The thin shell approximation model is being used in the Satellite Based Augmentation Systems (SBAS), such as the Wide Area Augmentation System (WAAS), which is operational in the USA, where the model may not affect the WAAS operation, because this region mostly consists of the mid latitude ionosphere, where the spatial and temporal variations in the TEC are relatively less than those at high and low latitudes. Whereas in the Indian region, which encompasses the latitudes ranging from the magnetic equator to the northern anomaly crest and beyond, the effective height of the IPP may vary.

## 3 Data

In the equatorial and low latitudes, the plasma dynamics associated with the Appleton ionization anomaly and the electrojet current system greatly modify the vertical structure of the ionosphere, thereby changing the centroid of ionization mass distribution from latitude to latitude. Therefore, with a view to study the altitude variation of the peak electron density ($h_m F_2 \approx h_p F_2$) in the Indian sector, the ionosonde data

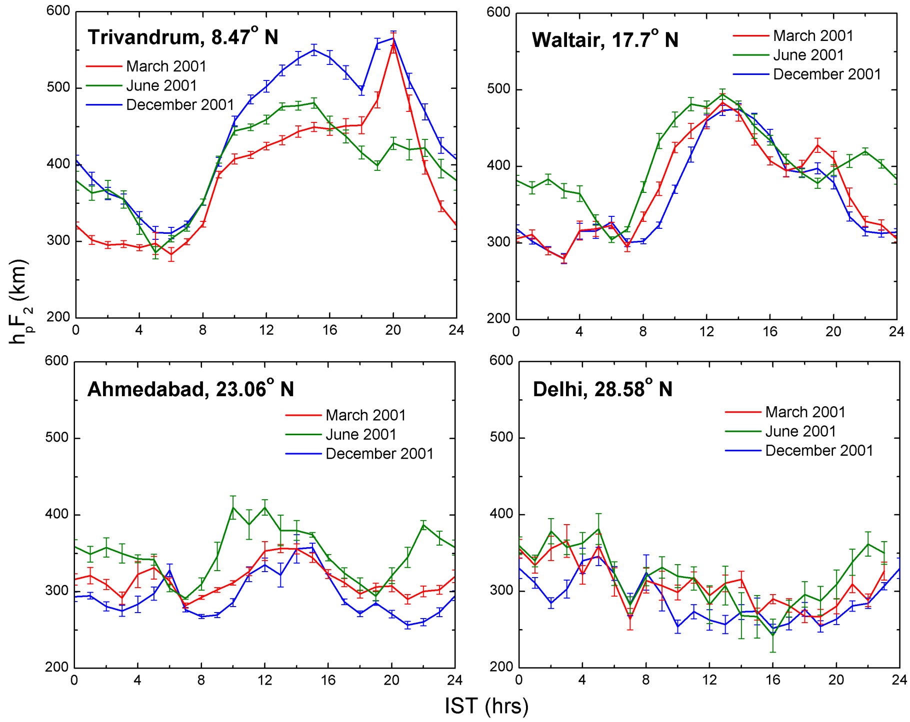


**Fig. 1.** The monthly mean diurnal variation of $h_pF_2$ of four Indian stations Trivandrum, Waltair, Ahmedabad and Delhi for the months of March, June and December 2001. The error bars indicate the standard deviation of the data for the month.

from four Indian stations (Trivandrum, Waltair, Ahmedabad and Delhi) for the year 2001 are considered, as detailed in Table 1. Along with this ionosonde data, the TEC data measured from the dual frequency GPS receivers deployed at different locations (18) in India are also used for examining the effect of the IPP altitude variation in the conversion of slant TEC to vertical TEC.

## 4 Results

### 4.1 Peak electron density altitude ($hpF_2$) variations in the Indian region

The altitude of the peak electron density of the F2-layer ($N_{\max}F_2$) is usually taken as nearly equal to $h_pF_2$ (altitude at 0.834 of $f_oF_2$). The mean diurnal variations of $h_pF_2$ for the months of March, June and December 2001, representing the three different seasons, namely equinox, summer and winter, respectively, from the four different Indian stations, Trivandrum (8.4° N, 76.9° E), Waltair (17.7° N, 83.3° E), Ahmedabad (23° N, 76.6° E) and Delhi (28.5° N, 77.2° E), where identical ionosondes (KEL, Australia) are simultaneously in operation, are presented in Fig. 1. It may be seen from this figure, that the F-region peak altitude varies between 275 km at the day minimum to about 500 km during noon to post-noon hours at Trivandrum and Waltair, while the variation is much less in a day at Ahmedabad and Delhi during June 2001. During December 2001, while Waltair, Ahmedabad and Delhi show similar variation, the heights at Trivandrum show a higher variability, with daytime peak values as large as 575 km. This variability in altitude is expected because the equatorial electrojet is stronger in winter months compared to summer months and consequently, the F-region is elevated to higher altitudes at the equator due to increased $\boldsymbol{E}\times\boldsymbol{B}$ drift. Similarly, during March 2001 at Trivandrum, the F-layer peak altitude variability is higher, but one of the interesting features to be noticed here is that there is a significant post-sunset upward movement of the F-layer at the equator (Trivandrum) and at the sub-tropical latitude (Waltair). At Ahmedabad and Delhi the mean altitude of the F-region varies marginally (from 300 to 350 km), while at the equatorial station, Trivandrum and the sub-tropical station, Waltair it shows a large variability.

In Figs. 2a, b and c, the surface maps are presented of the variation of the monthly mean diurnal variation of the altitude of the peak electron density, as a function of latitude and local time, for the three different seasons, namely equinox, summer and winter, for the high solar activity year of 2001, using the data listed in Table 1. It may be readily seen from these figures that the altitude ($h_pF_2$) is maximum around the equatorial region in all three different seasons, with diurnal peaks occurring around the pre-sunset hours during the equinox and winter months, and around the post-noon hours during summer. Further, it may also be noticed that

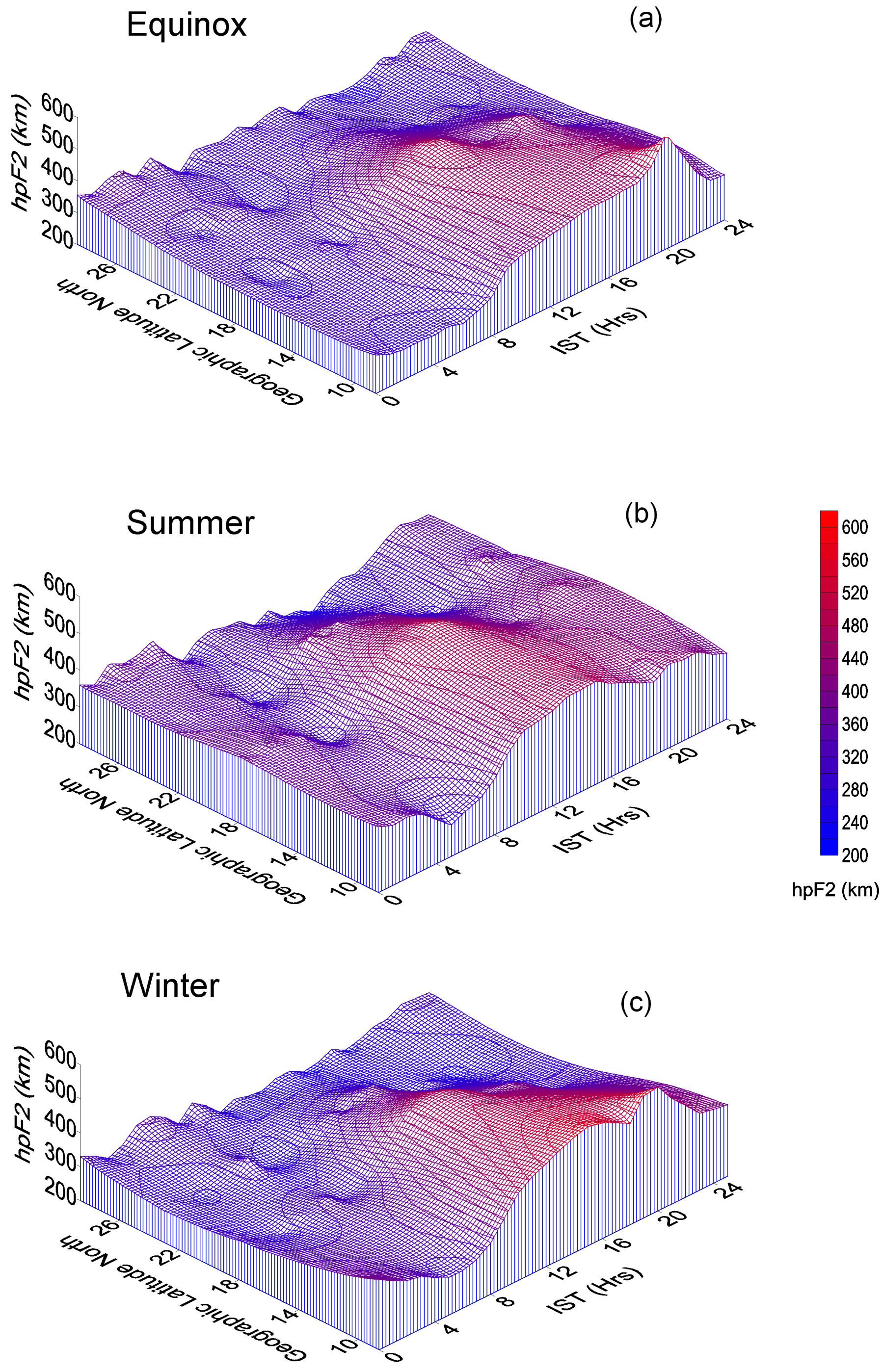


**Fig. 2. (a, b** and **c)** showing the surface maps of the monthly mean diurnal variation of the altitude of the peak electron density ($h_pF_2$) as a function of local time and latitude for the three different seasons (year 2001) in the Indian sector.

the peak electron density altitude ($h_pF_2$) decreases significantly with the increase of the latitude in the Indian sector. The surface plots also reveal a higher diurnal variability of the F-layer peak electron density altitude up to the latitude of about 22° N from the equator and for higher latitudes beyond 22° N, this altitude variation is marginal and is not very significant. On the other hand, at mid-latitudes, the diurnal and seasonal variations, as well as the latitudinal variations in the peak electron density altitude, are not significant compared to those at the equatorial and low-latitude sectors. Hence,

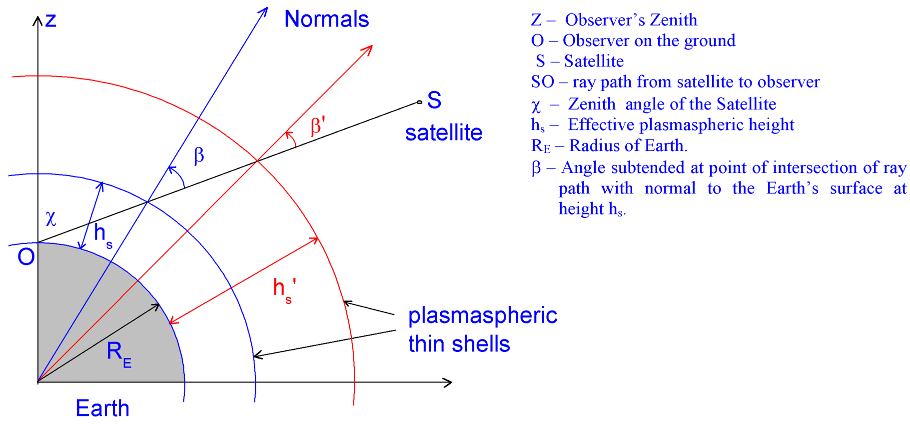


**Fig. 3.** The schematic diagram showing the geometry of the configuration in the conversion of oblique to zenithal TEC from two different IPP altitude,s $h_s$ and $h_{s'}$.

the use of the IPP altitude of 350 km in the conversion of slant to vertical TEC in the mid-latitude sectors may not introduce any significant differences in the computed range delays and errors. In view of the high variability of the altitude of the peak electron density in the Indian equatorial and low-latitude regions, an attempt is made to examine the validity of using the IPP altitude of 350 km and to identify any other suitable altitude(s) that need to be used in the Indian sector. It may be mentioned here that Birch et al. (2002), using an inverse technique (described in Sect. 4.2), with the data of the European sector, have arrived at IPP altitudes ranging from 600 to 1200 km, with an average effective altitude of 750 km.

### 4.2 Computation of IPP altitude using inverse technique

To illustrate the change in the obliquity factor that is used in the conversion of slant TEC to vertical TEC, due to changes in the assumed altitude of IPP, the geometry of the ray path from satellite to ground through the ionospheric pierce point is schematically represented in Fig. 3. In this figure it may be seen that the angle "$\beta$" subtended at the point of intersection of the ray path, with the normal to the Earth's surface at altitude $h_s$, changes to $\beta$' at altitude $h_s$' and thus gives rise to two different values of TEC for the two different IPP altitudes ($h_s$ and $h_s'$) while converting from slant to vertical TEC or vice versa. The description of the different parameters relevant to the geometry are provided along with the figure. Here, the angle $\beta$ is related to the zenith angle ($\chi$) at the ground by the relation (Birch et al., 2002)

$$\sin\beta = \frac{\sin\chi}{[1 + h_s/R_E]}\,, \tag{1}$$

where $R_E$ is the radius of the Earth.

The approach is to determine the effective height by comparing the TEC from a pair of satellites observed simultaneously along slant and zenithal paths. Thus, we have identified a total of 26 pairs of satellites observed simultaneously along the slant and zenithal paths from Waltair during April 2004 and determined the correlation between slant and the vertical TEC and evaluated the plasmaspheric effective height from the gradient "m" ($\sec\beta$) by the inversion technique, as described by Birch et al. (2002).

Assuming the ionosphere and protonosphere to be spatially uniform, and if $Bs$ and $Bz$ are the slant and zenithal satellite biases including a receiver bias (i.e. $Bz$ is the receiver bias + zenith satellite bias, and $Bs$ is the receiver bias + slant satellite bias), the measured slant and zenith TEC $R_s$ and $R_z$, respectively, are given by

$$R_z = I + Bz \tag{2}$$

$$R_s = I\sec\beta + Bs\,, \tag{3}$$

where $I$ is the true vertical TEC. From the above two equations

$$R_s = R_z\sec\beta + (Bs - -Bz\sec\beta). \tag{4}$$

Thus, the slant TEC ($R_s$) and the vertical TEC ($R_z$) from the two satellites (slant and zenithal) are linear with a gradient (slope) m=sec$\beta$, while the bias terms $Bs$ and $Bz$ are constants. And from Eq. (1), we have

$$h_s = R_E\left(\frac{m}{\sqrt{m^2-1}}\sin\chi - 1\right) \tag{5}$$

which gives the value of IPP height ($h_s$), if the zenith angle ($\chi$) at the ground is known.

The TEC measurements recorded from satellite passes whose elevation angles are greater than 85° are considered as zenith TEC measurements, and the simultaneously recorded TEC from the off-zenith satellite passes (<85°) are taken as the slant TEC measurements. From the data of slant TEC and zenithal TEC of the pairs of satellites chosen, a linear plot is drawn between the slant TEC and vertical TEC, to verify the linearity as in Eq. (4). The best estimate of their

**Table 2.** PP Height estimates from slant/zenithal TEC values.

| Zenith PRN no. | Slant PRN no. | Time IST | Mean Elevation | No of Points taken | Corr Coeff. | $m$ | $\Delta m$ | $m$, if $hs$=350 km | $hs$ (km) calculated |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 3 | 5.87 | 45.31 | 18 | 0.93 | 1.394 | 0.139 | 1.34161 | 60.06 |
| 1 | 13 | 0.89 | 49.65 | 17 | 0.88 | 1.292 | 0.126 | 1.2666 | 143.49 |
| 1 | 20 | 1.03 | 27.74 | 14 | 0.697 | 1.145 | 0.239 | 1.8376 | 5205.90 |
| 1 | 27 | 1.16 | 23.217 | 15 | 0.962 | 1.233 | 0.096 | 2.0366 | 3637.58 |
| 1 | 31 | 1.03 | 58.875 | 15 | 0.912 | 1.141 | 0.127 | 1.1471 | 467.92 |
| 4 | 7 | 7.34 | 42.568 | 16 | 0.985 | 1.419 | 0.0685 | 1.3966 | 242.37 |
| 4 | 8 | 7.34 | 24.876 | 15 | 0.934 | 2.213 | 0.203 | 1.9595 | 108.12 |
| 4 | 24 | 7.26 | 47.498 | 13 | 0.830 | 1.196 | 0.221 | 1.302 | 1475.83 |
| 4 | 28 | 7.12 | 50.505 | 15 | 0.991 | 1.367 | 0.044 | 1.2534 | –427.96 |
| 6 | 17 | 13.87 | 26.740 | 14 | 0.780 | 1.710 | 0.395 | 1.8786 | 643.05 |
| 6 | 18 | 13.86 | 43.158 | 16 | 0.959 | 1.279 | 0.104 | 1.3842 | 1083.37 |
| 6 | 21 | 13.83 | 30.388 | 17 | 0.2593 | 1.214 | 0.272 | 1.7371 | 3390.27 |
| 6 | 22 | 13.86 | 15.61 | 18 | 0.694 | 1.840 | 0.350 | 2.4506 | 938.79 |
| 6 | 26 | 13.84 | 53.679 | 21 | 0.898 | 1.258 | 0.177 | 1.2084 | –151.37 |
| 6 | 29 | 13.94 | 39.616 | 16 | 0.787 | 1.5286 | 0.361 | 1.4636 | 117.99 |
| 6 | 30 | 13.86 | 21.682 | 19 | 0.6719 | 1.3744 | 0.237 | 2.1124 | 2258.94 |
| 10 | 17 | 10.65 | 50.873 | 16 | 0.919 | 1.2 | 0.1376 | 1.2478 | 902.11 |
| 10 | 24 | 10.67 | 37.11 | 16 | 0.893 | 1.4819 | 0.1994 | 1.5275 | 513.54 |
| 10 | 29 | 10.66 | 19.250 | 17 | 0.722 | 2.1395 | 0.1889 | 2.2410 | 432.70 |
| 10 | 30 | 10.67 | 28.088 | 16 | 0.8673 | 1.3778 | 0.211 | 1.8238 | 1799.61 |
| 15 | 3 | 17.94 | 16.498 | 12 | 0.7842 | 1.411 | 0.353 | 2.3979 | 2287.77 |
| 15 | 14 | 18.1 | 51.83 | 11 | 0.894 | 1.667 | 0.203 | 1.2338 | –1449.98 |
| 15 | 18 | 17.93 | 35.231 | 15 | 0.8998 | 1.980 | 0.2663 | 1.5802 | –341.45 |
| 15 | 21 | 17.94 | 37.9 | 13 | 0.805 | 1.155 | 0.2345 | 1.5066 | 3675.69 |
| 15 | 22 | 18.04 | 47.013 | 15 | 0.8627 | 1.788 | 0.290 | 1.3105 | –1130.85 |
| 15 | 25 | 18.17 | 36.05 | 14 | 0.772 | 1.797 | 0.189 | 1.5567 | –171.41 |

linear gradient (slope m = sec $\beta$) is derived using the standard regression analysis method. For each of the zenithal satellite passes all the simultaneously available slant satellite passes are considered, to derive the gradient (m) values during a month, taking only one point in each of the satellite pairs in the regression analysis. In Table 2 are the results obtained from the data sets chosen, which include correlation coefficients between vTEC (from zenithal pass) and the sTEC (from the slant pass), gradients (m) derived by linear regression, mean elevation angle of the slant pass, the effective IPP height ($h_s$) computed using Eq. (5), the mean time of the pass and the expected value of the gradient "m" for the IPP height of 350 km for comparison. From Table 2 it may be noticed that the correlation between the slant and the vertical TEC is fairly significant in most of the cases, as may be seen from some of the typical plots presented in Fig. 4. However, it may be noted that the gradient "m" (sec$\beta$) is highly variable and lies between 1.141 and 2.667, indicating the effect of the large latitudinal electron density gradients in the Indian region. The values of "m", theoretically computed for an altitude of 350 km for different elevation angles of the satellite passes, are also shown in Table 2 for comparison, along with the values of the gradients derived from the present analysis. The height estimates derived from these gradients are highly variable and in some cases, they are negative, which is unrealistic.

In Fig. 5, the variation of the gradient m is shown as a function of elevation angle of the satellite (Birch et al., 2002).

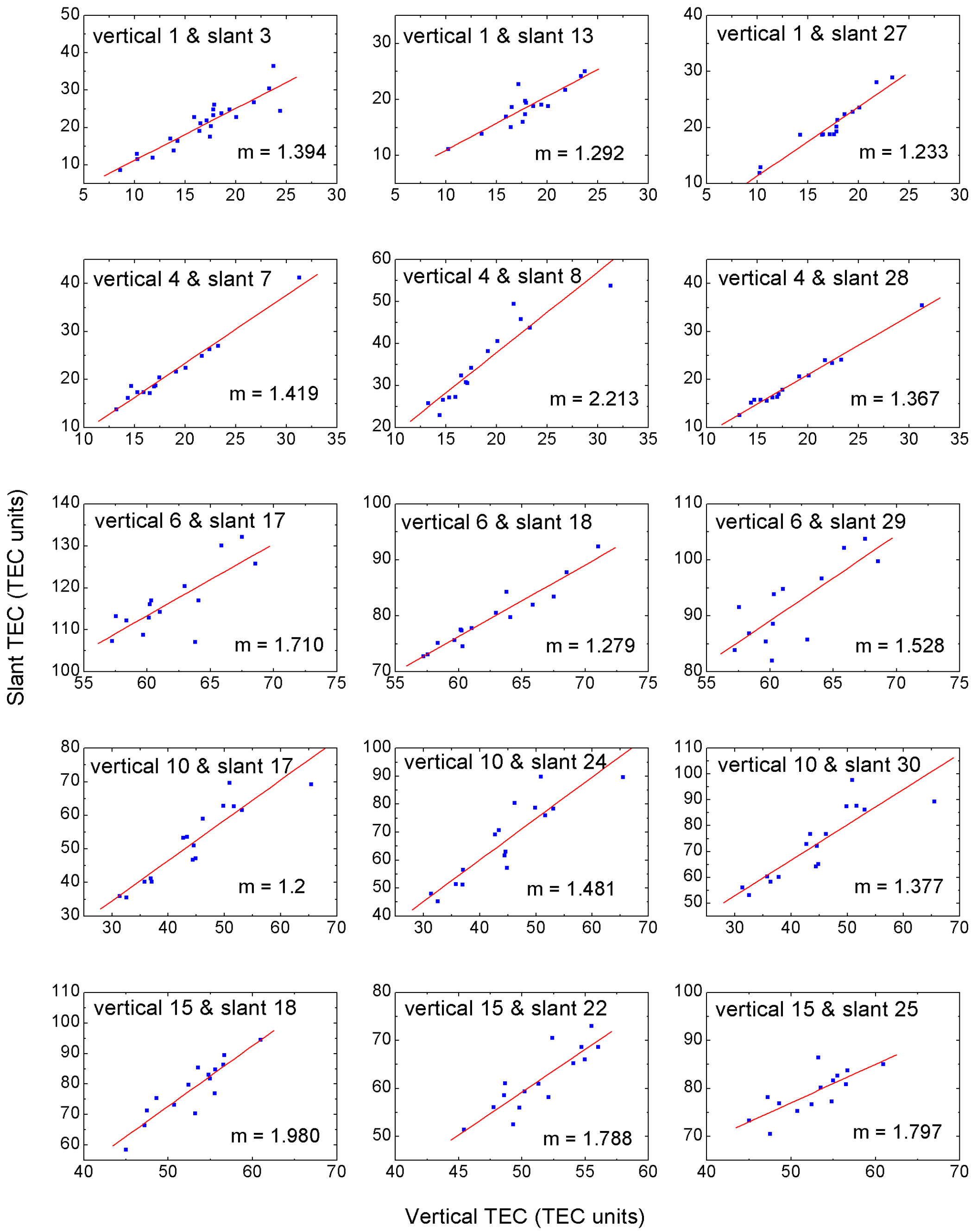


**Fig. 4.** Examples showing the gradients ($m$) of slant TEC versus zenithal TEC derived from simultaneously observed satellite pairs of data chosen.

Each of the solid curves in this figure represent the theoretically expected variation of slope (m) for different altitudes ranging from 300 to 1200 km (in steps of 100 km). If all the experimentally computed gradients align on any one of these curves, the altitude corresponding to that particular curve is taken as the IPP altitude. However, it may be seen that the gradients evaluated from the experimental data of TEC over Waltair show a considerable scatter (red color dots with error bars) and do not align on any single theoretical height curve, clearly indicating that the effective height of the IPP is highly variable from observation to observation, particularly for elevation angles lower than 50°, over the Indian region. Thus, the assumptions made in this inverse technique (Birch et al., 2002) for estimating the effective height of the ionosphere have limitations in the Indian region. The Indian ionosphere covers the equatorial and low latitudes beyond the northern

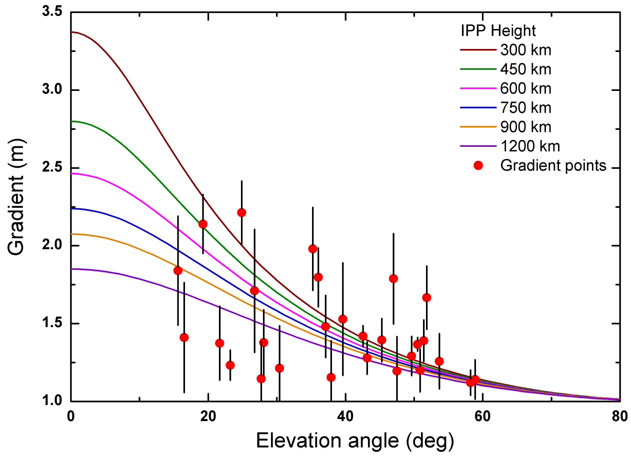


**Fig. 5.** Variation of the computed gradients ($m$) obtained with different elevation angles mapped onto the theoretically expected gradients for the different heights chosen.

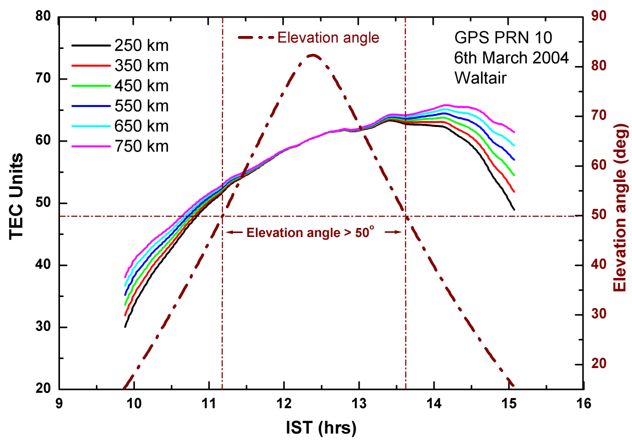


**Fig. 6.** Variation of vertical TEC for different IPP altitudes and the corresponding elevation angle of the satellite. The elevation angle of the satellite is given on the right-hand side of the y-axis.

crest of the equatorial ionization anomaly, where the spatial and temporal variation of TEC are significant, limiting the assumption that the TEC is horizontally homogenous. Also, the visibility of the satellites at zenith angles is good at locations with geographic latitudes situated around 55° over the globe, since the inclination of the GPS orbits is also 55°. Whereas in the Indian equatorial and low-latitude sector the zenithal satellite passes are much less. Thus, in this region the thin shell model which is strongly based on the assumptions of spatial uniformity of the ionosphere, may not hold true owing to the limitations imposed by the electron density gradients.

Therefore, at equatorial and sub-tropical latitudes any single weighted mean average height cannot be considered representative for a particular station, and the effective height depends on the time and location of observation and the vertical ionization distribution at that location. However, if the modulation of ionization density by the equatorial plasma transport over a location and its altitude structure can be parameterized, depending on the conditions prevailing on any given day, the effective height can probably be determined, based on the skewness of the F-region electron density profile and the centroid of its vertical ionization distribution, the study of which needs to be attempted with a larger data base comprising of multiple ionospheric parameters.

### 4.3 IPP altitude and the satellite elevation angle

Using the measured GPS-TEC data, an alternate attempt is made to assess the effect of the choice of the IPP altitude in the conversion of the slant to vertical TEC in the Indian sector for different altitudes varying from 250 to 750 km (in steps of 100 km). Theoretically, from Eq. (3) the vertical TEC is given by the product of slant TEC and cos$\beta$. If a plot of cos$\beta$ is made as a function of satellite elevation angle for different IPP heights, which essentially indicates the vertical TEC spread as a function of elevation angle for a given slant TEC value, a threshold for the elevation angle could be defined. Keeping this condition in mind, the vTEC converted from the measured sTEC for some typical GPS satellite passes recorded over a few locations in India are presented in Figs. 6 and 7, for the different altitudes considered above.

It may be seen from Fig. 6 that the TEC did not show much of a variation with a change in the IPP altitude for satellite elevation angles greater than about 50°. However, for elevation angles less than 50°, the TEC computed with different IPP altitudes shows a significant deviation. Further, it is noted that this dispersion in TEC is higher (≈15 TEC units) at 15:00 LT, where the ambient diurnal value is higher than that at 10 hrs LT (≈8 TEC units) during which the TEC is in the building-up process. Similar examples from four other different stations for different GPS satellite passes with different PRN numbers are presented in Fig. 7. It may also be seen from these figures that the commonly used IPP altitude of 350 km seems to be valid even in the Indian sector with satellite elevation angles greater than about 50°. The use of any of the above IPP altitudes (250 to 750 km) for satellites with elevation angles lower than about 50° is likely to give rise to varying range delays. Thus, the results obtained from the present study agree with results reported from similar studies by Birch et al. (2002), particularly with reference to the effect of the elevation angles of the satellite passes. However, it may be emphasized here that these conversions are based on the assumption that the ionosphere is a uniform thin shell, which may not be equally valid for all the Indian latitudes.

## 5 Summary

The Indian ionospheric region encompasses the range of latitudes from the equator to anomaly crest and beyond, where

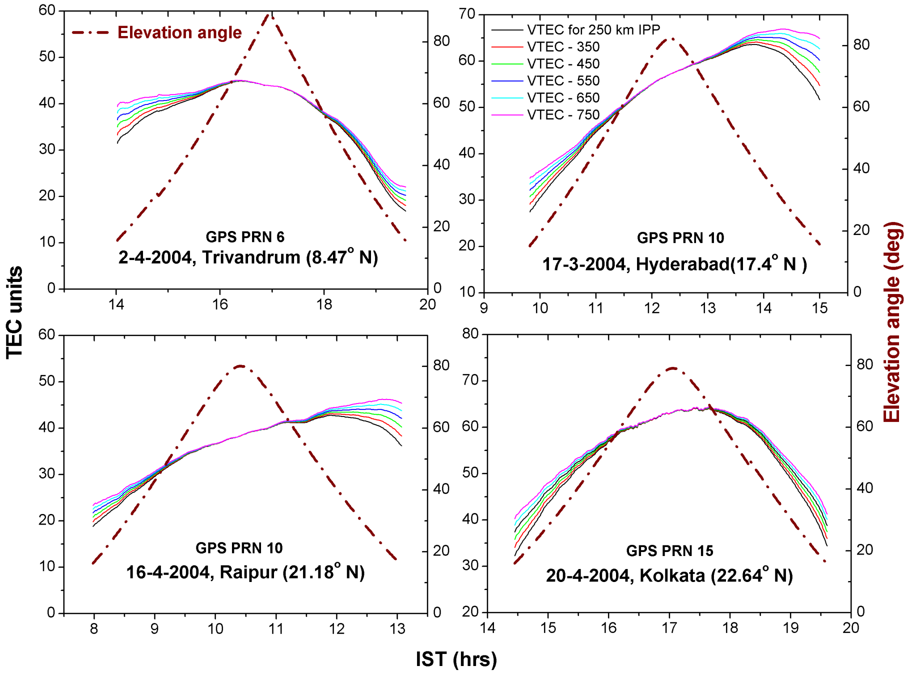


**Fig. 7.** Variation of vertical TEC for different IPP altitudes and the corresponding elevation angle of the satellite from four different Indian stations. The elevation angle of the satellite is given on the right-hand side of the y-axis.

the F-layer of the ionosphere varies both in altitude as well in space and time. The altitude of the peak electron density ($h_pF_2$) measured from the data of four identical ionosondes located at different parts of India, Trivandrum, Waltair, Ahmedabad and Delhi has revealed that the $h_pF_2$ varies significantly from day to day and from day to night, and also from equator to the anomaly crest and beyond. At the equator, the variation of $h_pF_2$ is found to be maximum with 275 km in the night to 575 km during the day, whereas at Ahmedabad and Delhi this variation is found to be marginal (300 to 350 km). Hence, whether the use of a constant value of the IPP altitude of 350 km, commonly used in the mid latitude sector, is valid or not for the Indian sector is the topic under investigation. The attempts made in this regard to arrive at any suitable value of IPP using the inverse technique suggested by Birch et al. (2002) did not yield any consistent value of the IPP altitude. The alternate attempt made using the experimentally measured GPS slant TEC in the Indian sector, to compute the vertical TEC for different discrete IPP altitudes ranging from 250 to 750 km (in steps of 100 km) clearly suggest that the elevation angle of the satellite pass plays an important role. For elevation angles greater than 50°, the IPP altitude of 350 km may also be effectively used in the Indian sector. However, in the case of satellite passes with elevation angles lower than about 50°, the computed vertical TEC deviates significantly with a change in IPP altitude. Therefore, it is inferred that the commonly used IPP altitude of 350 km is valid and can also be used in the Indian sector but for elevation angles of the satellite passes greater than about 50°.

Further, in the cases of low elevation angle passes (Fig. 5) the non-alignment of the computed gradients (m or sec $\beta$) on any single theoretical height curve, as well as the dispersion observed in TEC (Figs. 6 and 7), indicates that the effective height is highly variable from observation to observation, pointing out that at equatorial and sub-tropical latitudes any single weighted mean average height cannot be considered to be representative for all elevation angles of the satellites viewed from a station and that the effective height depends on the time of day, the location of observation and the vertical ionization distribution at that location.

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