AGU PUBLICATIONS

Radio Science

RESEARCH ARTICLE
10.1002/2014RS005372

Key Points:
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- Applicable for regions with spatial gradients
- Useful for single-station measurements

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Citation:
Thampi, S. V., M. S. Bagiya, D. Chakrabarty, Y. B. Acharya, and M. Yamamoto (2014), An ensemble average method to estimate absolute TEC using radio beacon-based differential phase measurements: Applicability to regions of large latitudinal gradients in plasma density, *Radio Sci.*, *49*, 1153–1161, doi:10.1002/2014RS005372.

Received 8 JAN 2014
Accepted 5 OCT 2014
Accepted article online 8 OCT 2014
Published online 3 DEC 2014

An ensemble average method to estimate absolute TEC using radio beacon-based differential phase measurements: Applicability to regions of large latitudinal gradients in plasma density

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Abstract A GNU Radio Beacon Receiver (GRBR) system for total electron content (TEC) measurements using 150 and 400 MHz transmissions from Low-Earth Orbiting Satellites (LEOS) is fabricated in house and made operational at Ahmedabad (23.04°N, 72.54°E geographic, dip latitude 17°N) since May 2013. This system receives the 150 and 400 MHz transmissions from high-inclination LEOS. The first few days of observations are presented in this work to bring out the efficacy of an ensemble average method to convert the relative TECs to absolute TECs. This method is a modified version of the differential Doppler-based method proposed by de Mendonca (1962) and suitable even for ionospheric regions with large spatial gradients. Comparison of TECs derived from a collocated GPS receiver shows that the absolute TECs estimated by this method are reliable estimates over regions with large spatial gradient. This method is useful even when only one receiving station is available. The differences between these observations are discussed to bring out the importance of the spatial differences between the ionospheric pierce points of these satellites. A few examples of the latitudinal variation of TEC during different local times using GRBR measurements are also presented, which demonstrates the potential of radio beacon measurements in capturing the large-scale plasma transport processes in the low-latitude ionosphere.

1. Introduction

The successful launch of the first artificial satellite Sputnik I provided the first useful data of the electron content of the ionosphere and its spatial structure. Since then, there were many LEOS, mostly in polar orbits, which could give information on the spatial variability of the ionosphere using onboard instruments like Langmuir probes for in situ measurements and radio beacons for remote sensing and navigation. The satellite beacon contributions to the studies of the structure of the ionosphere using ground-based observations from different regions have been reviewed by *Davies* [1980].

Over the Indian region radio beacon studies of the latitudinal distribution of the ionospheric total electron content (TEC) were initiated in the early 1960s with the recording of 20, 40, and 41 MHz signals from the orbiting explorer (BE-B and BE-C) satellites. *Rastogi and Sharma* [1971] described the results of TEC measurements over Ahmedabad. They also compared the TEC data with the *F* peak density (N_{max}) obtained from ionosonde data. Further, the latitudinal variations of TEC were obtained by combining the data from satellite passes recorded over Kodaikanal and Ahmedabad to investigate the strength of the equatorial ionization anomaly (EIA) as well as its day-to-day variability [*Rastogi et al.*, 1973, 1975]. Apart from this, there had been several studies using radio beacons onboard ATS-6, which is a geostationary satellite and thus basically gives the temporal variation of TEC, when observed from a particular ground station. Using such observations from several stations, the EIA characteristics were studied [*Deshpande et al.*, 1977; *Sethia et al.*, 1979, 1980]. Later, TEC observations using Transit beacons were done during the total solar eclipse event of 16 February 1980 from Rangapur in the totality zone, and Ahmedabad and Rajkot, away from totality zone. Decrease in TEC of about 20% over Rangapur was observed, whereas the decrease was only 8% over Ahmedabad and Rajkot [*Deshpande et al.*, 1982a, 1982b]. This was the only campaign when the 150 and 400 MHz signals from LEOS were recorded over Ahmedabad. With the emergence of tomography as a powerful tool [*Austen et al.*, 1988] to study the large-scale features of the terrestrial ionosphere, radio beacon observations received a renewed interest. There had been a few attempts to use the radio beacon observations to study the equatorial features and for the tomographic imaging of the low-latitude region [*Thampi et al*., 2007 and references therein; *Mridula et al*., 2011; *Siefring et al*., 2011]. However, observations of TEC variations using VHF/UHF beacon data from orbiting satellites had been rather limited from the EIA crest regions over Indian longitudes.

In this paper, we present the radio beacon observations from Ahmedabad (23.04°N, 72°E geographic) using a newly installed GNU Radio Beacon Receiver (GRBR). GNU is a Unix/Linux-like operating system, and GNU is a recursive acronym for "GNU is Not Unix." An ensemble average method to convert the observed relative slant TEC to absolute TEC is presented. Also, the GRBR- TEC values are compared with the TEC values derived from a collocated GPS receiver. The observed differences are discussed vis-à-vis the ionospheric gradients over the equatorial ionization anomaly region and the differences in the ionospheric pierce points of the two observations. Finally, the GRBR-TEC observations are used to generate the latitudinal structure of EIA, during different local times, showcasing the potential of radio beacons onboard high-inclination satellites.

2. Data

The GNU Radio Beacon Receiver (GRBR) was first developed by *Yamamoto* [2008] using the open-source hardware called Universal Software Radio Peripheral along with the open-source software toolkit for the software-defined radio. A GRBR system is fabricated in house and installed at the Physical Research Laboratory, Ahmedabad (23.04°N, 72.54°E geographic, dip latitude 17°N), and is operational since May 2013. The GRBR receives the 150 and 400 MHz transmissions from the polar-orbiting satellites—COSMOS satellites (COSMOS 2407, COSMOS 2414, COSMOS 2454, and COSMOS 2463) and DMSP F15. Both these frequencies are derived from a common reference frequency, *fr* = 50 MHz.

For these frequencies in the VHF/UHF range, the bending and other higher-order effects can be ignored, and hence, the TEC along the straight line between the transmitter and the receiver is directly proportional to the phase change experienced by the signal, as a result of the changing index of refraction of the ionosphere. The TEC data from LEOS are obtained using the differential phase (often termed as differential Doppler) measurements between two coherent frequencies. The phase difference between 150 and 400 MHz is given by

$$\Delta\phi = \frac{\pi A}{f_r c}\left[\frac{1}{q^2} - \frac{1}{p^2}\right]\int N ds \tag{1}$$

where $A = \frac{e^2}{4\pi^2 m\varepsilon_o}$, $p = 8$, $q = 3$, and $\Delta\Phi$ is in cycles [*Davies*, 1980].

A major challenge in obtaining absolute TEC measurements by differential phase measurements using VHF/UHF beacons is that there is always an unknown bias, resulting from the $2n\pi$ ambiguity that causes a TEC offset. Several approaches are generally used for the estimation of this unknown TEC offset, as discussed later in this paper. Once the absolute TEC is estimated, this technique can be used to study the latitudinal variation of TEC in the case of LEOS that are in the high-inclination polar orbits or the longitudinal variation of TEC in the case of LEOS that are in the low-inclination equatorial orbits (for example, the C/NOFS satellite).

The basic data of GRBR include the relative slant TECs and the signal intensities of both 150 and 400 MHz with a sampling rate of 8 Hz, which is finally averaged to obtain one TEC data point at every second. A typical pass observed by GRBR is shown in Figure 1. This is a pass of COSMOS 2454 satellite. It can be seen that we have ~ 14 min (~120 s to 975 s) of good data (Figure 1a). Once the receiver gets locked (these receivers basically record digitized I and Q signals), the small oscillations in the signal power do not affect the "phase-locked" condition at both these frequency levels, and hence, the TEC can be estimated. The small changes in the signal may correspond to a phase change of a few degrees, which will change the TEC only in decimal levels.

The differential phase between the 150 and 400 MHz signals, measured at the receiver, would be between 0 and 2π, and when we start counting the phase from zero and cumulate these phase values, it is possible to obtain continuous phase records. Hence, the relative TECs show a minimum value at the point of observation, where the line-of-sight distance is the minimum (Figure 1b). But there is a $2n\pi$ ambiguity (phase offset) involved in such measurements, i.e., the number of complete cycles elapsed remains unknown, which needs to be evaluated. The procedure used for the estimation of absolute TECs will be discussed in detail in

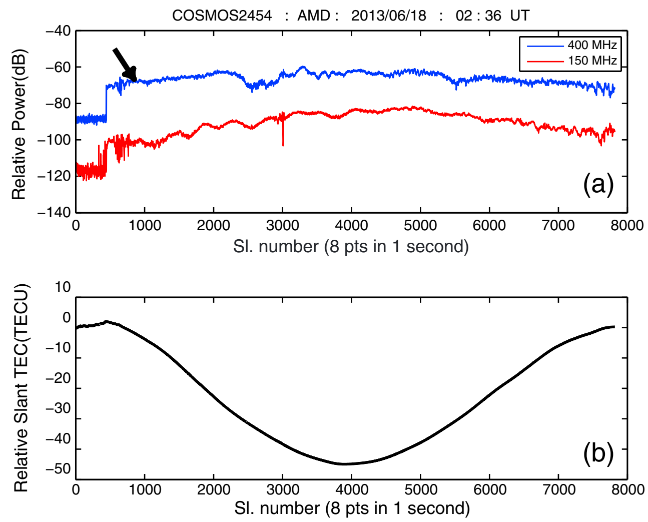

Figure 1. GRBR observations from Ahmedabad, using Cosmos 2454 satellite pass on 18 June 2013, at 02:36: UT. (a) The signal power at two frequencies and the (b) relative total electron content variation are shown. The numbers on the *x* axis correspond to the sequential observation number (which are 8 s^{-1}) so that the time in second from the start is obtained by dividing those numbers by 8. The small arrow indicates the time when the receiver gets locked to the signal.

section 3. The local time wherever it is mentioned corresponds to the actual local time corresponding to the longitude of the satellite pass and not the Indian Standard Time.

For comparison purpose, we have also used TEC measurements by a collocated GPS receiver. This is a dual-frequency GISTM GSV4004B receiver which gives simultaneous line-of-sight TEC data from several GPS satellites. The observed slant TEC values are then converted to vertical TEC values using an obliquity factor or mapping function, which is a function of the elevation angle of the satellite. The procedure to estimate the TEC is given in *Bagiya et al.* [2009]. For this study, an elevation mask of 30° is used to eliminate the multipath and troposphere scattering effects both of which are more prominent at lower elevation angles. Hence, at any instant four to five GPS satellites (identified with different pseudorandom noise (PRN) codes) are available which are at different ionospheric pierce point (IPP) locations and hence give different TEC values.

For the present analysis we have used the data for the period 14–21 June 2013. The *Ap* values (http://wdc.kugi.kyoto-u.ac.jp/cgi-bin/kp-cgi) were less than 5 for the period 14–19 June 2013, whereas the *Ap* values were 11 and 18 for 20 and 21 June 2013, respectively. The *Dst* values show that there was no major geomagnetic storm on these days. However, the *AL* indices reveal that moderate enhancements in the westward auroral electrojet current were present during 18, 20, and 21 June 2013 when hourly *AL* indices reached ~401 nT, −396 nT, and −501 nT, respectively (http://wdc.kugi.kyoto-u.ac.jp///dstae///wwwtmp/WWW_dstae00024229.dat). This indicates toward the possible presence of moderate auroral substorm activities on these days, and the other days can be considered as geomagnetic quiet days.

3. Methods of Absolute TEC Estimation

The estimate of the unknown phase offset is the most crucial element in obtaining the latitudinal/longitudinal variation of TEC from radio beacons onboard polar-/equatorial-orbiting satellites. In most of the early beacon studies wherever differential Doppler is used, Faraday rotation and/or group delay measurements were available, so these were used to limit the $2n\pi$ ambiguity [e.g., *Deshpande et al.*, 1982a]. When only the phase measurements are available, a popular method used to limit the phase ambiguity is the "two-station method" [*Leitinger et al.*, 1975]. When two closely spaced receivers track the same satellite, it is possible that there will be a region of overlap. For two stations, aligned in longitude/latitude (in the case of equatorial/polar orbits) monitoring the same satellite pass, it is assumed that the vertical TEC from each is the same at a common latitude, which is observed simultaneously by both the receiving stations. Measurements corresponding to a small-latitude region give a finite number of equations, from which the two constants (corresponding to the phase offsets at two stations) are estimated using a least squares method. This method of finding the phase offsets has been extended for use with more than two stations [*Kersley et al.*, 1993]. However, we need at least two nearby stations to use this method. For data from a single station, a simple method to compute the absolute TECs is reported by *Ciraolo and Spalla* [1997]. This assumes a quasi-linear dependence of vertical TEC on latitude, and hence, the first differences are almost constant. In other words, this method makes use of the linearity between the differences Δ(relative vertical TEC) and $\Delta \cos\chi$, where χ is the zenith angle, and using a linear fit between these two, the unknown phase offset is

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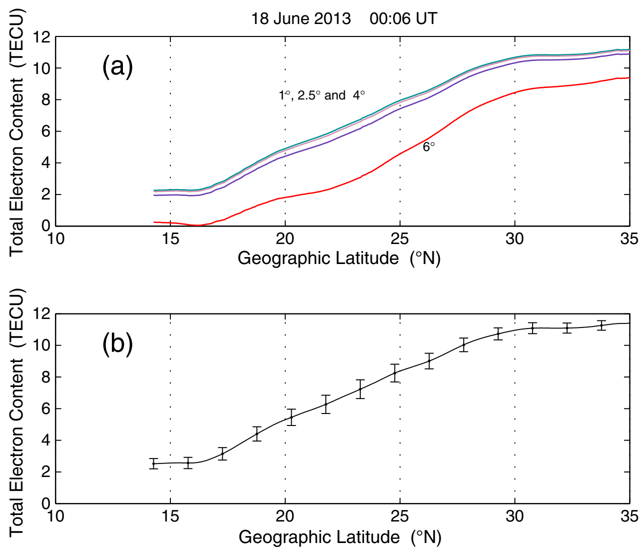

Figure 2. (a) Example of the iterative approach to determine the absolute TEC. The regions chosen for quasi-linearity approximation are shown. (b) Latitude variation of mean TEC, along with the standard deviations.

obtained as the slope. However, the quasi-linear dependence of vertical TEC on latitude will be true only for a small region for ionospheric conditions with large gradients.

For equatorial-orbiting satellites, which give the longitudinal variation of TEC, *Tulasi Ram et al.* [2012] have reported a method based on the assumption that the TEC varies linearly with horizontal distance. This is true for a longitude span of ±4–5°, in the case of low-inclination satellite passes, such as C/NOFS, where the TEC variation as function of satellite position is the longitudinal variation primarily due to local time or solar zenith angle variation. In this method, the unknown phase offset is determined by a weighted least squares fitting with bisquare weighting, where data points with high-elevation angle are given more weight and outliers far from the fitted line are given less weight. However, they mentioned that this method may not be suitable to derive the absolute TEC from polar-orbiting (or high-inclination) satellites, particularly for low-latitude stations, due to large gradients associated with the presence of the EIA [*Tulasi Ram et al.*, 2012].

For polar-orbiting satellites, *de Mendonça* [1962] reported another method of finding the unknown phase offset using data from single station. This also assumes a quasi-linear variation of absolute TEC with latitude but uses a differential approach to solve the equations [*de Mendonça*, 1962]. It is assumed that if the unknown phase offset is properly estimated, the resultant absolute TEC variation would be linear for some interval of time. In other words, this method utilizes the observations near the maximum elevation region, for example, ±3° around the maximum elevation, and assumes that the TEC variation in this particular region is linear with time (= latitude). Now different offsets are continuously applied so that the distribution becomes "flat,"

$$\text{i.e.,}\quad \frac{d^2(\text{TEC})}{\mathrm{d}x^2} = 0,$$

where TEC is the absolute vertical value and x is the IPP latitude. Satisfying this condition ensures that we do not have a local maxima or local minima within the region considered. The major shortcoming of this method is that the region of linearity is chosen quite arbitrarily in this method, and this method cannot intrinsically identify a region where this assumption is truly valid. As in the case of the method by *Ciraolo and Spalla* [1997], this may cause serious errors over the EIA region. To circumvent this problem, we modified the procedure by *de Mendonça* [1962] into an iterative algorithm.

In this approach, the region of quasi-linearity which is considered for the calculation is varied in steps (of ±0.5°), and the absolute TECs are estimated in each case. In other words, first, we consider a region of ±0.5° around the point of maximum elevation (~ 100 data points) and estimate the unknown TEC offset. Now the region is expanded in a step of 0.5°, and the unknown TEC offset is again estimated. If the assumption of the "region of linearity" is still valid, this would give an estimate which is very close to the previous estimate. This procedure is repeated several times, in steps of ±0.5°, until the estimation deviates quite significantly (can be from 20% to more than 50%) from the previous estimates. It must be mentioned here that the latitude region of linearity also will vary, for instance, it can be 4–5°, when the ionosphere is flat, and it would be even $<3°$, if the region considered is in the vicinity of gradients. These are evident from the examples shown in Figures 2 and 3. The unknown TEC offset ($2n\pi$ ambiguity) is then determined as the average of the ensemble of all the closely spaced values, and the standard deviation is considered as a "range of deviation." Hence, the final estimate of the latitudinal variation of absolute TEC is given as a "mean TEC" and a "standard deviation," which defines the

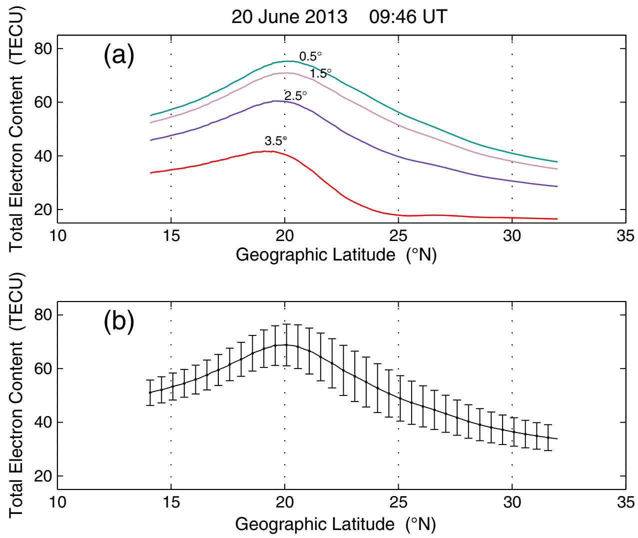

Figure 3. Same as Figure 2 but for a case when EIA is well developed.

range of "possible" TEC values. This iterative procedure (each calculation is repeated till the offset deviation increases beyond a certain value) automatically takes care of the variability of the gradients that could be present in the ionosphere.

Figure 2 shows an example of the situation when the ionosphere is flat, i.e., before the development of EIA over the region. This is a pass at 00:06 UT (05:14 LT). We start the iteration with considering the quasi-linear variation of TEC for a region spanning ±0.5° around the location of observation and obtain the first estimate of the TEC offset using the differential method. After this estimation, this TEC offset is added to the relative slant TEC values and then converted to absolute vertical TEC by multiplying with the geometry factor. The resultant first estimate of vertical TEC with IPP latitude is shown as the green curve in Figure 2a. Now the process is repeated by incrementing the latitudinal span by 0.5°. It can be seen that the TEC estimates are quite close to each other up to ±4°, i.e., the eighth iteration (Figure 2a). This is the point where we stop the iteration. The final TEC variation is the average of all these estimates, and the standard deviation gives the "error bar," which defines the range of possible TEC variation. This standard deviation is determined by the range of the latitude span used in the calculation. It may be noted that in Figure 2a, only three iterations are shown for clarity. Figure 2a also shows another case with the step size of ±6°; the TEC estimate deviates from all the other values by ~ 3 total electron content unit (TECU, 1 TECU = 10^{16} el m^{-2}) (~30% deviation from the previous maximum). Figure 2b shows the latitude variation of absolute TECs. In this case, we have not encountered a very large latitudinal gradient, so the ionospheric variability is truly quasi-linear over a significant region. This is reflected in the smaller standard deviations (~ 0.3 to 0.5 TECU, i.e., ~5%). This is not the case when the EIA is developed over the region. It may be noted that the method presented here is taking the ensemble average of a set of solutions, but the error bar of the TEC may be a misnomer as it is derived from the sample variance of point estimates with different latitude spans. This does not really reflect the actual covariance structure of the unknown parameters. However, standard deviation is still a valid term within this framework. The purpose of showing the mean and standard deviation (as error bar) is to give an idea about how much TEC can vary, when we consider different latitude scales.

Figure 3 shows an example when the EIA is well developed. This is a pass at 9:46 UT (14:46 LT). Here also, we start the iteration by considering the quasi-linear variation of TEC for a region spanning ±0.5° around the location of observation and obtain the first estimate of the phase offset. In the next iterations with ±1°, 1.5°, and ±2°, we get the estimates which are very close to the first estimate. When the latitudinal span is increased to ±2.5° (fifth iteration), the TEC just begins to deviate a little more (Figure 3a). This is where we stop the iteration. It may be noted that in Figure 3a, also, only three iterations are shown for clarity of presentation. When we use a latitudinal span of ±3.5° around the location, the TEC values deviate considerably, and the structure itself gets distorted (Figure 3a). Figure 3b shows the latitude variation of absolute vertical TECs thus obtained by averaging the values of the five iterations (±0.5° to ±2.5°). The maximum standard deviation is around the crest region (±9 TECU, i.e., ~ 12%), and it decreases toward the trough region and the region beyond the EIA crest (~ ± 4.5 TECU, i.e., ~9%).

In this case, the ionospheric region is replete with a well-developed EIA, and hence, there is a significant latitudinal gradient. The maximum TEC (crest of the EIA) is at 20°N latitude, just 3° away (toward the south) from the GRBR location. Hence, the assumption of the quasi-linear variation of TEC naturally breaks down near this, and that is the reason the iteration deviates from the previous estimates. These examples clearly show that we cannot arbitrarily fix the region of quasi-linear variation of TEC with latitude to one particular

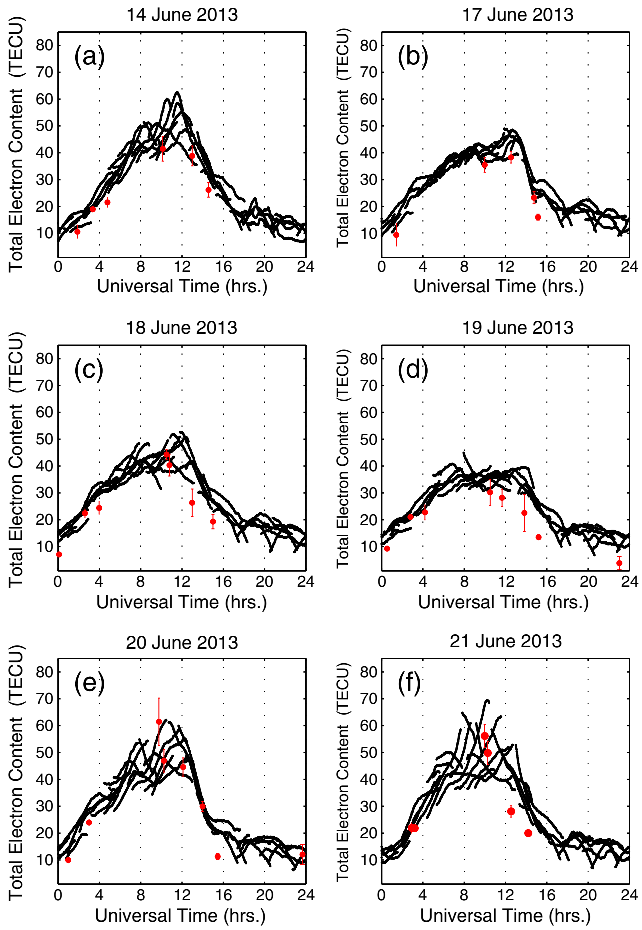

Figure 4. The GRBR-TEC values over Ahmedabad, along with the temporal variation of TEC derived from a collocated GPS receiver.

value for all local times and receiver locations, for the estimation of the unknown phase offset. It may also be noted that the convergence of TEC values (within few TECU) also varies from case to case. For example, when the ionosphere does not have any significant latitudinal gradient, the deviation is also very small (0.6 TECU; see Figure 2b), whereas for the case with fully developed EIA, the deviation is larger even within the two adjacent iterations (Figure 3a). Hence, while choosing the convergence of iteration, we cannot fix arbitrarily any TEC value. The data are analyzed case by case. The maximum deviation we have encountered is 9 TECU, within 2.5°, which is shown in Figure 3. On most of the other occasions, when the EIA is prominent, we could use five to six iterations (2.5° to 3°) and the deviations in TECs are 4–6 TECU (within 10%). For the other local times, we have used 9–10 iterations and the deviations in these cases are less than 3 TECU (~ 5% or less).

It may be noted from Figures 2 and 3 that as the latitude span is increased, the TEC values appear to decrease systematically/monotonically. Hence, the offset value corresponding to the minimum latitudinal span may also be taken as an option for the unknown TEC offset. However, we do not have a priori information to fix one latitude span, as the region which gives the most linear TEC distribution. The novelty in this method is that the absolute TEC is estimated with several increasing intervals which are like estimating TEC using a model with different discretization lengths. Together, these estimates form an ensemble, and this ensemble is then used to estimate an error bar for the unknown TEC, much in the same way as errors are estimated for climate models. Divergence of the estimates when the latitudinal span is sufficiently large is used as a guideline to estimate the latitudinal scale. In other words, once the region of linearity is increased enough, the solution diverges and this is an indication of the correct latitudinal span.

4. Comparison of the GRBR Observations With GPS-TEC Measurements

The GRBR observations give the latitudinal variation of TEC. However, since only a few satellites are operational, the maximum number of passes may be up to eight or nine, for a given day. In this case, we get excellent spatial information, but the temporal coverage is limited. In contrast to this, ground-based GPS measurements give continuous estimates, with some inherent spatial variation, due to the fact that different PRNs view slightly different ionospheric pierce points at a given time. However, we can still compare the two measurements, if we use the absolute GRBR-TEC values at the point of closest approach with the GPS receiver. Figure 4 shows such a comparison. For each day, we have five to eight beacon TEC points, which correspond to the maximum number of good quality beacon passes on that day. We have omitted the plots for 15 and 16 June, because the number of good satellite passes was less than 5. However, the comparison shows similar nature for these days as well.

When making such a comparison, three important facts need to be considered: (1) the difference between the IPP locations of the individual satellites, (2) the errors in GRBR and GPS-TEC estimates, and (3) the altitude difference between these satellites—GPS satellites are at ~20,000 km, whereas the LEO orbits are ~900–1000 km, which is mostly (may not be entirely) ionospheric electron content, and the TEC measured by GPS include the total electron content, i.e., ionospheric electron content (IEC) + plasmaspheric electron content (PEC), and often the difference between two such measurements are used to estimate PECs [*Lanyi and Roth*, 1988; *Ciraolo and Spalla*, 1997; *Lunt et al.*, 1999; *Manju et al.*, 2008; *Mridula et al.*, 2011]. However, we do not use the term ionospheric electron content (IEC) and total electron content (TEC) respectively for GRBR-TECs and GPS-TECs but prefer to use the terms GRBR-TEC and GPS-TEC respectively, because as we discuss later, the difference in our case do not necessarily represent PEC, because of the spatial gradients present in the region. It is also important to mention here that we are not using the average GPS-TEC values (which are usually obtained by averaging all the individual PRNs) for comparison because the differences in TEC values obtained from individual PRNS become significant over regions with considerable spatial gradients. Hence, TECs from the individual PRNs are plotted as such along with GRBR-TECs in Figure 4.

For all the days, it can be seen that both measurements show an overall agreement. For instance, on 14, 20, and 21 June (Figures 4a, 4e, and 4f), the diurnal maximum of GPS-TEC at Ahmedabad shows higher values compared to the other days (indicating a well-developed EIA crest), and the GRBR-TEC shows the same trend. On 19 June, there is a broad diurnal maximum of only around 40 TECU in GPS-TEC (indicating a weak EIA), with the overall low TEC levels from 9 to 14 UT compared to the other days. The GRBR-TEC also shows a similar trend. This shows that the method of estimation of absolute TECs is viable to give true estimates of the variations over EIA region. This is a very important aspect, since the major challenge in using the phase measurements using beacons on board polar-orbiting satellites to investigate the EIA variation lies in the reliable estimate of the unknown offset. In this context, the iterative approach presented here gives very reasonable estimates of TEC, even at situations when large latitudinal gradients are present.

In almost all the cases (except at 1015 UT on 20 June), the GPS-TEC values are consistently higher than the GRBR-TECs with maximum difference of ~10–12 TECU occasionally. Sometimes the difference is as small as 2 TECU, and on other occasions the difference lies within 4–6 TECU. The differences are maximum around 10–16 UT, the time when large latitudinal gradients are present. It can be seen that the GPS-TECs also show the largest spread during this period, owing to the spatial differences (in terms of IPP location and gradients) among the GPS satellites.

As mentioned earlier, the differences between GRBR-TEC and GPS-TEC can arise due to the altitude difference between the two satellites. In the present investigation, the GPS-TEC and LEO TEC data are carefully scrutinized to investigate the impact of the presence of large spatial gradients in the ionosphere (such as that occurring in the vicinity of the EIA crest during daytime) in the estimation of PEC using this technique. The locations of GPS satellites (identified by different PRNs) have a longitudinal spread of ~7° among the different PRNs, at any instant of time. This significantly affects the PEC estimations, if we take the difference of the mean GPS-TEC and the GRBR-TEC, because while obtaining the average GPSTEC, we have considered a longitudinally averaged region of ~7°, and the maximum difference among GPS-TECs can be even up to ~15 TECU. Hence, it may not be logical to use the average GPS-TEC value for the estimation of PEC, especially over the EIA crest region, where a large spatial gradient is expected. Similarly, if we take the individual PRNs, estimation of PEC can vary considerably, depending on the location of the ionospheric pierce points (of the GPS satellite and the beacon satellite), and often there is a chance that the ionospheric spatial gradients are mixed up with the PEC estimates. This can often give rise to the overestimation of the PEC values. We also need to consider the fact that the total biases involved in GPS measurements can lead to errors of a few TEC units. All these factors can contribute significantly to the errors in PEC estimation.

5. Exploring the Applicability of This Method to Capture TEC Variation Over Regions Having Large Latitudinal Gradients

Figure 5 shows some examples of latitudinal variation of TEC deduced from GRBR-TEC observations on 6 days. For each satellite pass, the mean absolute TEC with standard deviations is plotted with latitude. It can be seen that the signature of the EIA, which is the prominent large-scale low-latitude feature, is present on all days except 19 June 2013 (Figure 5d). The temporal variation of GPS-TEC from Ahmedabad also does not show a diurnal peak on this day, compared to the other days, indicating toward an ill-developed EIA. The examination of the provisional magnetic data (http://wdciig.res.in/WebUI/ProvisionalArchData.aspx) shows

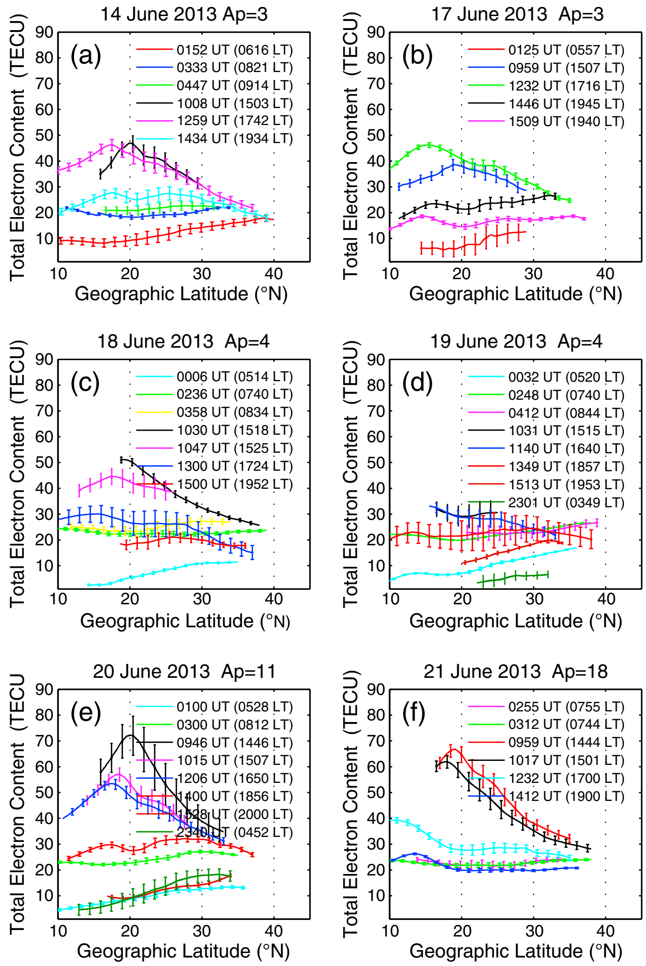

Figure 5. Examples of the latitude variation of TEC at different LTs on different days, derived from GRBR observations.

that equatorial electrojet (EEJ) was weak on this day and there was a very strong counter electrojet in the afternoon hours (during 8–12 UT, not illustrated), possibly due to a moderate substorm activity in the previous night (http://wdc.kugi.kyoto-u.ac.jp/aeasy/index.html). This is quite expected, since the basic electric field which drives the EEJ and EIA is the same. Many such observations which show clear corroborations with EEJ and TEC over the crest region are reported in literature [e.g., *Deshpande et al.*, 1977; *Sethia et al.*, 1979; *Huang et al.*, 1989; *Abdu et al.*, 1993; *Hajra et al.*, 2009]. It may also be noted that there is a characteristic time delay associated with the changes in the electric field to manifest in the EIA crest density [*Raghavarao et al.*, 1978; *Sastri*, 1990]. Usually, a lag of ~2 h for the change in the electric field to be manifested in the EIA crest densities is quite expected [*Rush and Richmond*, 1973; *Raghavarao et al.*, 1978], which explains the absence of the EIA signature in the beacon passes at 1031 UT and 11:40 UT.

The strong EIA signature on the other days also has a clear correspondence with the diurnal pattern of GPS-TEC over Ahmedabad. If we examine the general features, it can be seen that the crest is farthest in latitude around 09:40–10 UT, which is ~15 LT over this region. This is consistent with the earlier observations over Indian region [e.g., *Sastri*, 1990]. If we compare the crest locations on the days when EIA is developed, it can be seen that at any given LT, the crest location does not change much. This can be attributed to the fact that there is not much day-to-day variation of the zonal electric field amplitude during the daytime over Indian region [*Scherliess and Fejer*, 1999]. Apart from this, there are considerable day-to-day variations in the electron content over this region during daytime, mainly owing to the variability of neutral winds. It may be noted that the absolute value of electron content, at any given local time, over the crest region does not solely depend on electric field, whereas the crest location is determined by the electric field alone. However, a detailed discussion on this aspect is beyond the scope of this paper and will be addressed in subsequent reports with supporting information. The examples shown here clearly show (1) the potential of the radio beacons on board high-inclination LEOS to capture the EIA variability, even with observations from a single location, and (2) the applicability of the iterative approach to determine reliable estimates of absolute TECs even on occasions when large latitudinal gradients are present.

6. Concluding Remarks

A new digital radio beacon receiver (GRBR) is fabricated and made operational at Ahmedabad, a station near the vicinity of the EIA crest location, since May 2013. An ensemble average method to convert the relative TECs to absolute TECs is presented, which is a modified version of the differential method proposed by *de Mendonça* [1962]. Comparison with a collocated GPS receiver shows that the absolute TEC values thus obtained are reliable estimates of TEC even over the regions/local times, even when large spatial gradients are present. The differences between GRBR-TEC and GPS-TEC observations are suggested to be due to the spatial differences between the ionospheric pierce points of these satellites as well as the plasmaspheric electron content. However, it is seen that spatial differences among these satellites can cause significant uncertainly in the PEC estimation, especially when the EIA crest is developing. The analysis of the beacon data also shows that the latitudinal variation of absolute TEC at different local times derived using the iterative method can effectively capture the evolution and variability of EIA. The method presented here is very useful because it can give reliable estimates of TEC variation with observations from only one receiving station.

Acknowledgments
The work is supported by Department of Space, Government of India. S.T. thanks Science and Engineering Research Board, India, for the Woman Excellence Award grant. The authors acknowledge M.B. Dhadania, Sachin Panchal, Mitesh Bhavsar, Kedar A Phadke, Gaurav Hirani, and Fazlul Islam Laskar for their participation in the fabrication, installation, and operation of GRBR system. We also acknowledge Nidhi Kotecha and Chaitalee Patel for their work for the fabrication of the GRBR system. We thank the Indian Institute of Geomagnetism for providing the online archival of recent geomagnetic data and WDC-C2, Kyoto university, for providing the geomagnetic indices. S.T. thanks R. Sekar and Harish Chandra for the very useful discussions.

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