Comparison of GPS TEC measurements with IRI TEC prediction at the equatorial latitude station, Chumphon, Thailand

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We have analyzed the total electron content (TEC) derived from dual-frequency GPS receivers (GPS TEC) at the Chumpon station, Thailand, during the period 2004–2006. The diurnal, monthly, and seasonal variation in the measured TEC is compared with the TEC derived from the IRI-2007 model as well as the TEC obtained from the International GNSS service (IGS). To date, TEC data at equatorial latitudes are limited. The Chumphon station (10.72°N, 99.37°E) is located at the equatorial latitude and the dip latitude of 3°N. The TEC from the IRI-2007 model is based on the actual F_2 plasma frequency (f_oF_2) measurement. The results of our study show that the TEC derived from the IRI-2007 model agrees with the GPS TEC data mostly in the morning hours, but that it generally underestimates the GPS TEC. The maximum differences are about 15 TECU during the daytime and 5 TECU during the nighttime. The underestimation is more evident at daytime than at nighttime. The noon-bite out phenomena are clearly seen for the IRI-2007 TEC, but not on the IGS TEC and GPS TEC. The general underestimation of the IRI-2007 model can be explained from the exclusion of the plasmasphere, whereas the large difference during noon bite-outs is caused by the difference in the slab thickness in the ionosphere between the IRI-2007 model and the actual measurement. When compared with the TEC from the IGS model, the TEC measurements at Chumpon appear to be quite similar.
Key words: GPS TEC, IRI-2007 TEC, IGS TEC, TEC comparison, TEC measurement, TEC prediction, equatorial latitude.

1. Introduction

The Global Position System (GPS), low-orbit navigation satellites, such as TRANSIT, and space technologies set the need to improve our understanding of the structure and activities of both the topside and bottomside ionospheres. Total Electron Content (TEC) is an important ionospheric parameter which directly affects the propagation of radio waves through the ionosphere. In the equatorial region, the TEC gradient may be one cause of the equatorial bubbles phenomenon (Yeh *et al*., 1979; Das Gupta *et al*., 1983; Rama Rao *et al*., 2004). TEC measurements assist in the development of ionospheric models, such as the International Reference Ionosphere (IRI) (Bilitza, 2001; Bilitza and Reinisch, 2008). The increase in the amount of TEC data that have become available during the last decades has largely been due to the rapid increase in the amount of Global Position System TEC (GPS TEC) data over land. The increasing number of GPS sites has provided an important database to study the ionosphere. Compared with the long record of over 70 years of ionospheric observation from ground-based measurements, TEC records from GPS are relatively short. Many published studies report comparisons of the measured TEC data obtained from different

techniques at various locations with various models, such as the IRI models (Bilitza *et al*., 1998; Jakowski *et al*., 1998; Ezquer *et al*., 1998, 2004; Huang and Reinisch, 2001; Sethi *et al*., 2001; Gulyaeva *et al*., 2002; Belehaki *et al*., 2003, 2004; Orús *et al*., 2003; Jodogne *et al*., 2004; Mosert *et al*., 2004). However, at the equatorial latitudes, such as at Chumphon station, Thailand, comparisons between TEC based on observation and that of the IRI models are scarce.

The objective of the study reported here was to compare the GPS TEC data recorded at the equatorial latitudinal location in Chumphon station, Thailand with the TEC obtained from the IRI-2007 model (Bilitza, 2001; Bilitza and Reinisch, 2008) and the IGS TEC. This monitoring station is a part of the South East Asia Low Latitude Ionosphere Observation Network (SEALION) (Maruyama *et al*., 2007). The aims of SEALION are to observe, monitor, and forecast the ionospheric variation in the Asia Pacific region near the magnetic equator. It is a joint project among the following institutions and countries: National Institute of Information and Communications Technology (NICT), Japan, King Mongkut's Institute of Technology Ladkrabang (KMITL), Thailand, Chiang Mai University (CMU), Thailand, National Institute of Aeronautics and Space (LAPAN), Indonesia, Hanoi Institute of Geophysics (HIG), Vietnamese Academy of Science and Technology, Vietnam, Center for Space Science and Applied Research (CSSAR), Chinese Academy of Sciences, China, and Ky-

oto University, Japan. The GPS TEC data measured during the period 2004–2006 were analyzed and compared to the IRI models and IGS TEC based on the diurnal, monthly, and seasonal variations.

2. Data Used
2.1 GPS TEC data

The GPS TEC data used in this study were recorded by the GPS receiver (10.72°N, 99.37°E) from 2004 to 2006. TEC is defined as the total electron content (electron/m^2) of a vertical column of 1-m^2 cross-section (Goodwin *et al.*, 1995). This definition of TEC is actually the definition of the vertical TEC (VTEC) through the piercing point with the obliquity factor (Lin, 2001; Brunini *et al.*, 2004; Cabrera *et al.*, 2005). The slant TEC (STEC) is defined as the line integral of the electron density from all GPS satellites visible from each of these receivers above a user-specified elevation cut-off angle (usually 15°) (Cabrera *et al.*, 2005; Jin and Park, 2007; Zeilhofer *et al.*, 2009). In the GPS system, every satellite transmits the signals on two frequencies ($f_1 = 1575.42$ MHz and $f_2 = 1227.60$ MHz). The dual-frequency GPS receiver is used for the GPS TEC measurement system, which consists of a micro strip antenna, an amplifier, a TEC Meter, and a computer. The GPS receiver starts functioning when it continuously receives between four and 12 GPS signals that will lead to the computation of the STEC values.

The STEC from a satellite to a receiver can be obtained from the difference between the pseudoranges (P_1 and P_2) or the difference between the carrier phases (L_1 and L_2) of the two frequencies (Blewitt, 1990), i.e.,

$$\text{STEC} = \frac{2 \left(f_1 f_2 \right)^2}{k \left(f_1^2 - f_2^2 \right)} \left(P_2 - P_1 \right) + \tau^{\text{r}} + \tau^{\text{s}}, \qquad (1)$$

or

$$\text{STEC} = \frac{2 \left(f_1 f_2 \right)^2}{k \left(f_1^2 - f_2^2 \right)} \left(L_1 \lambda_1 - L_2 \lambda_2 \right) + \varepsilon^{\text{r}} + \varepsilon^{\text{s}}, \qquad (2)$$

where k, related to the ionosphere refraction, is 80.62 (m^3/s^2); λ_1, and λ_2 are the wavelengths corresponding to f_1 and f_2, repectively; τ^{r}, and ε^{r} are the differential code biases corresponding to the pseudoranges (P_1 and P_2), and the carrier phases (L_1 and L_2), respectively; τ^{s}, and ε^{s} are the inter-frequency biases corresponding to the pseudoranges (P_1 and P_2), and the carrier phases (L_1 and L_2), respectively.

VTEC, in el/m^2, can be computed from Ma and Maruyama (2003) as

$$\text{VTEC} = \text{STEC} \times \cos \chi, \qquad (3)$$

where the zenith angle χ is expressed as

$$\chi = \arcsin \left(\frac{R_{\text{E}} \cos \alpha}{R_{\text{E}} + h} \right), \qquad (4)$$

where α is the elevation angle of the satellite, R_{E} is the mean radius of the Earth, and h is the height of the ionospheric layer, which is assumed to be 400 km.

The STEC that is computed based on the carrier phase in Eq. (2) is generally less noisy than that from Eq. (1);

however, the ambiguity in the integer value of L, known as a cycle slip, often arises. The cycle slip correction can typically be made with the aid of pseudorange difference information. To obtain the VTEC, we compute

$$\text{VTEC} = (\text{STEC} - b_{\text{s}} - b_{\text{r}}) \times \cos \chi, \qquad (5)$$

where b_{s} and b_{r} are the estimated satellite and receiver biases, respectively. In this work, the satellite bias is obtained from NICT based on the GPS Earth Observation Network (GEONET), set up by the Geographical Survey Institute (GSI) of Japan, which has more than 1,000 GPS receivers spread throughout Japan (Miyazaki *et al.*, 1997). The receiver bias for a single receiver at Chumpon station is calculated using the minimum variance method (Ma and Maruyama, 2003).

2.2 IRI TEC data

With the goal of establishing an international standard for the specification of ionospheric parameters based on all worldwide available data from both ground-based and satellite observations, the International Reference Ionosphere (IRI) project was initiated by the Committee on Space Research (COSPAR) and by the International Union of Radio Science (URSI) in the late 1960s. COSPAR and URSI specifically asked for an empirical IRI model to avoid the uncertainties of the evolving theoretical understanding of ionospheric processes and coupling to the regimes below and above. The IRI model is continually upgraded as new data and new modeling approaches become available, and this process has resulted in several major milestone editions of IRI (Rawer *et al.*, 1978a, b, 1981; Bilitza, 1990, 2001; Bilitza and Rawer, 1996) that progress from a set of tables for typical conditions to a global model for all phases of the solar cycle. More information on the IRI project, including information on the IRI Newsletter and the IRI electronic mailer, can be found on the IRI homepage at http://IRI.gsfc.nasa.gov/.

The corresponding IRI TEC predictions (IRI TEC) are calculated from the IRI-2007 models (Bilitza and Reinisch, 2008) using the location, dates, and period of time as inputs to the model. The IRI-2007, a new empirical standard model of the ionosphere, is improved from the limitations of the previous IRI-2001 model. To predict the IRI TEC from IRI-2007, we can access the site at http://ccmc.gsfc.nasa.gov/modelweb/models/iri_vitmo.php/, which has more recently also become available as an interactive web interface accessible from the IRI homepage. In this study, we use the IRI-2007 TEC with the F_2 plasma frequency ($f_{\text{o}}F_2$) measurement option.

2.3 IGS TEC data

IGS TEC data are maintained and monitored by the International GNSS service (IGS). The IGS relies on an international network of over 350 continuously operating dual-frequency GPS stations (Dow *et al.*, 2009). The Central Bureau for the service is located at the Jet Propulsion Laboratory, which maintains the Central Bureau Information System (CBIS) and ensures access to IGS products and information. An international Governing Board oversees all aspects of the IGS. The IGS has been an approved service of the International Association of Geodesy since 1994 and recognized as a member of the Federation of Astronomi-
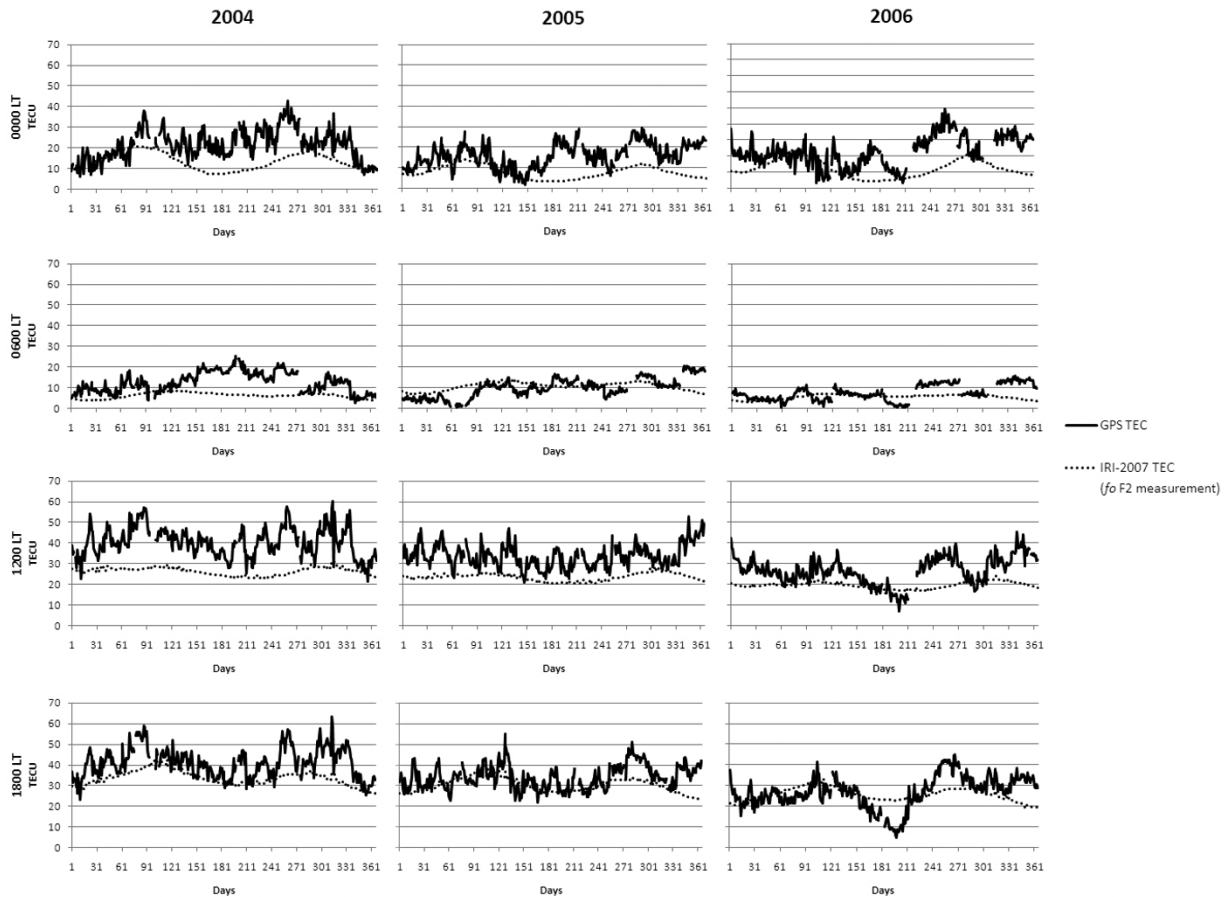
Fig. 1. Diurnal median values of GPS TEC and IRI-2007 TEC at the Chumphon station for 0000 LT, 0600 LT, 1200 LT and 1800 LT during the period 2004–2006.

cal and Geophysical Data Analysis Services (FAGS) since 1996. The IGS collects, archives, and distributes GPS observation data sets. It provides the TEC map data available on the Internet, and these data can be accessed from the File Transfer Protocol (FTP) site: ftp://igscb.jpl.nasa.gov/.

In this work, we use the 2-h text data of global TEC maps with the different code biases in the IONEX (The IONosphere Map EXchange) format via the following FTP site: ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex/. The final TEC map data estimates are provided by three centers on the same day (COD, JPL, and UPC with associated final product labels CODG, JPLG, and UPCG) together with the corresponding final combined IGS values (labeled as IGSG).

3. Results of the Analysis

3.1 Diurnal variation of the GPS TEC and TEC from the IRI-2007 model

Figure 1 shows the comparison between the diurnal median values of GPS TEC and IRI-2007 TEC (in TEC units of $10^{16}/ \, m^2 = 1$ TECU) at Chumphon station from 2004 to 2006, a period of low solar activity. Each curve shows the variation of TEC versus the hours representing different times of day, including 0000 LT (midnight), 0600 LT (pre-sunrise), 1200 LT (midday), and 1800 LT (pre-sunset), respectively. The solid line denotes GPS TEC from our observation and the dotted line is the IRI-2007 predictions.

The IRI-2007 model underestimates the observed TEC from GPS TEC data because the GPS TEC computes the TEC from ground all the way up to the plasmasphere, but the IRI-2007 model includes the ionosphere only. The largest deviation is evident at 1200 LT in 2004. For 2004 and 2005, the large difference is seen at midday. The largest differences between GPS TEC values and IRI-2007 TEC values are at the midday time in 2004. The GPS TEC values differ from IRI-2007 TEC values at about 15 TECU. The IRI-2007 model predicted the TEC data well at pre-sunset hours in 2004 and 2005.

3.2 Seasonal comparison of GPS TEC, IGS TEC and IRI TEC

Since the IRI 2007 model is based on the TEC derived from the ionogram, while the GPS TEC and IGS TEC data are derived from GPS data, it would be interesting to compare them with the IGS TEC obtained from the GIM TEC map. We use the IGS TEC map data at 10°N and 100°E, the location of Singapore, which is the nearest monitoring location to the Chumphon station. In Fig. 2, we show the seasonal median TEC comparison of GPS TEC, IGS TEC, and IRI-2007 TEC from 2004 to 2006. The periods of study are classified into three seasons, including the equinox (March, April, September, and October), summer (May, June, July, and August), and winter (January, February, November, and December).

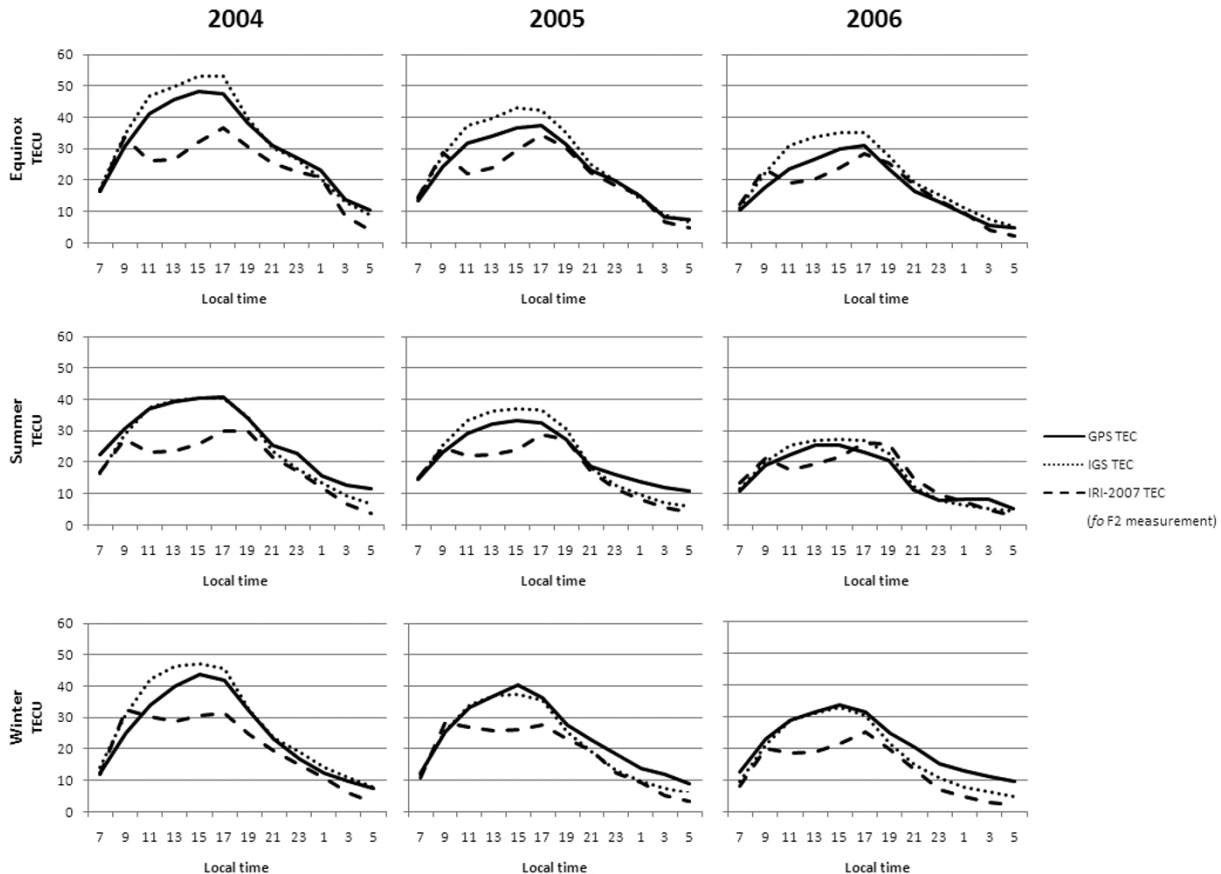As seen from Fig. 2, the IRI model generally underes-

Fig. 2. Seasonal median values of GPS TEC, IGS TEC and IRI-2007 TEC at a Chumphon station for the three seasons, namely, equinox, summer and winter, respectively, during the period 2004–2006.

timates the observed TEC, with the underestimation being more evident at daytime than nighttime, particularly during the noon bite-out periods. The noon-bite out events are clearly seen on the IRI-2007 TEC, but not on the IGS TEC and GPS TEC. The IRI-2007 TEC and the observed TEC are very similar during the nighttime of the equinox in 2005 and 2006. A similar seasonal trend on GPS TEC and IRI TEC (IRI-2001 TEC) has been reported by Mosert *et al.* (2007) using data from Ebro (40.8°N, 0.5°E). The significant difference observed is that GPS TEC is greater than IRI TEC according to the altitude (altitudes are about 20,200 km and 2,000 km for the GPS TEC and IRI TEC, respectively). In addition, Jin and Park (2007) studied the comparison of TEC at the grid point (37.5°N, 127.0°E) over South Korea, estimated from GPS and IRI-2001 TEC in different seasons. Their results showed that maximum TEC values occurred at about the noontime, between 1100 LT and 1500 LT.

The IGS TEC is generally higher than the GPS TEC at about 5 TECU during the daytime of the equinox, but it is lower than the GPS TEC at about 5 TECU during the nighttime in the winter of 2005 and 2006. The satellite biases derived by NICT do not provide the accuracy bias estimation (Ma and Maruyama, 2003). However, Ma and Maruyama (2003) calculated that the standard deviation of the satellite bias in GEONET ranges from 0.23 to 1.89 TECU for the 9-day windows. To determine the receiver bias, we esti-

mate the receiver biases on the 5-day average of STEC and TEC values for each month during 2004–2006. We find that the average receiver bias is up to 4.28 TECU. For the IGS TEC, the data from TEC map has a root-mean square error (RMSE) of about 4.53 TECU (Hernandez-Pajares *et al.*, 2008). The IRI-2007 values follow the IGS model more closely in the early morning than any other time of day. The maximum difference between the GPS TEC and the IRI-2007 TEC are about 15 TECU during the daytime and about 5 TECU at the nighttime.

The large difference between the GPS TEC and IRI TEC during noontime indicates that the ionosphere at Chumpon or the equatorial area is expanded to cover a larger thickness than at other times. At the equatorial latitude, the steepest gradients, sharp peaks and deep valleys, and density crests are on both sides of the equator, as explained by Bilitza and Reinisch (2008). The occurrence of a prominent trough accompanied by maximum TEC values in the pre-noon and the afternoon at equatorial latitudes is referred to as a noon bite-out, which is a characteristic feature at an equatorial station that falls in the trough of the equatorial anomaly (Maeda, 1955; Rastogi, 1959). The noon bite-out phenomenon is the result of interaction and the relative role played by the production, loss, and movements terms in the continuity equation of the electron density at the peak of the layer. The TEC movement includes the effects of vertical drift, horizontal diffusion of ionization along the field

lines, and neutral winds. Martyn (1955) and Rao (1966) showed that the pre-noon peak in the diurnal variation at equatorial latitudes is influenced by horizontal winds in addition to production and loss processes, while the afternoon peak is determined by vertical drifts and diffusion.

The IRI-TEC model is not directly constructed from the measured TEC database, but the TEC calculation is conducted from f_oF_2. The height profile of electron density is calculated based on the f_oF_2, step-by-step. The f_oF_2 is the most important parameter in the IRI model because IRI historically is based on an extension of the CCIR f_oF_2 model. The density profile is then integrated along the vertical line to obtain TEC. In this process, topside electron density may not be adequately modeled, i.e., the thickness is too small for IRI topside density profile. The discrepancy between TEC measurements and IRI results suggest that this error is most significant during the hours when the noon bite-out develops. It is larger than the plasmaspheric model that was previously reported (Bishop *et al.*, 2009). The relative contribution of plasmasphere TEC (P-TEC) is larger in the nighttime (Yizengaw *et al.*, 2008). In other words, the slab thickness becomes quite large during the noon bit-out of f_oF_2. Thus, during the noon bite-out periods, this discrepancy cannot be ascribed to ignorance of the plasmasphere in the IRI model. Rather. it should be the difference of slab thickness in the ionosphere.

4. Summary

In this work, the GPS TEC derived from the TEC data at Chumpon equatorial station, Thailand is compared with the IRI TEC (IRI-2007 TEC) and the IGS TEC from 2004 to 2006. The maximum differences are about 15 TECU during the daytime and about 5 TECU during the nighttime. When compared with the IGS TEC, we find that the GPS TEC measurements from the Chumphon station and those from the IGS model are quite similar, and both are higher than the TEC predicted from the IRI-2007 model. The IRI-2007 model fits the GPS TEC data mostly in the morning hours, but generally underestimates the GPS TEC since the plasmasphere is not included in the model. The underestimation is more apparent at daytime than nighttime, particularly during the noon bite-outs. This discrepancy is larger than the effects of the plasmaspheric model that was previously reported. This difference during daytime indicates that it is due to the difference of slab thickness in the ionosphere between the IRI model and the measured data.

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