Radio tomography imaging based on navigation systems

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Abstract

Methods of radio tomography (RT) based on the low- and high-orbital navigational systems and radio occultation data are considered. Examples of RT imaging of the ionosphere in different regions of the world illustrate the use of low-orbital and high-orbital radio tomography (LORT and HORT, respectively) separately and in combination with each other. RT methods allow studying of various ionospheric structures: troughs, travelling ionospheric disturbances (TIDs), spots of enhanced ionizations, patches, blobs, wavelike structures, manifestations of particle precipitation. The possibilities for the application of RT systems together with other methods of UV and radio sounding are discussed.

1. Introduction

Methods of ionospheric radio tomography (RT) using satellite navigation based on low-orbiting (LO) satellite systems like the American Transit and the Russian Tsikada are actively developed during two past decades. Presently, there are about ten receiving systems of LO tomography operating in different regions of the world. In recent years, receiving networks of high-orbital (HO) satellite navigation such as the American GPS, the Russian GLONASS, and the European Galileo are advancing rapidly. To date, there are thousands receivers of high-orbital satellite signals. The international IGS networks includes about fifteen hundred receivers. Another satellite-based systems are those intended for UV sounding and the FormoSat-3/COSMIC satellite system for receiving the GPS radio signals and making UV measurements. We present and discuss the results of studying the structure and the dynamics of the ionosphere with combinations of different methods based on different RT systems.

2. Radio tomography using low-orbital satellite navigation

The ionospheric studies based on the low-orbiting navigational satellite systems started to develop more than 20 years ago [1-3]. The methods of ionospheric radio tomography allow reconstructing the spatial distributions of electron concentration from the data obtained in the experiments on ionospheric radio sounding. In LORT experiments, two coherent satellite signals at 150/400 MHz transmitted from the satellite are measured at a network of several ground-based receiver stations arranged along the satellite path and spaced by a few hundred kilometers from each other. With such systems it is possible to reconstruct 2D RT images of electron density distributions in a plane containing the satellite path (height-latitude cross-sections) witin a latitudinal span of several thousand kilometers for a time interval of 10-20 minutes. The resolution of LORT may reach 20-30 km and even 10 km, if the receiving networks are sufficiently dense and the ray bending is taken into account. LORT methods were successfully applied to study various ionospheric irregularities such as troughs, crests of the equatorial anomaly (EA), manifestations of particle precipitation, spots of ionization, bubbles, wave and wavelike structures, travelling ionospheric disturbances related to AGW, and many others. Examples of reconstructing the aforementioned structures are discussed in our presentation. The analysis of LORT images allowed us to reveal some unprecedented details of the EA: orientation of the matured "core" of EA in the direction of geomagnetic field, noticeable asymmetry between the southern and northern edges of EA, penetration of the plasma flow into the *E*-region ionosphere caused by the "fountain-effect" and other [4]. LORT technique is suitable for providing not only two-dimensional cross-sections of ionospheric plasma density but also plasma fluxes by analyzing time-successive RT images [5]. Examples are given of determination, from experimental data, of average vertical fluxes and 2D plasma fluxes in the ionosphere. LORT images of equatorial, midlatitude, subauroral and auroral ionosphere obtained in different conditions of solar and geophysical activity are presented. We compare the ionization in the upper atmosphere inferred from the LORT cross-sections with the fluxes of ionizing particles measured by DMSP satellites. Multiextremal patterns of ionization and wavelike disturbances with spatial scales ranging from tens to

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hundreds kilometers are revealed in the RT images of the ionosphere during the geomagnetic storms. In this case, the spatial scales of the corpuscular precipitations widely varied from few to ten degrees in latitude [6].

The results of studying the structure of the ionospheric plasma distribution from data obtained at the transcontinental Russian radio tomographic chain, which is the world's longest, are presented. The 4000 km long tomographic chain extends from the Svalbard Archipelago to Sochi. The unique feature of this upgraded radio tomographic system is that for the first time observations cover a wide sector of the ionosphere from high latitudes (polar cap and auroral region) to low latitudes. As an example, Fig.1 shows the ionospheric LORT cross-section above the Sochi—Moscow—Svalbard chain. Around Svalbard Archipelago (78°-79°) wavelike disturbances on the scale of the order of 50 km are revealed. In the central part of the image (59°–67°) we observe an almost halved electron concentration compared to its maximum values in the south and in the north flanks. Quasi-wave structures with scales of 50–150 km are clearly seen in the south part of the reconstruction within latitudinal interval 42°-55°. Fig. 2 shows fragment of RT reconstruction of the ionosphere between Svalbard and Sochi on March 03, 2010 at 14:43 UT. Ionospheric trough is revealed at about 68°. To the south from the trough within the latitudinal interval 60°—67°, about four maxima of TIDs with a period of about 100-150 km are revealed. Taking into account the geometry of the experiment and the characteristic tilt of TIDs, we may suppose that they are propagating from the north. These examples of RT images correspond to practically quiet geomagnetic conditions (the Kp index does not exceed 2.7). Thus complex structure of plasma distribution is observed even in the undisturbed ionosphere.

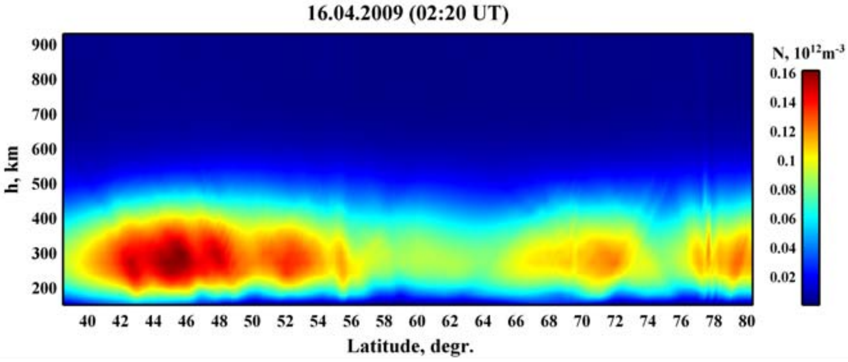

Figure 1. Example of LORT image of the ionosphere above Sochi - Svalbard chain on April 16, 2009 at 02:20UT

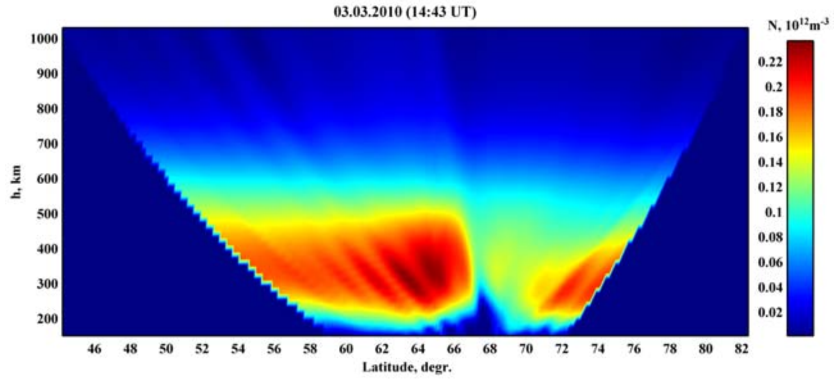

Figure 2. Fragment of LORT image of the ionosphere above Russian chain on March 03, 2010 at 14:43UT

3. Radio tomography using high-orbital satellite navigation

Satellite Navigation by GPS, GLONASS, Galileo opens new possibilities for studying and monitoring the ionosphere and plasmasphere [3, 6]. However, low angular velocity of high-orbital satellites makes the allowance for the temporal variability of the ionosphere an issue of key importance. This means that the radio tomographic problem should be stated in its 4D formulation (three spatial coordinates and time). The major specific features of the 4D RT problem are its large dimensionality and essential incompleteness of the data. Unlike the 2D LORT, 4D HORT requires either an additional procedure for the interpolation of the obtained solutions in the regions of missing data, or finding of a smoothed solution. The spatial resolution of HORT is noticeably lower than that in case of LORT; horizontal resolution is, as a rule, about 100 km. A higher resolution can be reached only with very dense receiving networks such as those in Japan and California [3, 6]. HORT reconstructions of the ionosphere were carried out in different regions of the world and in different solar-geophysical conditions. The HORT results are well supported by the data of the global ionosonde network. This study clearly demonstrates the potential of HORT method in the investigation of very complex ionospheric structures including the cross-polar plasma flows observed during strong ionospheric storms. Fig.3 illustrates the evolution of the ionospheric trough above Europe in the evening on April 17, 2003. The severalfold widening of the trough accompanied by the background general night-time decrease in electron density is clearly seen on TEC maps (Fig. 3a,b) and in the submeridional vertical cross-sections along 21°E (Fig. 3c,d). Fig.4 displays the anomalous enhancements in electron density (up to $3 \cdot 10^{12}$ m^{-3}) in Arctic region during the geomagnetic storm of October 29-31, 2003. The increase in electron concentration in the nightside ionosphere is due to the convection of plasma from the dayside to the nightside. Regions of enhanced ionization often look like "tongues" with irregular "spotty" structure (Fig. 4a,b) apparent also in the vertical cross-sections (the cross-sections along the lines indicated on TEC maps) (Fig. 4c,d). Such complex structure of the irregularities is perhaps associated with the ionospheric plasma instability and different-scale wavelike structures. An example is presented in Fig. 5, where the vertical TEC inferred from HORT reconstructions in Arctic are shown in a grayscale (from 0 to 5 TECU). Interesting circumpolar ring-shaped structures associated with the plasma flows from the dayside ionosphere to the night-side are apparent in the image.

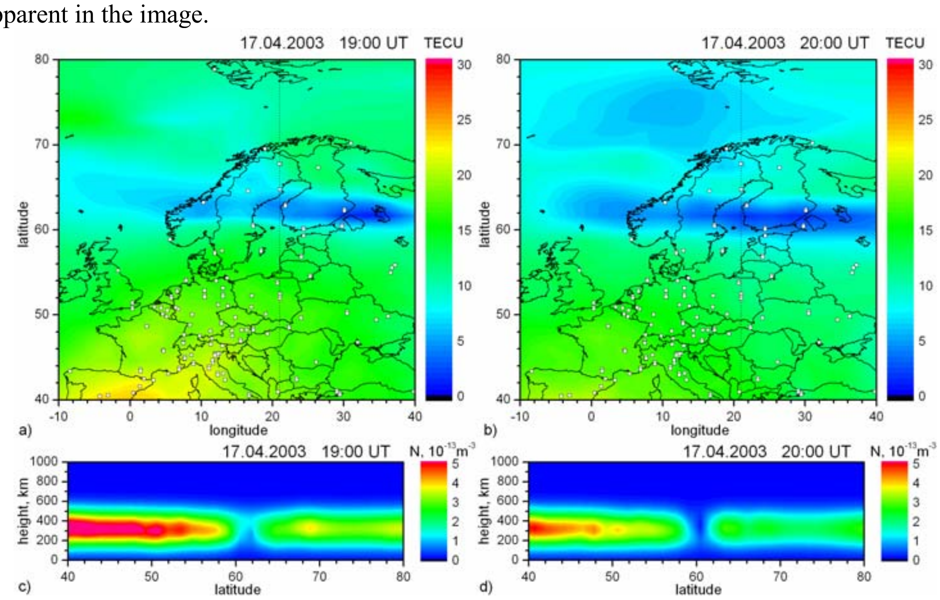

Figure 3. Examples of HORT images containing the ionospheric trough above Europe April27, 2003

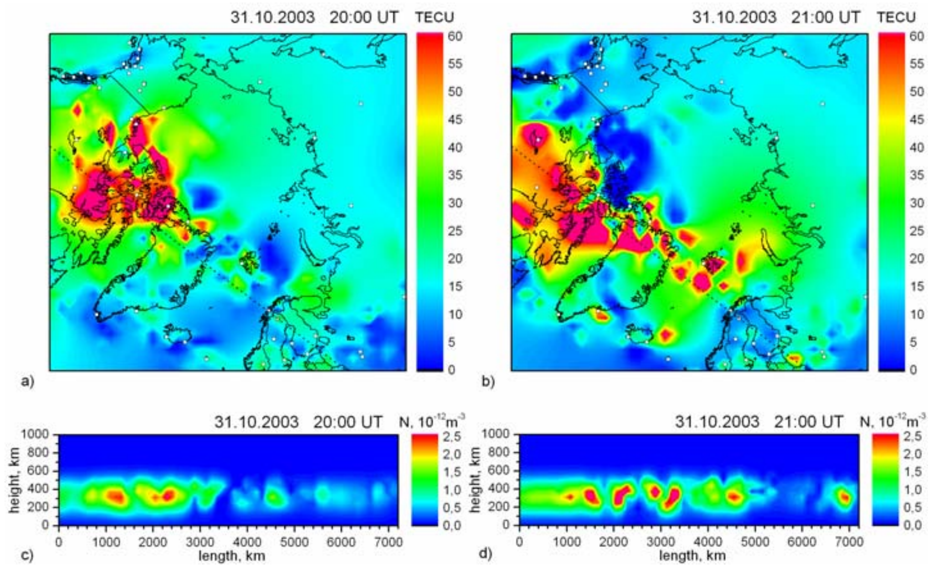

Figure 4. Examples of HORT images in Arctic during the severe geomagnetic storm on 29.10.2003

Figure 5. Vertical TEC in Arctic according to 4D HORT, grayscale (0-5 TECU)

4. Combination with other sounding techniques

The existing systems such as FormoSat-3/COSMIC and others implementing the Occultation Technique (OT) allow us to obtain the quasi-tangential projections of electron density (N). The RT technique with ground receivers implies that the ionosphere is sounded from a wide range of the positions of the transmitting and receiving systems. In this relation, the OT providing the integrals of N over a set of quasi-tangential rays (satellite-to-satellite paths) is a particular case of the tomographic method; therefore, the OT data can rather easily be incorporated into the radio tomographic scheme. In the presentation we show the examples of a common scheme which includes both RT and OT. The existing systems for UV imaging (GUVI, SSULI, and FormoSat-3/COSMIC) allow one to obtain integrals of N squared. These data of UV sounding may also be included into the tomographic scheme. We discuss the possibilities and examples of the combined application of OT, UV-sounding and RT. General problems of the radio tomography of the near-Earth space are considered and the uniqueness, limitations and accuracy of RT imaging are considered.

5. Conclusion

The satellite RT system is distributed sounding system: moving navigational satellites and a network of ground-based receivers give an opportunity to continuously sound the medium in various directions and reconstruct the spatial structure of ionosphere. Combination of LORT and HORT systems provides noticeable advantages including the possibility for obtaining 3D distributions of the ionospheric plasma in vast regions. The combined application of RT, OT and UV sounding improve the quality of RT imaging.

6. Acknowledgments

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7. References

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