GNSS-Based Radio Tomographic Studies of the Ionosphere at Different Latitudes

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ABSTRACT

We present the results of ionospheric imaging by the radio tomographic (RT) methods based on the Navigation Satellite Systems (GNSS). GNSS include the first-generation low orbiting (LO) systems (Tsikada, Transit, etc.) and second-generation high orbiting (HO) systems (GPS and GLONASS, which have been put in operation, and Galileo, BeiDou, and QZSS systems, which are currently under development in Europe, China, and Japan). The GNSS constellations and the networks of ground receivers are suitable for probing the ionosphere along different rays and processing the obtained data by tomographic inversion procedures. The results discussed in this work are obtained by the methods of low orbiting and high orbiting radio tomography (LORT and HORT, respectively). We present the examples of tomographic images of the subequatorial, midlatitude, subauroral, and auroral ionosphere in different regions of the world. The RT images of the Arctic ionosphere demonstrate different structures (characteristic circumpolar ring structures, ionization patches, tongues of ionization (TOIs), etc.) The GNSS RT methods are suitable for imaging the ionospheric disturbances caused by the tsunami wave propagation. We analyze the ionospheric disturbances after the strongest Tohoku earthquake in Japan (March 11, 2011). The RT reconstructions are compared to the measurements by the ionosondes and Global Ionospheric Maps (GIM).

1. INTRODUCTION

The existing GNSS constellations and the corresponding networks of ground receivers make it possible to probe the ionosphere along different directions and to apply the RT methods to reconstruct the spatial distributions of electron concentration in the ionosphere. The sets of rays connecting the radio transmitters onboard the LO and HO satellites with the ground receivers intersect the near-Earth environment. The measurements along these rays give the group delays and phase paths data (in the case of LORT, only the phase paths) on the corresponding rays. Thus, by measuring satellite radio signals along these sets of rays, one implements radio probing of the ionosphere along different directions, which provides the integrals (differences of the integrals) of the refractive index of the near-Earth environment. The set of such integrals is suitable for applying the RT approaches.

Different types of RT are referred to as the low-orbiting and high-orbiting ionospheric RT (LORT and HORT, [1-6]). In the linear statement of RT problem, the horizontal and vertical resolution of ray RT is 20-30 km and 30-40 km, respectively. By taking into account the refraction of rays, one can improve the resolution of LORT imaging to 10-20 km, which makes this method suitable for studying the fine structure of the ionosphere. The HORT problems are specific by high dimensionality and essential incompleteness of the data. Due to the relatively slow motion of the GPS/GLONASS satellites, in the HORT problems we should take into account the time variations of the ionosphere, which leads in the 4D tomographic problems (three spatial coordinates and time). It is necessary to introduce the additional procedure of interpolation of the found solutions in the regions where the data are absent or, alternatively, to search for a smoothed (averaged) solution [5]. The nonuniform coverage of different territories by the receiving networks precludes from reaching the vertical and horizontal resolution of HORT higher than 100 km with a time step 60-20 min. In the regions with dense receiving networks (Europe, USA, Alaska, Japan), resolution can be improved up to 30-50 km with a time interval of 30-10 min between the neighboring HORT snapshots. The spatial resolution of 10-30 km and a time step of up to 2 min between the successive images can only be achieved in California and Japan, where the GPS/GLONASS receiving networks are extremely dense.

3. THE EXAMPLES OF RT IMAGES

The studies in the different regions of the world (Europe, North America, and Asia) have shown the RT methods are an efficient and versatile instrument for reconstructing various ionospheric structures from GNSS data. These methods were successfully applied for studying the equatorial anomaly (EA), ionization troughs, complicated distributions of ionospheric plasma with numerous depletions and enhancements, traveling ionospheric disturbances (TIDs), blobs, patches, tongues of ionization, etc. [1-4, 7-9]. In contrast to the ionosondes, which use HF radio waves, the LORT and HORT approaches are not only highly efficient during the undisturbed periods. These methods are also suitable for studying the ionosphere during the magnetic storms since the absorption can be typically disregarded in the LORT and HORT problems due to the high frequency of the used radio signals.

The example in Fig. 1 illustrates the evolution of the ionospheric trough above Europe on October 8, 2012 (Kp = 4). The vertical TEC maps calculated from the four-dimensional (4D) HORT images show a wide and deep trough emerging at 58N-63N at 20:00UT. During three hours after its formation (from 21:00 to 23:00 UT), the trough gradually splits and migrates south. The evolution of the trough above the North America on October 8 and 9, 2012 (01:00-03:00 UT) is illustrated in Fig. 2. It can be seen that during the geomagnetic storm on October 9, 2012 (Kp = 6), the trough was located significantly further south (40N-50N) (bottom panel, Fig. 2).

The LORT experiments at the low-latitude Manila-Shanghai chain in the South-East Asia revealed several structural peculiarities of EA, which are caused by the fountain effect. Namely, it was established that the mature EA core (the area where the electron density is close to maximal) in the post-noon ionosphere is aligned with the geomagnetic field; the flanks of EA are strongly asymmetric; and the thickness of the ionospheric layer experiences noticeable variations [7]. Typically, the crest of the anomaly migrates from the east to west; the patterns of the structure and dynamics observed during the geomagnetic storms are more complicated [10, 11]. This is illustrated in Fig.3, which shows the vertical TEC maps for different time intervals during the geomagnetic storm of December 15, 2006. In this case, the ionospheric plasma distribution in the EA region is highly structured. The observed complicated plasma pattern with numerous spots of increased and decreased TEC was formed, inter alia, by the particle precipitation [10].

We have also carried out RT studies in the Arctic region. The RT images reveal the structures which can probably be interpreted as the tongues of ionization, i.e. large flows of the dayside ionospheric plasma entrained antisunwards by the convection from the dayside to the nightside ionosphere through the polar cap. The plasma flows are structured into the patches (regions with enhanced ionization attaining 10 000 km lengthwise and 1500 across the flow, characterized by steep gradients of electron concentration, and observed in the high-latitude and polar ionosphere). Figure 4 shows the examples of these structures. The zone of enhanced ionization in the reconstructions stretches from the dayside ionosphere (American sector) to the nightside ionosphere (European sector).

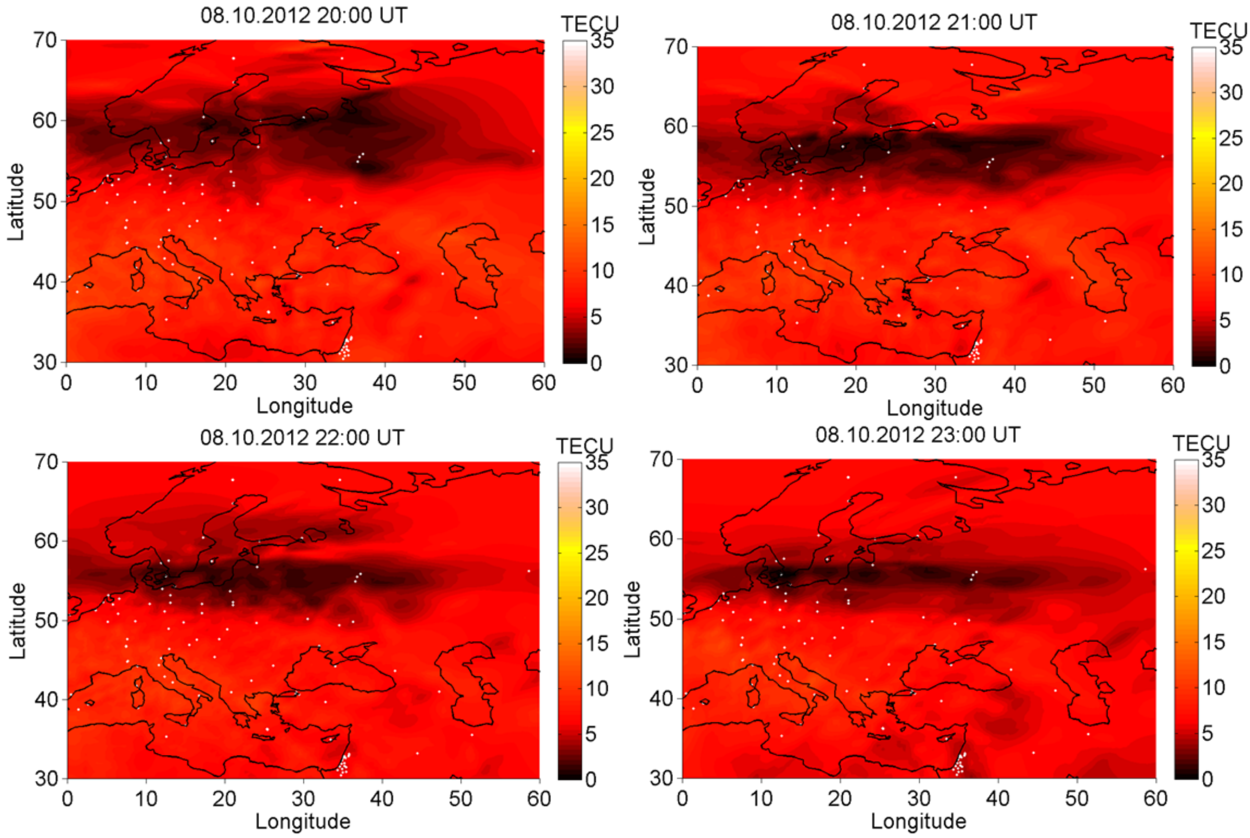

Figure 1. The example of evolution of the ionization trough above Europe on October 8, 2012, 20:00-23:00 UT

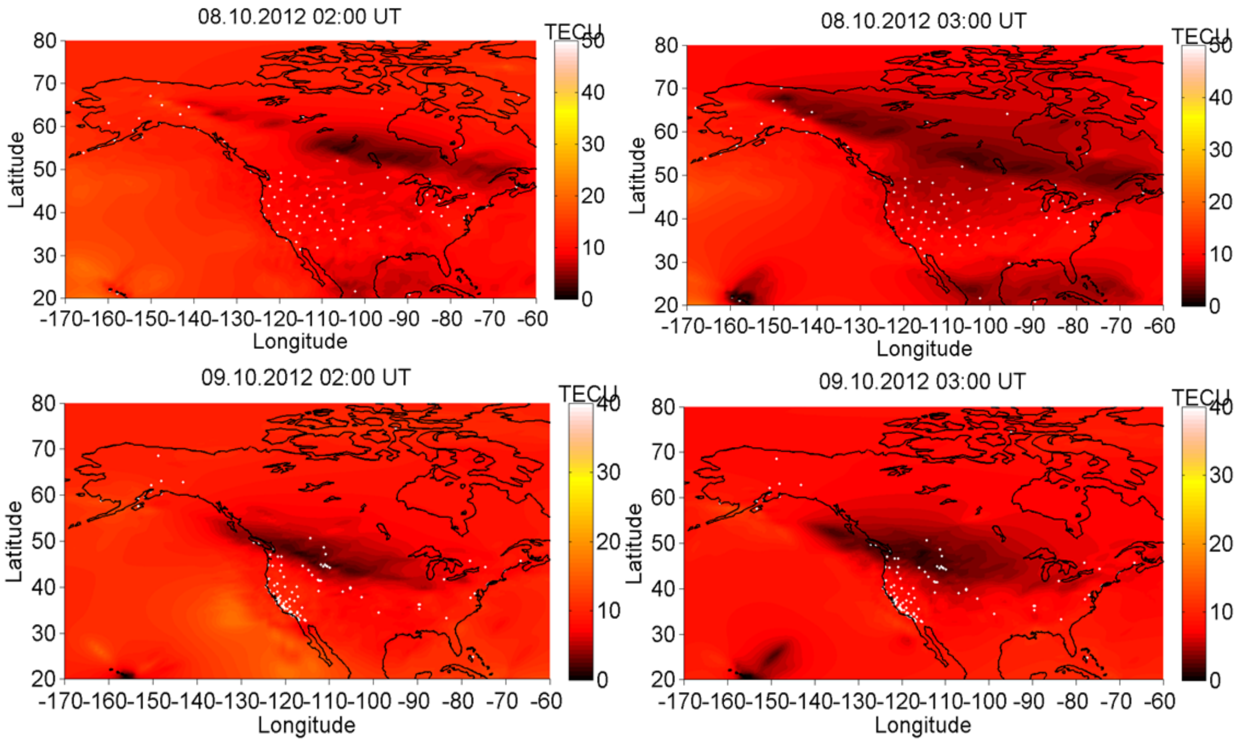

Figure 2. The example of evolution of the ionization trough above North America on October 8 and 9, 2012, 02:00-03:00 UT

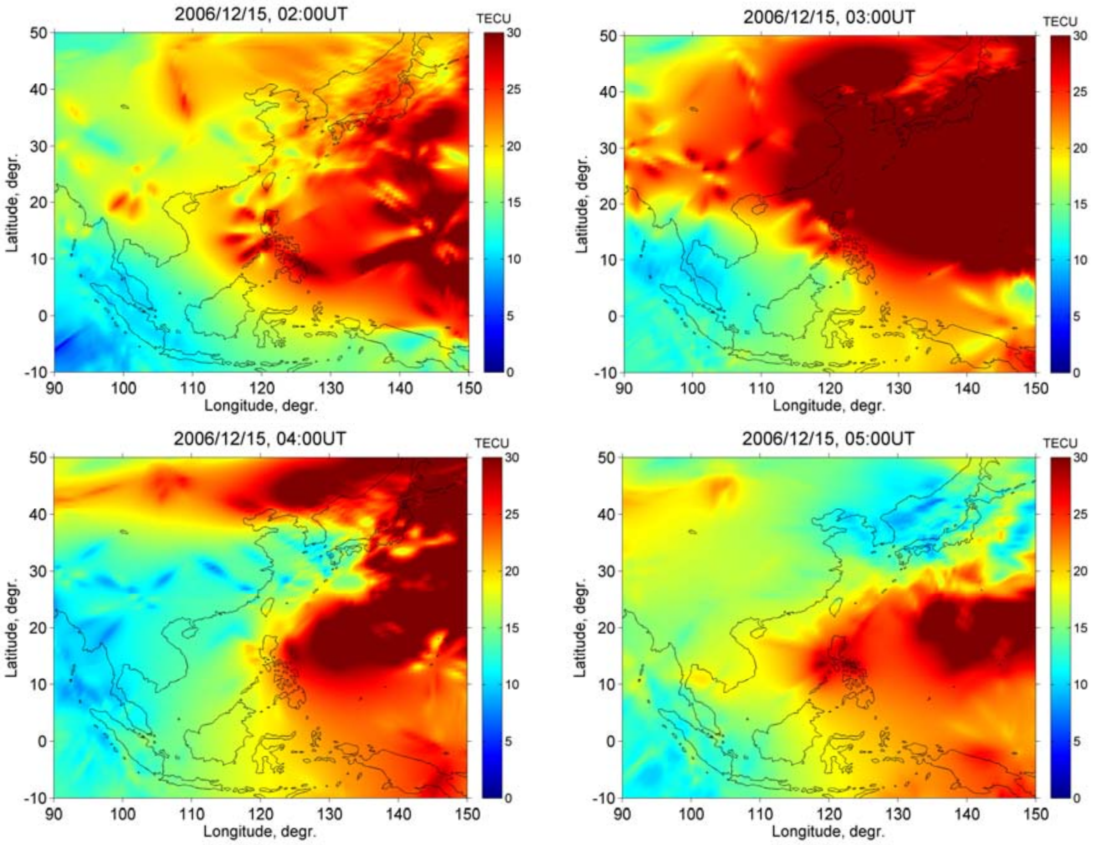

Figure 3. TEC maps in the South East Asia during the geomagnetic storm on December 15, 2006 (02:00UT-05:00UT)

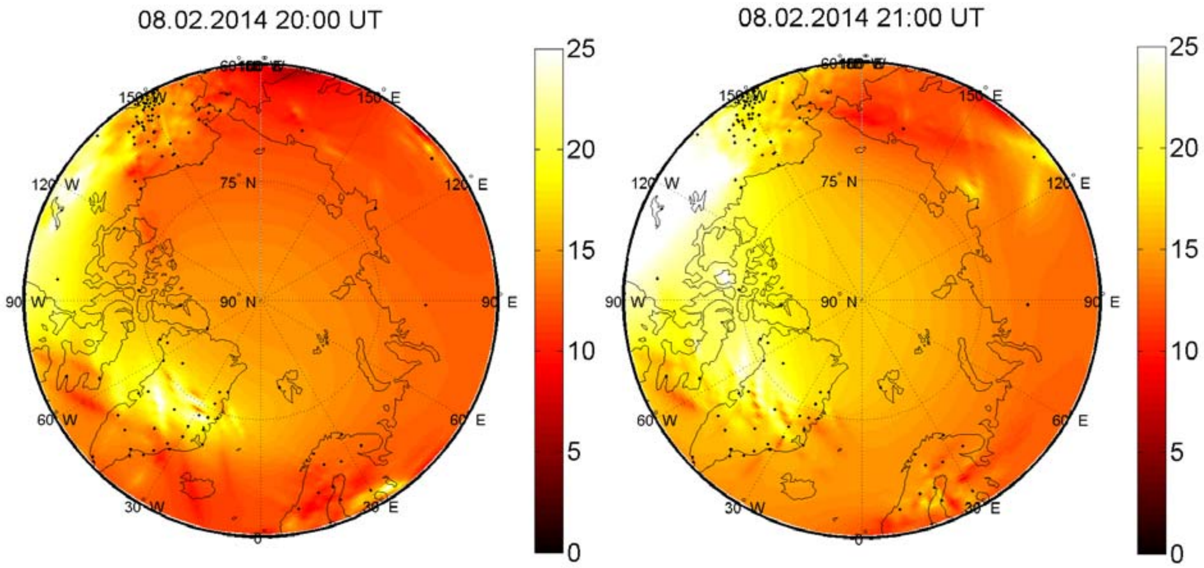

Figure 4. TEC maps above the Arctic region on February 8, 2014 (20:00 and 21:00 UT.)

At 20:00, the highly ionized region in the central part of Greenland was fragmented into a series of large structures with high TEC (up to 25 TECU) separated by narrow linear zones of depleted plasma (up to 10 TECU). In the ionosphere above the northwestern USA in the region covered by dense GPS receiving network, there is a region with complicated ionization distribution with numerous “spots”. The pattern of ionization in the RT image at 21:00 UT is generally similar to the distribution identified at 20:00; however, the background ionization within the TOI is higher, and the very flow of high TEC is wider. Local patches are observed above Scandinavia and Siberia.

We carried out numerous comparisons of the LORT and HORT images with the measurements by the ionosondes in Europe, Russia, America, and South East Asia. The example in Fig. 5 shows the LORT image of the ionosphere above the U.S. West Coast (left) and the geometry of the RT experiment (right) (the positions of the receivers and COSMOS-2407 satellite trajectory are depicted). TEC maps above North America are shown in Fig. 6. The HORT and LORT reconstructions are similar; the deep trough at 48-52N is observed in both the LORT and HORT images.

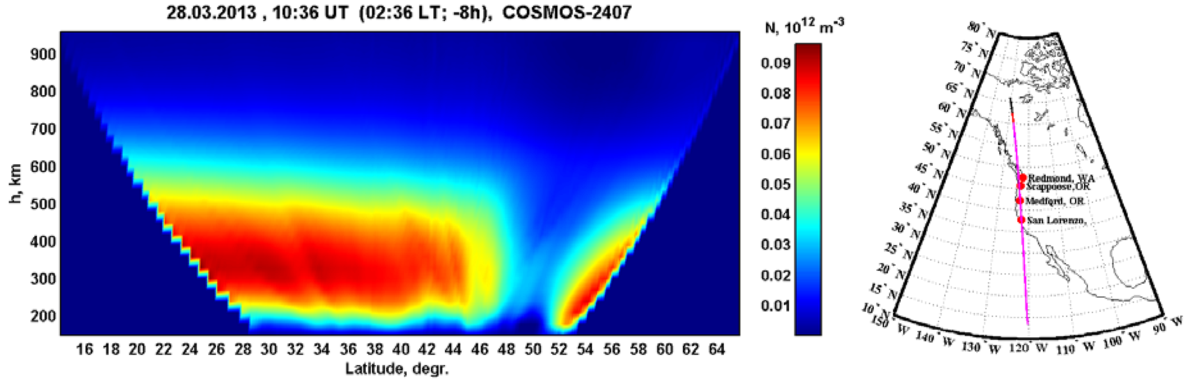

Figure 5. LORT image of the ionosphere on March 28, 2013, 10:36UT, and the geometry of the experiment

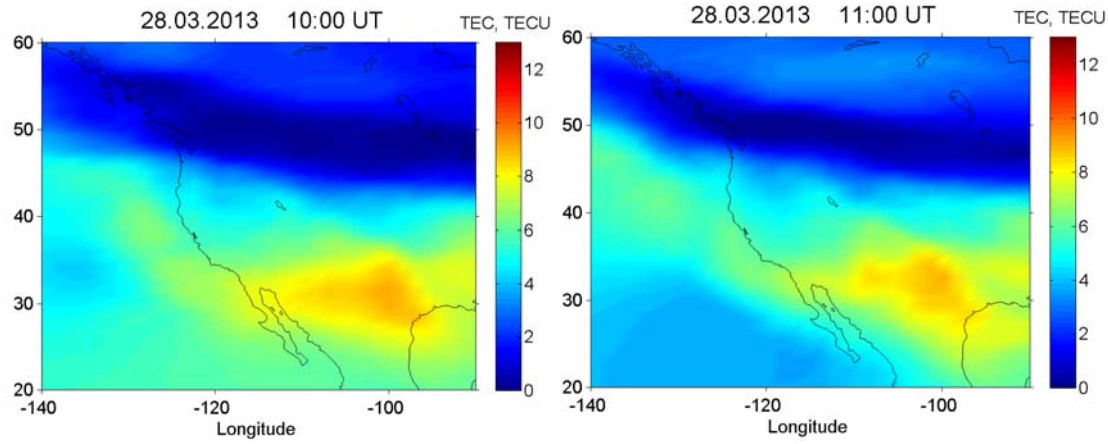

Figure 6. TEC maps above North America on March 28, 2013, 10:00-11:00UT

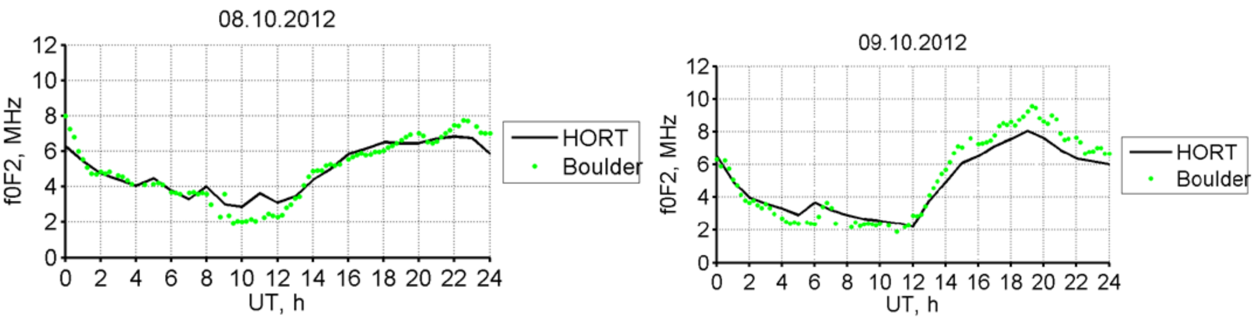

Figure 7. The comparison the HORT-based critical frequencies with the ionosonde measurements at Boulder on October 8, 2012 (left) and on October 9, 2012 (right)

Figure 7 illustrates the variations in critical frequency f_0F2 on October 8 and 9, 2012, which were calculated for the region of North America from HORT reconstructions and Boulder ionosonde data. The analysis based on thousands of comparisons indicates that the diurnal behavior of f_0F2 retrieved from HORT quite closely agrees with the ionosonde data. The discrepancies in critical frequencies are far below 0.5 MHz during the geomagnetically quiet periods and above 1 MHz during the disturbances.

We applied HORT analysis to study the ionospheric perturbations above Japan after the Tohoku mega-earthquake. The time resolution (interval between the successive images) was 2--4 min. The perturbations in vertical TEC one hour after the main shock are displayed in Fig. 9 [12].

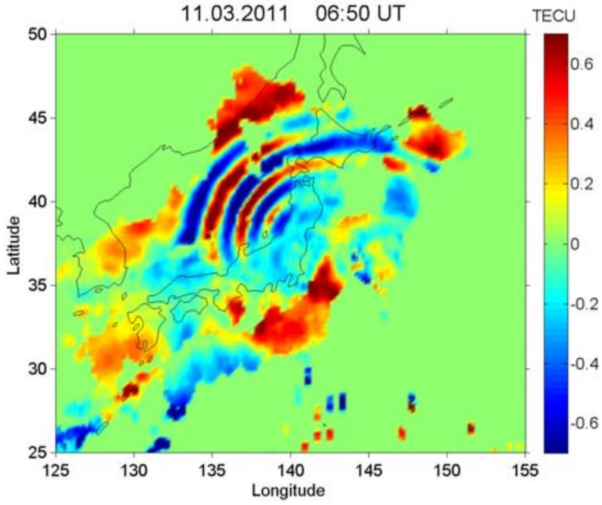

Figure 8. The TEC waves, caused by the AGW from the Tohoku mega-earthquake, diverging from the epicenter of the event.

Since recently, 2D Global Ionospheric TEC Maps (GIM) generated from the IGS data with the assumed thin shell model have become widely used in the ionospheric research. Considering this, we compared the GIM maps with the RT images. The maps of vertical TEC derived from the GIM maps and HORT reconstructions on March 9, 2012 at 00:00 UT are shown in Figs. 8 and 9.

A deep ionization trough at 58N-60N and local ionization features above Scandinavia are observed in the HORT reconstruction (Fig. 8). In contrast to HORT, the smooth GIM map (Fig. 9) does not resolve the ionization trough. The local irregularities, distinctly pronounced in the HORT images, are smoothed out in the GIM maps, where they form a single (continuous) extended area of high ionization above Scandinavia. The GIM-based TEC are higher than the corresponding HORT-based values. The GIM data are generally smoother than the results provided by HORT.

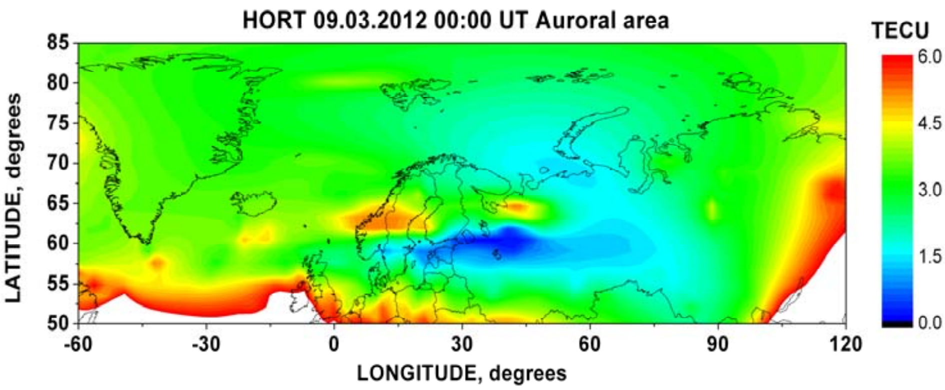

Figure 9. Vertical TEC map based on HORT, March 9, 2012, 00:00UT

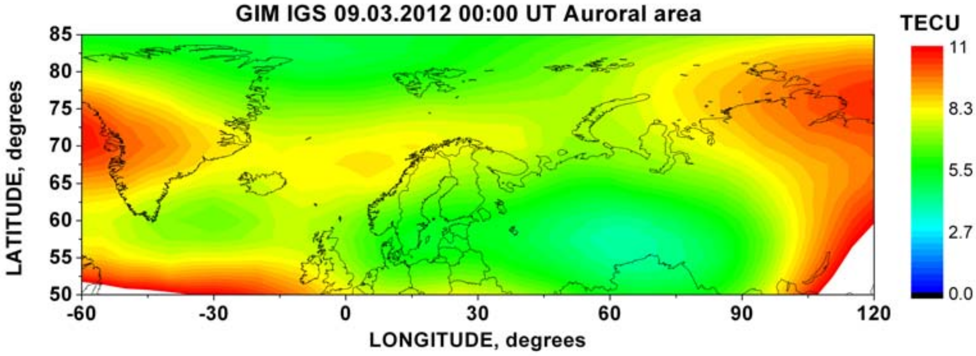

Figure 10. Vertical TEC map based of GIM, March 9, 2012, 00:00UT

During the severe geomagnetic disturbances, when the structure and dynamics of the ionosphere experience strong and rapid variations, the smoothed GIM TEC distributions can drastically differ from both the HORT TEC and almost instantaneous LORT TEC snapshots. The GIM TEC data during these periods should be used with caution.

4. CONCLUSIONS

The existing systems implementing the radio occultation (RO) approach (FormoSat-3/COSMIC and other systems that record the signals from the GPS/GLONASS satellites at HO satellites) provide the quasi tangential projections of electron density *N*. The combination of the RT and RO methods, which supports the RT data by the probing data on the satellite-to-satellite paths (RO data), can significantly improve vertical resolution of RT reconstructions. The existing UV sounder systems (GUVI, SSULI) provide the integrals of *N* squared. In this case, the data from UV sounders can be incorporated into the common tomographic iterative scheme; however, the data should be consistent in terms of accuracy. The combination of LORT and HORT systems provides significant advantages: HORT yields 3D distributions of the ionospheric plasma over vast regions, and LORT provides significantly higher resolution.

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