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Paper:

Total Electron Content Observations by Dense Regional and Worldwide International Networks of GNSS

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Two-dimensional ionospheric total electron content (TEC) maps have been derived from ground-based Global Navigation Satellite System (GNSS) receiver networks and applied to studies of various ionospheric disturbances since the mid-1990s. For the purpose of monitoring and researching ionospheric conditions and ionospheric space weather phenomena, we have developed TEC maps of areas over Japan using the dense GNSS network, GNSS Earth Observation NETwork (GEONET), which consists of about 1300 stations and is operated by the Geospatial Information Authority of Japan (GSI). Currently, we are providing high-resolution, two-dimensional maps of absolute TEC, detrended TEC, rate of TEC change index (ROTI), and loss-of-lock on GPS signal over Japan on a real-time basis. Such high-resolution TEC maps using dense GNSS receiver networks are one of the most effective ways to observe, on a scale of several 100 km to 1000 km, ionospheric variations caused by traveling ionospheric disturbances and/or equatorial plasma bubbles, which can degrade single-frequency and differential GNSS positioning/navigation. We have collected all the available GNSS receiver data in the world to expand the TEC observation area. Currently, however, dense GNSS receiver networks are available in only limited areas, such as Japan, North America, and Europe. To expand the two-dimensional TEC observation with high resolution, we have conducted the Dense Regional and Worldwide International GNSS TEC observation (DRAWING-TEC) project, which is engaged in three activities: (1) standardizing GNSS-TEC data, (2) developing a new high-resolution TEC mapping technique, and (3) sharing the standardized TEC data or the information of GNSS receiver network. We have developed a new standardized TEC format, GNSS-TEC EXchange (GTEX), which is included in the Formatted Tables of ITU-R SG 3 Databanks related to Recommendation ITU-R P.311. Sharing the GTEX TEC data would be easier than sharing the GPS/GNSS data among those in the international ionospheric researcher community. The DRAWING-TEC project would promote studies of medium-scale ionospheric variations and their effect on GNSS.

Keywords: GNSS, ionosphere, total electron content, TEC, loss-of-lock

1. Introduction

The Earth's atmosphere at an altitude of 60 km or higher is partially ionized by solar EUV and a part of it is present as ionized gas (plasma). This plasma-rich region in the atmosphere is called the ionosphere. The electron density in the ionosphere is generally highest at an altitude of about 300 km. The ionosphere is well known to affect trans-ionospheric transmissions with satellites for communications, positioning, and navigation purposes. The ionosphere varies greatly under the influence of the activities of the sun, the magnetosphere, and the lower atmosphere, and it sometimes interferes with satellite communications and degrades precise satellite positioning. It is known that errors in the Global Navigation Satellite System (GNSS), including GPS, are caused by several factors, including satellite clock error, trajectory error, or multi-path effects, but the most significant factor is the propagation delay of GNSS signals in the ionosphere. Recently, in the multi-GNSS era, considerable efforts have been directed toward research on the ionospheric variations and their effects on precise GNSS positioning and navigation. A precise ionospheric total electron content (TEC) map or model is required to study ionospheric variations and to improve the ionospheric delay correction for

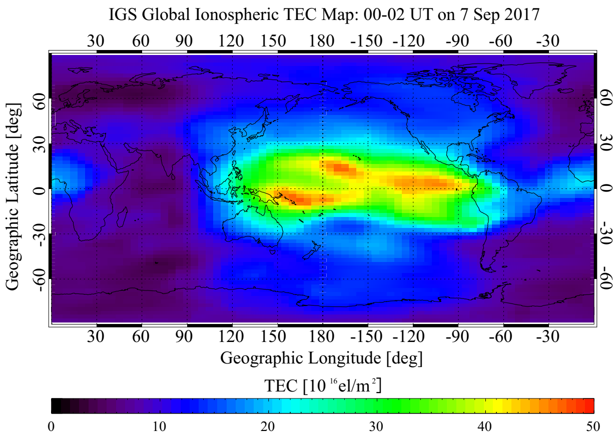


Fig. 1. An example IGS TEC map with spatial resolution of 5° in longitude and 2.5° in latitude, with a temporal resolution of 2 hours.

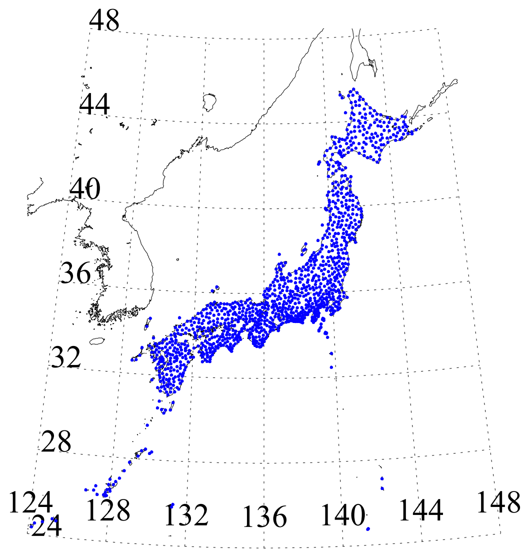


Fig. 2. Distribution of GPS stations of GEONET.

GNSS positioning.

Figure 1 is an example of the ionospheric TEC maps that are generally used, the Global Ionospheric Map (GIM) in the IONosphere map EXchange (IONEX) format, provided by the International GNSS Service (IGS) [1]. GIM TEC data cover the global ionosphere with a spatial resolution of 5° in longitude and 2.5° in latitude, with a temporal resolution of 2 hours. GIM is useful to study ionospheric variations with 1000 km to global scale (hereinafter referred to as "large-scale"), variations such as diurnal variation and the equatorial ionization anomaly, which is electron density enhancement located away from the magnetic equator.

Ionospheric variations on a scale of several 100 km to 1000 km (hereinafter referred to as "medium-scale"), caused by travelling ionospheric disturbances (TIDs) and/or equatorial plasma bubbles (EPBs) frequently observed at mid- and low-latitudes, can degrade single-frequency and differential GNSS positioning/navigation. The GIM does not have sufficient spatial and temporal resolution to reproduce these medium-scale ionospheric variations. To clarify generation and propagation mechanisms of medium-scale ionospheric phenomena and to investigate their effects on GNSS positioning, dense and wide-coverage ionospheric observations and the corresponding TEC mapping techniques are needed.

We have developed high-resolution, two-dimensional TEC observation systems using a dense GNSS receiver network in Japan, and we have conducted a project to expand their observation area using all the available GNSS receiver networks with the collaboration of space weather researchers in the world since 2011. In this paper, we introduce our high-resolution ionospheric TEC observations using dense GNSS receiver networks, including an outline of the project, named Dense Regional and Worldwide International Networks of GNSS-TEC observation (DRAWING-TEC).

2. High-Resolution TEC Observations over Japan

We have observed ionospheric disturbances using two-dimensional maps of TEC derived from the dense GNSS network, GNSS Earth Observation Network System (GEONET), which consists of about 1300 GPS receivers and is operated by the Geospatial Information Authority of Japan (GSI). The distribution of GNSS stations of GEONET is shown in **Fig. 2**. Currently, using only GPS data, we routinely provide two-dimensional maps of absolute TEC and detrended TEC with 60-, 30-, and 15-minute windows over Japan. The maps have a spatial resolution of 0.15° in longitude and 0.15° in latitude, with a temporal resolution of 30 seconds. The absolute TEC values were derived by applying a technique in which a weighted-least-square fitting is used to determine unknown instrumental biases, assuming that the hourly TEC average is uniform within the area covered by a given GPS receiver [2]. Detrended TEC data are derived from the perturbation components of TEC data by subtracting the running average of the corresponding time window for each line-of-sight (LOS) between satellite and receiver. Such a TEC mapping is the direct measure of ionospheric structures and useful to reveal spatial structures and temporal evolutions of medium-scale ionospheric phenomena such as TID, as shown in **Fig. 3** [3,4]. These data and quick-look maps from 1997 to the present are available on the NICT website (http://seg-web.nict.go.jp/GPS/GEONET/).

Figure 4 shows two-dimensional maps of absolute TEC (left), rate of TEC change index (ROTI) (middle), and loss-of-lock on GPS signal (LOL) rate during the time period 12:20–13:00 UT (21:20–22:00 JST) on Feb. 12, 2000, just after the main phase of a strong geomagnetic storm [5]. ROTI is the standard deviation of time differential TEC in five minutes, often used as the index of

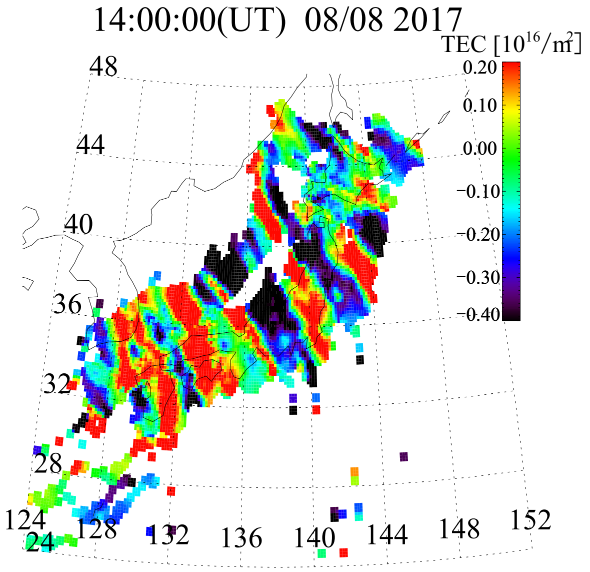


Fig. 3. High-resolution detrended TEC map with 60-min window derived using GEONET data. Typical nighttime medium-scale TIDs are captured over Japan.

ionospheric irregularity on a scale of several tens of km and considering the velocity of a LOS ionospheric pierce point at an assumed ionospheric height at 300 km [6, 7]. The LOL rate is the occurrence rate of cycle slip in GPS L1 or L2 signals for 5 minutes and derived using the loss of lock indicator in the Receiver INdependent EXchange format (RINEX) data of GPS. Fresnel-scale ionospheric irregularities, that is, several 100-m scale for GPS L1 and L2 signals, could cause GPS scintillation and, in the worst case, result in LOL on GPS signals. Although the LOL could be caused not only by several 100-m scale ionospheric irregularities but also by the multi-path effect or performance of the GPS receiver/antenna system, an increase in LOL rate occurring simultaneously in many receivers could be a proxy of the $\sim$100-m scale ionospheric irregularity. Small-scale structures, such as ionospheric irregularities with spatial scale from several tens of km down to several meters, may be generated by the nonlinear cascading process from the medium-scale and/or large-scale ionospheric structures. These small-scale structures are associated with a localized but intense ionospheric plasma-density gradient and can scintillate the GNSS radio wave. The small-scale structures can be monitored by the indices of GNSS data fluctuations, such as the ROTI and LOL rate. The dense GNSS network is helpful to monitor the location and motion of areas of the enhanced small-scale irregularities as well.

In **Fig. 4**, background absolute TEC values at 12:20 UT (21:20 JST) are 60 TECU (1 TECU = 10^{16}/m^2) or more in southern Japan and decrease with latitude. This TEC level is more than double the normal level in this season. The arrows indicate TEC depletion regions that have a zonal scale of several 100 km and extend in the meridional direction. These TEC depletion regions move eastward at $\sim$50 m/s. Corresponding to the TEC depletions, ROTI enhancements are seen in the same regions and move eastward at the same velocity. This indicates that ionospheric irregularities of several tens of kilometer scale exist in the TEC depletion regions. Similar to ROTI enhancements, LOL rate enhancements are seen in the same regions and move eastward at the same velocity. The LOL rate maps in **Fig. 4** show that LOL occurs over a wide area, indicating that many receivers suffer LOL for a significant number of GPS satellites simultaneously. Therefore, it is reasonable to consider that these LOL rate enhancements are caused by GPS scintillations due to the ionospheric irregularities.

Summarizing the ionospheric events in **Fig. 4**, TEC depletions with zonal widths of several 100 km and extend in the meridional direction are seen to move eastward in southern Japan. Ionospheric irregularities of both several tens of km scale and several 100-m scale occurred in these TEC depletion regions. These features are consistent with that of EPB frequently observed at low latitudes after sunset. EPBs are low density plasma "bubbles" in the ambient high density ionospheric plasma. They are basically caused by the nonlinear growth of Rayleigh-Taylor instability, which is enhanced after sunset due to local uplift of the bottomside ionosphere resulting from the dynamo effect by F-region neutral winds and the effect of rapid changes in E-region electric conductivity at sunset [8]. These bubbles intrude into the topside ionosphere, extending over several 1000 km along the magnetic field line. The plasma bubbles generally drift eastward with the background neutral wind. Although there is no strong relationship between the occurrence of EPB and geomagnetic storms in the climatology of EPB [9], the ionospheric disturbances observed in Japan and seen in **Fig. 4** are the EPB that developed to high altitude/latitude and reached southern Japan when the background ionosphere was extremely uplifted at medium and low latitudes due to the intense enhancement of an eastward electric field during the geomagnetic storms.

In addition to TID and EPB, high-resolution TEC maps can reveal ionospheric variations induced by lower atmospheric waves that are triggered by intense earthquakes. **Fig. 5** shows concentric waves detected in the detrended TEC map with a 10-min window about 70 minutes after the 2011 Tohoku earthquake [10]. These concentric waves in the ionosphere began to appear about 7 minutes after the onset of the earthquake at 14:46 JST (05:46 UT). The center of the concentric waves is located about 170 km to the southeast of the epicenter [11] (indicated by a star in **Fig. 5**) and near the estimated tsunami source [12]. Although the estimated extent of the focal region of the mainshock, a region of at least 450 km north-south and 200 km east-west [13], makes it necessary to consider the spatial scale of the mainshock and the tsunami source to reveal their precise positional relationship, it would be valid to consider the center of the ionospheric variation to be located southeast of the starting point of the rupture and located closer to the center of the estimated tsunami source area. This event helps to clarify the relationship between the ionosphere and the lower

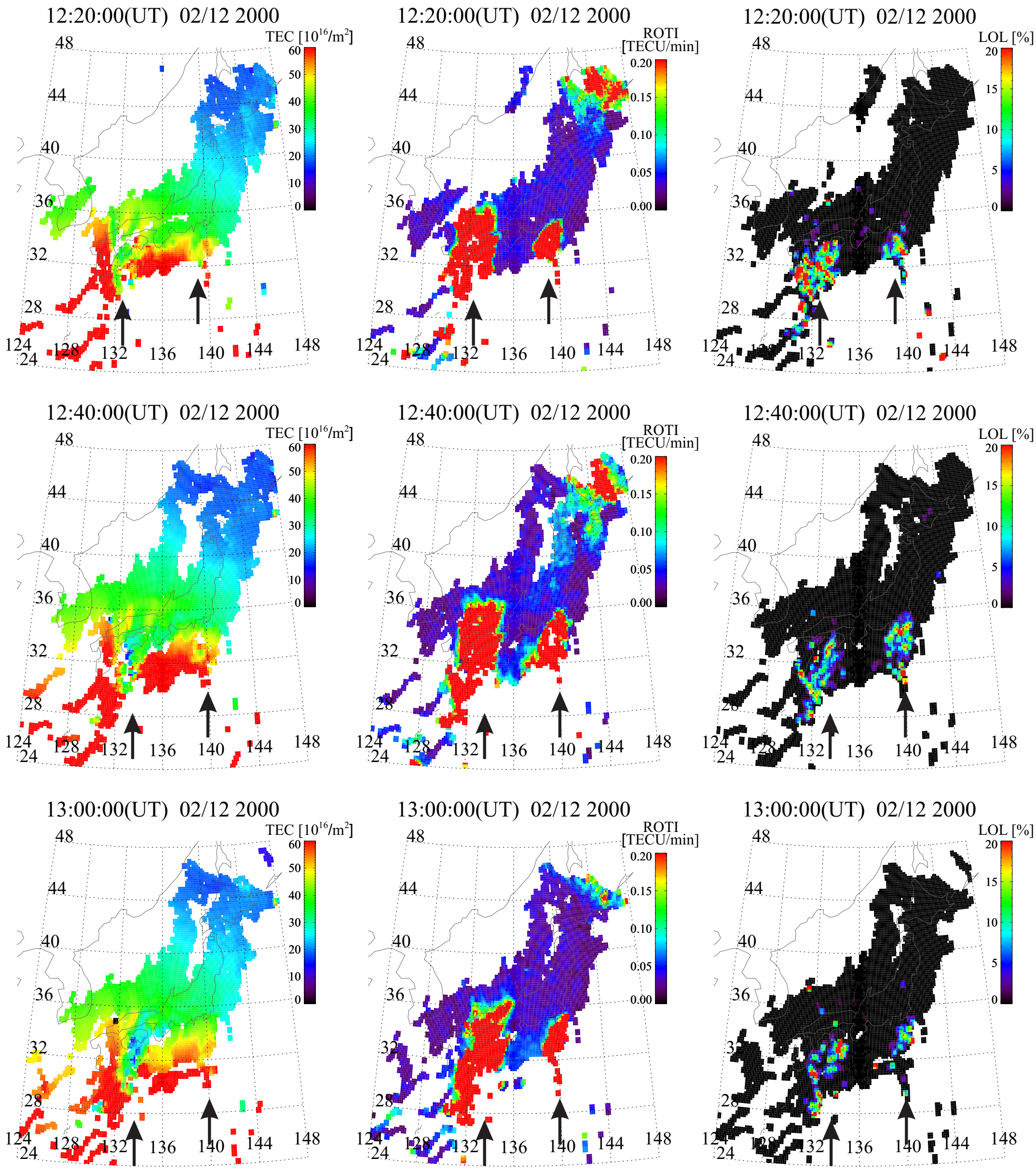


Fig. 4. Two-dimensional maps of absolute TEC (left), ROTI (middle), and loss-of-lock rate (right) 12:20–13:00 UT (21:20–22:00 JST) after the main phase of a strong geomagnetic storm on Feb. 12, 2000. Eastward moving plasma bubble structures designated by arrows were captured in absolute TEC maps.

atmosphere because of the clear causal connection. In addition, considering the fact that the ionosphere started to fluctuate about 7 minutes after the earthquake and that the center of the ionospheric variations corresponds closely to the tsunami source, further development of real-time ionospheric observation could allow us to monitor the tsunami arrival over a wide area. In order to clarify the quantitative relationship between a tsunami and ionosphere variation, it is necessary to research the generation and propagation mechanism of atmospheric waves while taking account of the spatial scale of the tsunami source.

3. DRAWING-TEC Project

As mentioned in the previous section, high-resolution, two-dimensional ionospheric density mapping using dense GNSS receiver networks is a powerful tool for monitoring medium-scale ionospheric variations, such as EPB and TIDs. We have collected all the available GNSS receiver data in the world to expand their observation area. **Fig. 6** shows the distribution of the GNSS stations as of 2017, more than 8000 stations whose data are collected by NICT. These GNSS data are provided by the International Geoscience Services (IGS), the University NAVSTAR Consortium (UNAVCO), Scripps Orbit and Permanent Array Center (SOPAC), and other global and regional data centers, totaling more than 50 data providers in all.

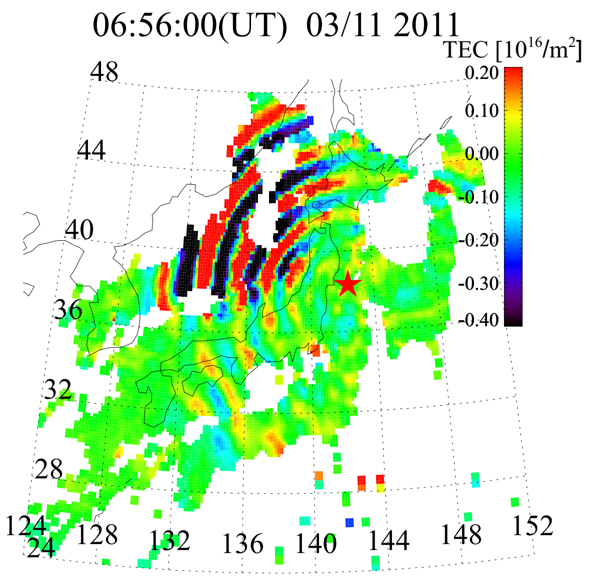


Fig. 5. Concentric waves detected by the detrended TEC map with 10-min window after the 2011 Tohoku earthquake. The star indicates the epicenter of the earthquake.

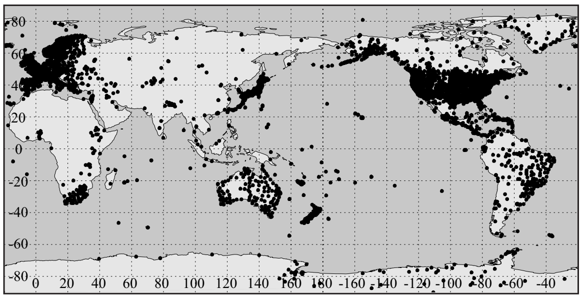
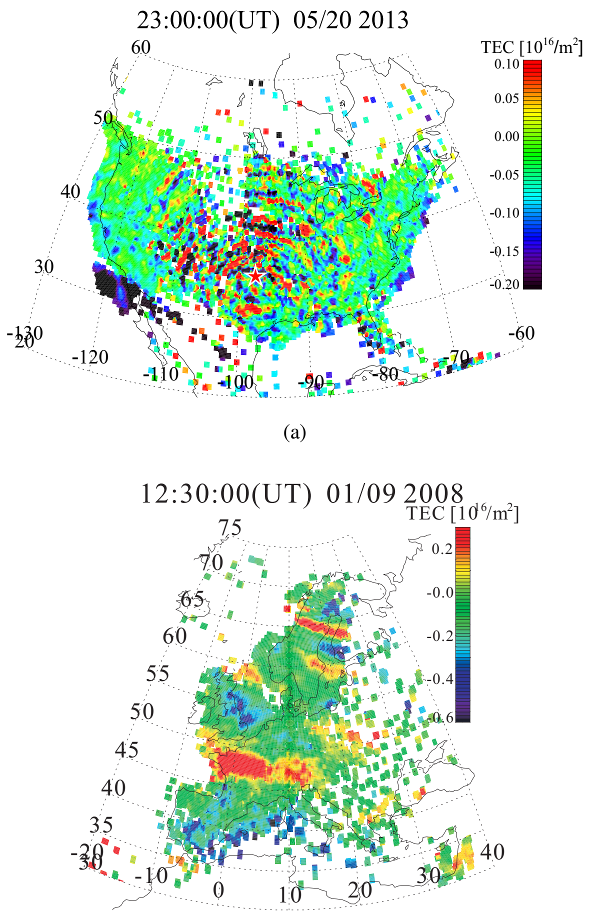


Fig. 6. Distribution of worldwide GNSS stations (more than 8000 stations as of 2017) whose data are routinely collected by NICT.



(a)

(b)

Fig. 7. (a) Concentric waves after the 2013 Moore EF5 Tornado over North America and (b) typical daytime MSTID over Europe, detected by the high-resolution detrended TEC maps.

In addition to Japan, dense regional GNSS receiver networks are available in North America and Europe. We have also provided high-resolution TEC maps of North America [14] and Europe [15].

Figure 7(a) shows concentric waves observed in the 20-min detrended TEC map over North America after the 2013 Moore EF5 tornado [16]. They were observed for more than 7 hours throughout North America. A comparison of the TEC observations and infrared cloud image from the GOES satellite indicates that the concentric waves are caused by supercell-induced atmospheric gravity waves. This observation is the first clear evidence of a severe meteorological event causing atmospheric waves propagating upward in the upper atmosphere and reaching the ionosphere.

Figure 7(b) shows a typical daytime medium-scale TID (MSTID) observed in the 60-min detrended TEC map over Europe [15]. MSTID can generally be classified into two types, nighttime and daytime MSTIDs, according to their appearance time and propagation direction. The typical nighttime MSTID shown in **Fig. 2** has a wavefront in the northwest-southeast direction and propagates southwestward in the northern hemisphere. On the other hand, the typical daytime MSTID has a wavefront elongated almost zonally and propagates almost southward in the northern hemisphere. Several characteristics of these MSTIDs, such as preferred directions and appearance times, are not adequately explained by the classical theory proposed by Hines [17], in which MSTIDs are an ionospheric manifestation of atmospheric gravity waves with great amplitude neutral wind oscillation. Recent observational and numerical simulation studies have suggested that the nighttime MSTID could be generated by electrodynamical forces with coupling between ionospheric E- and F-regions [18, 19]. Comparing characteristics of MSTIDs among different longitudes and latitudes using these high-resolution TEC maps can contribute to studies of mechanisms for generating both nighttime and daytime MSTIDs.

Currently, however, dense GNSS receiver networks are available only at limited areas, such as Japan, North

America, and Europe, as shown in **Fig. 6**. More GNSS receiver data are needed, especially in the sparse regions, namely, Asia, Africa, and the equatorial and polar regions, to study the overall spatial structure and temporal evolution of medium-scale ionospheric variations such as EPB and TID. The difficulty in collecting GNSS receiver network data in these regions may be attributed mainly to two reasons: one is a lack of information sharing of domestic GNSS receiver networks in the international ionospheric researcher community and the other is government and/or data provider policies to provide GNSS data only to domestic users. The second reason would be because GNSS receiver data include phase and pseudorange information that is quite valuable both commercially and militarily for various applications, such as precise positioning/navigation, meteorological observation, and ionospheric observation. In order to overcome this difficulty and to expand the high-resolution TEC observation area, we started a project, the Dense Regional and Worldwide International Networks of GNSS TEC Observation (DRAWING-TEC) in 2011.

The DRAWING-TEC project mainly consists of three subprojects:

1. Standardizing the GNSS-TEC data format for high-resolution TEC maps
2. Developing a new high-resolution TEC mapping technique using the standardized TEC data
3. Sharing the standardized TEC data and the data or information of GNSS receiver networks among the international ionosphere and GNSS researcher community.

Regarding item 1, one of the best-known standardized formats for GNSS-TEC data is the IONEX format [1]. Although the IONEX format data cover the global ionosphere, they describe only vertical TEC map data with a spatial resolution of 5° in longitude and 2.5° in latitude with a temporal resolution of 2 hours. Using the IONEX data, it is difficult to describe higher resolution TEC maps corresponding to the density of GPS/GNSS receiver networks. It is thus necessary to make a different format that could be applied in order to make the resolution of TEC maps flexible. We have developed a new standardized TEC format, GNSS-TEC EXchange (GTEX). The GTEX data format describes slant TEC for each GNSS satellite and is filed per day and per receiver, as is RINEX, the standardized GPS/GNSS format. The GTEX TEC format makes it possible to derive high-resolution TEC maps corresponding to the density of GNSS receiver networks, as shown in **Figs. 2** and **6**. Sharing the TEC data in the GTEX format would be easier than sharing the GPS/GNSS data among the members of the international ionospheric researcher community because the GTEX TEC data exclude information on GPS/GNSS data, except for information available as ionospheric observations. NICT, as a Japanese delegate to the International Telecommunication Union (ITU), first proposed the GTEX as a format for the international exchange and sharing of GNSS-TEC data. NICT submitted a contribution paper to meetings of Working Party 3L (ionospheric propagation and radio noise), Study Group 3 (SG3, radiowave propagation) of ITU-R in Geneva, Switzerland in Jun. 2013. The GTEX format was successfully approved as one of the standard data formats for trans-ionospheric data and included in Recommendation ITU-R P.311-16 Annex 1 in 2015 [20]. It was used by the Ionospheric Studies Task Force of the International Civil Aviation Organization (ICAO) Asia-Pacific Region as a standard format for sharing TEC data in the region to characterize the ionospheric behavior for aeronautical applications of GNSS [21].

Regarding item 2, we have developed the RNX2GTEX application in Linux and Windows versions to convert GPS/GNSS data to GTEX TEC data. Such applications are necessary to increase the numbers of GTEX-TEC users and data and to promote ionospheric studies. RNX2GTEX for Linux/Unix consists of a set of programs written in Fortran 77 and a shell script. RNX2GTEX for Windows is an application for creating GTEX data files from RINEX data using an Explorer-like GUI. These applications are open to the public and are available on the DRAWING-TEC website: http://seg-web.nict.go.jp/GPS/DRAWING-TEC.

Item 3 would be the most important to expand the TEC observation area and to promote studies of medium-scale ionospheric variations and their effect on GNSS. We have developed the GTEX database (ver. 1.0), which was derived from all the available online GNSS receiver data from 2000 to the present. This database is available via the DRAWING-TEC website on a request basis. NICT first conducted to form the Asia-Oceania Space Weather Alliance (AOSWA) [22] to share data and other information related to space weather in the Asia and Oceania regions. The 1st AOSWA workshop was held in Chiang Mai, Thailand in February 2012, hosted by NICT and Chiang Mai University. In this workshop, 76 space weather researchers from 30 organizations in 10 counties in the Asia-Oceania region discussed data and information of TEC and GNSS receiver networks. Since the first AOSWA workshop, we have started GTEX data sharing with some foreign institutes, such as King Mongkut's Institute of Technology Ladkrabang (KMITL) in Thailand and the Universiti Kebangsaan Malaysia (UKM) in Malaysia, to develop dense wide-coverage TEC maps, especially of the Asia-Oceania region.

One successful outcome of the DRAWING-TEC project has been the detection of EPB structures in two-dimensional TEC and ROTI maps in the Southeast Asia region. These maps were produced using 127 GNSS stations from the Malaysia Real-Time Kinematics GNSS Network (MyRTKnet), the Sumatran GPS Array (SuGAr), and the IGS International GNSS Service (IGS) networks, as shown in **Fig. 8** [23]. Although the equatorial region is one of the regions where it is difficult to use dense GNSS receiver network data for ionospheric research, reference [23] utilized these dense GNSS receiver networks in Southeast Asia to study the two-dimensional structure of ionospheric plasma irregularities and revealed latitudinal/longitudinal variations of EPBs, including the spatial periodicity of the EPBs, which could be associated with a wavelength of the quasiperiodic structures on the bottom side of the ionosphere seeding the Rayleigh-Taylor instability.

KMITL plays an important role in collecting GNSS data from different networks in Thailand. Currently, there are 22 GNSS stations operated by Japanese partners, including NICT, Kyoto University, and the Electronic Navigation Research Institute (ENRI) as well as Thai partners including KMITL, Chulalongkorn University, Chiang Mai University, the Department of Public Works and Town and Country Planning (DPT), and Aerothai. GNSS and GTEX data are available on the Thai Space Weather Information Center website: http://iono-gnss.kmitl.ac.th. By employing the TEC data in Thailand, the predawn plasma bubble cluster was detected after the reported disappearance of plasma bubbles [24].

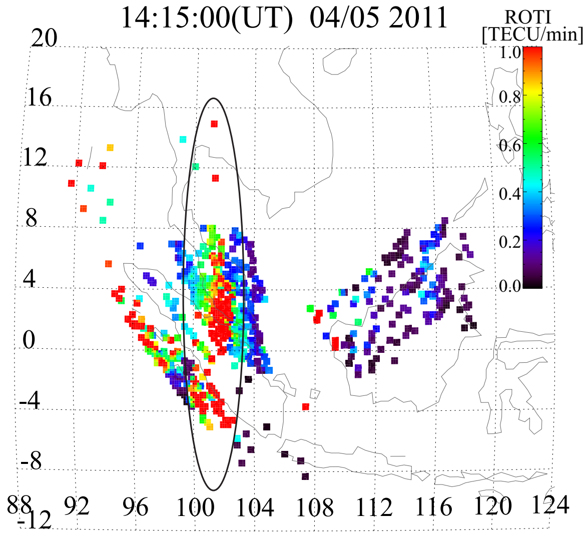


Fig. 8. A clear EPB structure (designated by an oval) detected in a two-dimensional ROTI map of Southeast Asia produced using 127 GNSS stations.

4. Summary and Future Perspectives

Several medium-scale (100 km to 1,000 km scale) ionospheric variations caused by TID and EPB can degrade GNSS positioning/navigation. Medium-scale concentric waves have recently been detected after huge earthquakes and severe meteorological events. However, these medium-scale ionospheric variations have not been sufficiently studied due to the lack of dense, wide-area ionospheric observations. We have developed a high-resolution, two-dimensional TEC observation system using dense regional GNSS receiver networks and studied the medium-scale ionospheric variations. It is necessary to expand the observation area for the study of the overall spatial structure and temporal evolution of ionospheric variation and their effects on GNSS positioning and navigation. We are conducting the DRAWING-TEC project to expand the observation area using all the available GNSS receiver networks through the collaboration of ionosphere and GNSS researchers in the world. This project consists of (1) standardizing GNSS-TEC data, (2) developing dense TEC mapping techniques, and (3) sharing the standardized TEC or GNSS receiver data throughout the world. We have developed a new TEC data format, GTEX, as well as a RINEX-to-GTEX data conversion application, RNX2GTEX. GTEX has been included in Recommendation ITU-R P.311-16 Annex 1. GTEX and/or GNSS receiver data sharing has expanded in some regions, such as Southeast Asia, and has revealed new characteristics of EPB.

Although we believe the DRAWING-TEC project will promote studies of medium-scale ionospheric variations and their effect on GNSS, there are still some challenges to their further promotion. The first one is upgrading the application to use multi-GNSS. In recent years, in addition to the United States' GPS, Japan's Quasi-Zenith Satellite System (QZSS), Russia's GLONASS, the European Union's Galileo, China's BeiDou, etc., have been widely used as global satellite navigation systems. By using the data of all the available GNSS, it becomes possible to observe the ionosphere more broadly and more densely. Currently, however, the RNX2GTEX application only supports GPS data. It is necessary to upgrade it for multi-GNSS compatibility. The GTEX format for multi-GNSS data may also need to be optimized, though the current version of GTEX format can support multi-GNSS. One of the other challenges is the use of GNSS data over the ocean, which is a large area devoid of high-resolution ionospheric observations. Permanently operated GNSS receiver networks are generally limited to land areas with much social or crustal activity. Although there are a few GNSS buoy networks, such as the Nationwide Ocean Wave information network for Ports and HArbourS (NOWPHAS) [25], to monitor ocean waves, their distribution is limited to narrow coastal areas (less than 20 km from the coast), and their recorded data are currently limited to wave information. Reference [26] proposes the new idea of establishing a dense buoy network in the western Pacific by implementing multi-instrument buoys that include GNSS receivers far from the coast. If the GNSS observation data of such a wide-coverage, dense GNSS buoy network becomes available, it will be a breakthrough system not only for tsunami monitoring but also for ionospheric monitoring, which can contribute to the estimation of tsunami source areas and the forecasting of tsunami arrivals.

GNSS positioning/navigation has become an indispensable infrastructure not only for military and aeronautical applications but also for public use in recent years, as car navigation systems and smartphones have become popular. In addition, more precise and uninterrupted GNSS navigation is required in the fields of agriculture, construction, mining, and self-driving cars. Frequently observed medium-scale ionospheric variations can degrade GNSS positioning/navigation and, in the worst case, make it unusable due to loss-of-lock on GNSS signals. For the safe use of GNSS positioning/navigation and the improvement of its precision and availability, it is necessary to monitor the ionospheric variations more precisely over a wider area and produce more adequate augmentation information. The DRAWING-TEC project can contribute to the safe and advanced use of GNSS in society now and in the future.

Acknowledgements

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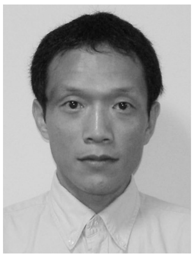

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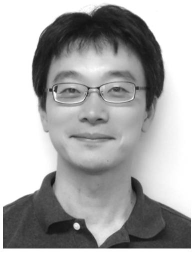

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