IMAGING OF THE IONOSPHERE BASED ON LOW-ORBITAL AND HIGH-ORBITAL RADIO TOMOGRAPHIC SYSTEMS

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INTRIDUCTION

Currently available low orbital (LO) satellite navigational systems (like the Russian "Tsykada" satellites and American "Transit" - Navy Navigation Satellite System) having nearly circular orbits at 1000-1150 km altitudes, and ground receiving chains provide a possibility to yield a series of tomographic data along a set of rays and to get 2D RT images of the ionosphere over a region 1-3 thousand kilometers as large within 10-15 minutes. The main results obtained in ionospheric LO RT are presented in a series of monograph and reviews [1-3]. In recent years receiving networks of high-orbital (HO) navigational systems such as GPS/GLONASS are actively developing. Ionospheric RT with HO systems is considered; results of HO RT are compared with those yielded by LO RT.

RT BASED ON LOW-ORBITAL SATELLITES

A series of RT experiments has been already and are being currently carried out in different regions of the world: in Europe, America and Asia [1-8]. RT images of the ionosphere along the path Moscow-Barentsburg (Svalbard) and over Alaska region during periods of geomagnetic storms in October 2003 (Fig.1) and in July 2004 (Fig.2) were obtained and analyzed. Geomagnetic storm of 29-31 October 2003 ranks as an extremely strong event (planetary index of geomagnetic activity reached its maximum Kp=9). As an example, shown in Fig.1a is ionospheric cross-section between Moscow and Barentsburg reconstructed from the data of 30.10.2003, 19:25UT (31.11.2003, 22:25LT). As seen from the reconstruction, a complicated structure with wavelike disturbances (with a maximum of $1.0*10^6$ el/cm^3 which is quite untypical in middle and subauroral latitudes) is observed in the late evening. Sharp gradients and abrupt wall-like drop in ionization at about 62º were revealed within this period also in the ionosphere over Alaska (Fig.1b). Fig.2a displays an example of tomographic reconstruction of the ionospheric cross-section along the path Moscow-Barentsburg during the geomagnetic storm on July 25, 2004 (Kp index amounted to 8). Almost vertical structure at 69º was observed on 25.07.04 at 14:17 UT. Wavelike structures at about 63º-64º are clearly seen in the reconstruction over Alaska during this storm on 25.07.04 at 05:27UT (Fig.2b).

Numerous experiments revealed a complexity and variability of the trough shapes, its width, slope and depth varying within a wide range [1-3]. An example of a narrow tilted trough is shown in Fig.3 in contours in units of 10^6cm^{-3}. The upper image is obtained with the data from Cordova-Delta chain in Alaska (RT data are available on the website [10]), and the bottom image is obtained 12 hours later using the data from a Russian RT chain arranged between Moscow and Murmansk. The coordinates of receivers are such that the Russian chain and the Alaskan chain are located on opposite sides of the Earth with a time shift of about 12 hours. As it is seen from the Fig.3, the RT sections of the ionosphere are qualitatively similar: a narrow tilted trough is apparent in both images; the northward edge of the trough has a specific ledge, and wavelike disturbances are seen to the north of the trough. Moreover, the qualitative similarity of the images remains 7 hours later (Fig.4): the trough has disappeared, and the ionosphere became nearly uniform (homogeneous). Therefore, the complex structure of the ionosphere has hardly changed anyhow within many hours (i.e., the Earth rotation with respect to quasi-stationary ionosphere has been observed). Such cases are rather rare and, as a rule, are observed under quiet geomagnetic conditions (in the cases shown, planetary geomagnetic activity index Kp does not exceed 2).

A series of specific features in the structure and dynamics of equatorial anomaly (EA) were found during RT experiments in near-equatorial latitudes: noon alignment of EA core with the direction of the geomagnetic field, essential asymmetry of EA edges and typical bite-out or constriction of the ionosphere to the north of EA core [5-7]. Moreover the possibilities of imaging of the E-region of the equatorial anomaly are discussed. RT analysis of strong ionospheric disturbances caused by anthropogenic effects, in particular, perturbations induced by rocket launches, industrial explosions, powerful HF radiation is carried out [1]. For a series of experiments, the results provided by radio tomography were compared with the data of ionosondes and incoherent scattering radars. The joint Russian-American experiment proved high quality of RT reconstructions and showed an agreement between RT results and radar cross-sections within the accuracy of the both methods [4]. Similarly, a consistency of ionosondes data and RT results within the limitations of the both methods should be mentioned [2, 3, 7]. The developed method for determination of ionospheric plasma flows from RT data makes it possible to study dynamical processes in the ionosphere [8].

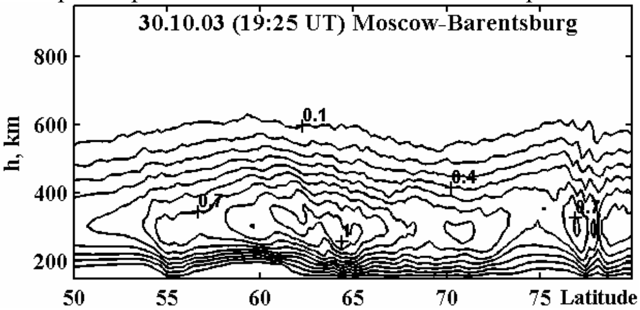

Fig.1a. RT image of the ionosphere between Moscow and Barentsburg (Svalbard) during magnetic storm at 19:25UT on 30.10.2003

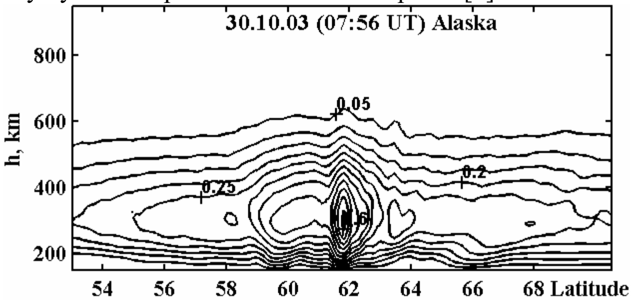

Fig.1b. RT image of the ionosphere in the Alaska region during geomagnetic storm at 07:56UT on 30.10.2003

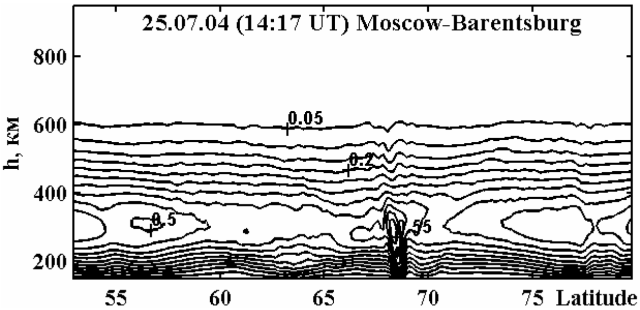

Fig.2a. RT image of the ionosphere between Moscow and Barentsburg during magnetic storm at 14:17UT on 25.07.2004

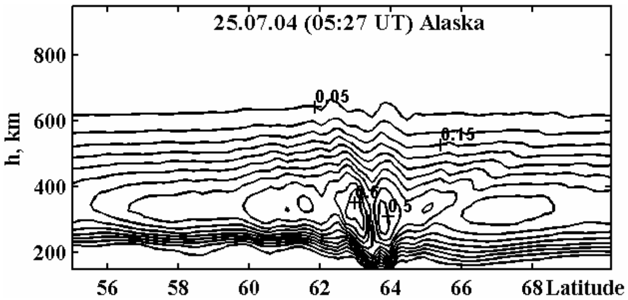

Fig.2b. RT image of the ionosphere in the Alaska region during magnetic storm at 05:27UT on 25.07.2004

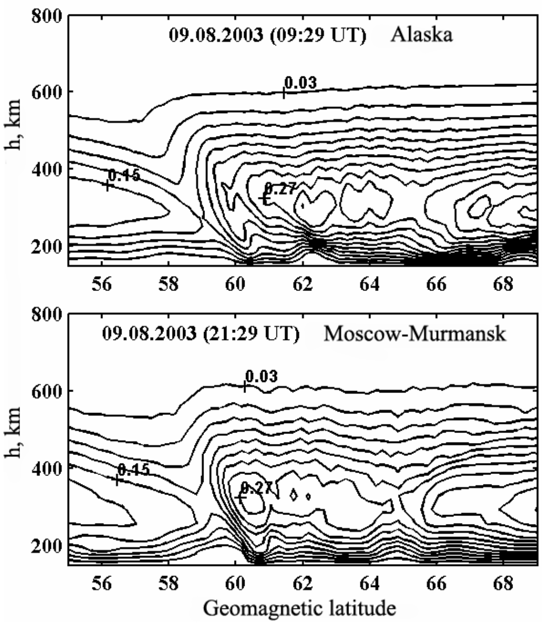

Fig.3. RT images of the ionosphere in the Alaska region at 09:29UT and along the path Moscow-Murmansk at 21:29UT on 09.08.2003

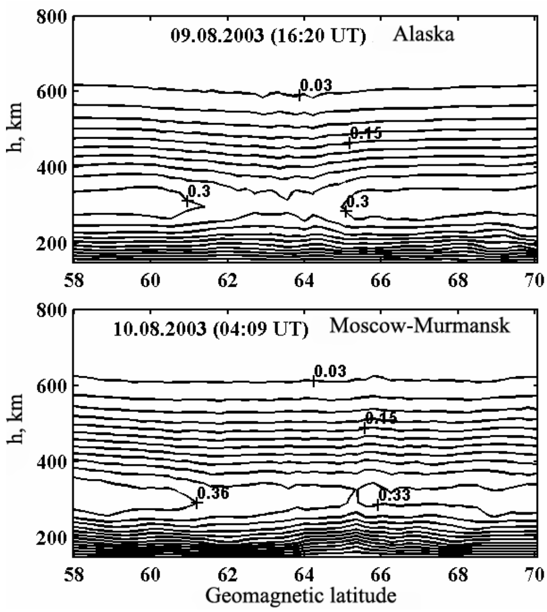

Fig.4. RT images of the ionosphere in the Alaska region at 16:20UT on 09.08.2003 and along the path Moscow-Murmansk at 04:09UT on 10.08.2003

RT BASED ON HIGH-ORBITAL GPS/GLONASS SATELLITES

Information obtained constantly at a network of GPS receivers of nearly global coverage, gives a possibility to state problems of regional and global reconstruction of electron density distribution in the ionosphere. For the solution of the problems of 4D (three spatial coordinates and time) RT based on the data from HO systems, one can use an approach developed in two-dimensional satellite ionospheric tomography. For the purposes of ionospheric RT monitoring, the use of phase data rather than the group delay data is preferable since the measurement accuracy is noticeably higher and noise level is much lower. Resolution of HO RT is much worse than that of LO RT. As a rule, horizontal resolution is not less than 100 km in Europe and the most part of USA. Only in the South California it is possible to attain 30-50-km horizontal resolution; vertical resolution in this case is also about 100 km.

Results of calculation of electron density N from 4D RT reconstructions during strong disturbances at 23:00 UT on 30 October and at 02:00 UT on 31 October 2003 are shown in Figs.5-6 in contours, in units of 10^6 cm^{-3} at 300 km altitude. Here, the positions of the spot of enhanced ionization on its coming in and going out of the European region are shown. The obtained values of electron density in the center part of the nighttime spot ($\sim (2\div2.5)\cdot10^6$ $см^{-3}$) noticeably exceed typical daytime values [9]. Changes in f0F2 on 30-31 October, 2003 as obtained from the RT results and the Athens ionosonde data are plotted in Fig.7. It can be seen that the both curves are quite similar. Changes in f0F2 on 30/31 October as determined from RT data and from closely spaced ionosonde in Chilton, Great Britain, are shown in Fig.8. The increase in ionospheric plasma frequency up to typical daytime values detected by ionosondes and determined from RT in the midnight of 30/31 October correspond to the pass of the spot of enhanced ionization over the Great Britain [9]. Thus, as a result of 4D radio tomography of the ionosphere over Europe, some specific features in ionospheric behavior during strong solar-geophysical disturbances have been revealed. Comparison of the results of RT reconstruction with independent measurements of ionosondes showed high quality and efficiency of the developed approaches and algorithms of 4D radio tomography based on GPS data.

The example of HO RT reconstruction of the equatorial anomaly in units TECU is shown in Fig.9. The northern and southern crests of the equatorial anomaly are clearly seen. Results of HO RT were compared with LO RT reconstructions. As an example, shown in Fig.10a is meridional LO RT cross-section of the ionosphere 22 October 2002, 12:38UT over Alaska region. Fig.10b represents meridional cross-section obtained by HO RT. As seen from the figures, complex structure of the ionosphere containing perturbations (Fig.10a) is reconstructed by HO RT much worse: resolution is evidently lacking, and not all maxima existing in the real ionosphere are revealed in the reconstruction (Fig.10b). But quasi-regular ionosphere is reconstructed with high accuracy.

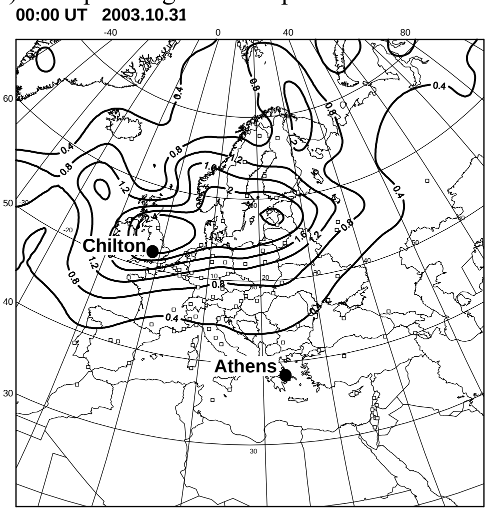

Fig.5. Contours of N at 300 km altitude on 31.10.2003 at 00:00UT as obtained from HO RT data

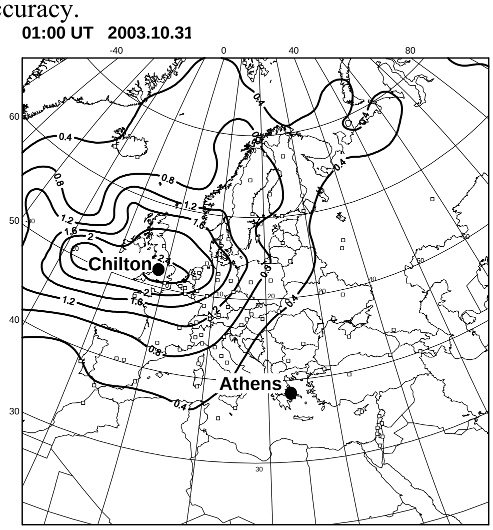

Fig.6. Contours of N at 300 km altitude on 31.10.2003 at 01:00UT as obtained from HO RT data

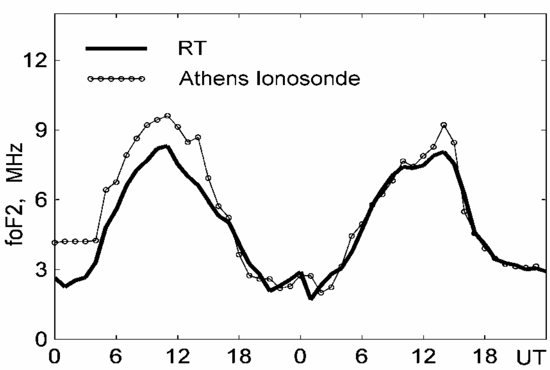

Fig.7. f0F2 as obtained from RT and Athens Ionosonde.

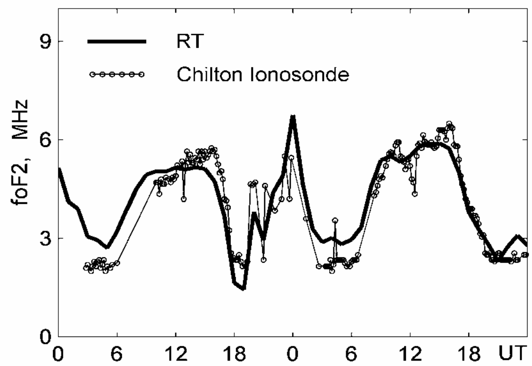

Fig.8. f0F2 as obtained from RT and Chilton Ionosonde.

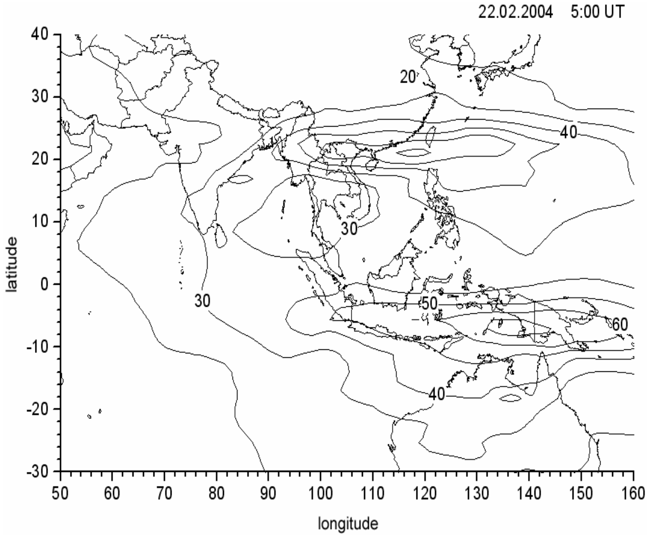

Fig.9. Vertical TEC obtained by HO RT from the data of 22.10.2004, 05:00 UT in the region of the equatorial anomaly.

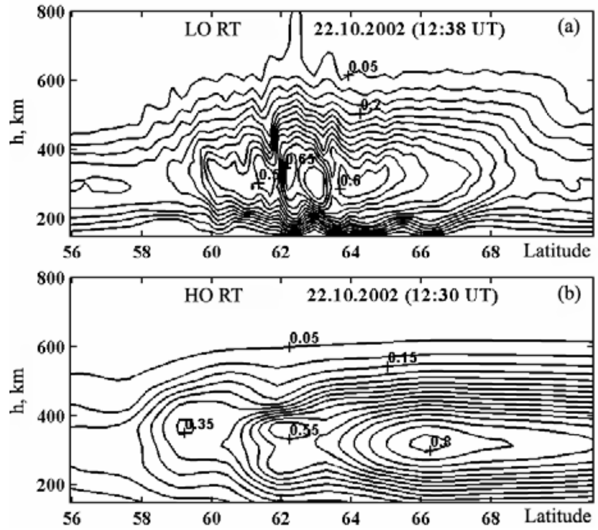

Fig.10. Meridional cross-sections of the ionosphere over Alaska obtained by LO RT from the data of 22.10.2002, 12:38 UT (a) and HO RT from the data of 22.10.2002, 12:30 UT (b).

SUMMARY

With LO RT it is possible to reconstruct "instantaneous" (5-8 minutes) 2D cross-sections of electron concentrations. The LO RT method also allows determination of plasma fluxes from the analysis of time-successive RT images of the ionosphere. If several receiving chains spaced a few hundreds kilometers apart are available, the 3D structure of the ionosphere can be reconstructed. The main essential limitation of the LO RT technique is the necessity of constructing systems with many receiving chains. HO RT allows reconstruction of 4D distributions of electron concentration (hourly or half-hourly 3D reconstructions). However, spatial resolution of HO RT is noticeably lower than that in case of LO RT, the same as the quality of reconstructing wave and wavelike disturbances. Thus, the use of a combination of radio tomographic systems of LO RT and HO RT allows realization of efficient regional and global monitoring of the near space.

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