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Structures of High- and Midlatitude Ionosphere in 23rd and 24th Solar Cycles: Results from Radio Tomography

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Abstract

The results of studying the structure of the high- and midlatitude ionosphere by the methods of satellite radio tomography (RT) are presented for different conditions of geomagnetic activity during the 23rd and 24th solar cycles. Special attention is paid to the results of RT studies obtained in different years based on the data from the Russian RT receiving chain installed along the geomagnetic meridian Svalbard–Murmansk–Moscow in the northwestern Russia and from two American RT systems in the West Coast of the United States and in Alaska. A variety of plasma structures of different shapes and intensities are observed in the RT reconstructions: ionization troughs (main ionization trough, auroral oval), multi–extrema wavelike perturbations, spots (blobs, patches), narrow plasma bands or threads elongated in the direction of the geomagnetic field, etc. Numerous examples of RT reconstructions are presented and structural features revealed by RT in the distribution of the ionospheric plasma are discussed.

1 Introduction

The high-latitude ionosphere is a region where the highly varying space weather factors (solar activity, dynamics of the magnetosphere) cause most severe effects. Even the ordinary regular variations in the interplanetary medium lead to a significant perturbation of the geomagnetic field, excite auroras, and generate irregularities in the ionosphere (the so-called geomagnetic substorms). These effects are particularly strong at night when the ionization by solar radiation which creates stable background electron density is absent. During severe anomalous disturbances associated with solar activity events (magnetic storms), the amplitude of the impact increases by an order of magnitude, and the auroral zone expands equatorward to the midlatitudes. Diagnosing the complex and variable distribution of the ionospheric plasma requires nonlocal methods capable of determining the spatio-temporal structure of the ionosphere not at a separate point but in a fairly large spatial interval. Among these nonlocal methods is satellite radio tomography (RT) of the ionosphere. It is remarkable that RT based on the use of VHF/UHF/L radio signals is an efficient diagnostic method for establishing the structure of the ionosphere not only during the relatively quiet periods but also during the geomagnetic storms when the ionosphere is highly inhomogeneous in time and space and the strong absorption can preclude stable operation of ionosondes that use HF radio waves.

2 Methods and Data

In this work, we used two modifications of the RT methods: those employing the signals from low-orbiting (LO) satellites and those based on the radio transmissions from high-orbiting (HO) satellites. The LORT method analyzes the signals of low-orbit satellites (Parus/Transit satellite navigation systems, satellites with CERTO beacons onboard, e.g., ePOP/CASSIOPE) recorded by the ground receives installed in a meridional chain with a spacing of a few hundred kilometers between the neighboring measurement sites. LORT yields two-dimensional (height–latitude) electron density distributions in the plane of the satellite trajectory above the receiving chain. LORT reconstructions cover a spatial sector of a few thousand kilometers with a time averaging of the order of 5–15 minutes [1]. The spatial resolution of LORT is 20–30 km horizontally and 30–40 km vertically. The time resolution of LORT is limited by the location of the meridional RT receiving chains and by the number of the operating LO satellites. The HORT method is based on the analysis of L1/L2 radio signals from GNSS satellites (GPS/GLONASS), recorded by the networks of ground receiving stations (IGS, UNAVCO, regional networks). The HORT method provides spatiotemporal (4D) distributions of electron concentration in the ionosphere (both global and regional) with a spatial resolution of the order of 70–100 km and with a time interval of 60–30 minutes between the consecutive reconstructions in the regions of fairly dense receiving networks [2]. The main results of the RT studies of the ionosphere are presented in [3, 4, 5]. It should also be noted that RT was successfully used for analyzing the ionospheric effects caused by anthropogenic factors (rocket launching, industrial explosions, modification of the ionosphere by high-power HF radiation of the Sura heating facility) [6, 7, 8].

3 Observations

The obtained RT reconstructions demonstrate a rich spectrum of ionospheric irregularities of different spatiotemporal scales. In the RT reconstructions, the width and depth of the ionization troughs vary widely. The example is presented in Fig. 1 where the LORT cross section of the ionosphere is reconstructed based on the data of the Russian RT receiving chain Moscow–Murmansk–Svalbard. Here, a fairly wide main ionization trough with a steep poleward wall is observed in the latitudinal interval from 61°N to 66°N in quiet geomagnetic conditions (Kp = 1). An example of a narrow ionization trough with a width of less than one degree in latitude observed close to the poleward wall of the main ionospheric trough ("trough-in-trough" pattern) in the weakly disturbed conditions is shown in Fig. 2. Here, the Kp index was at most 3.

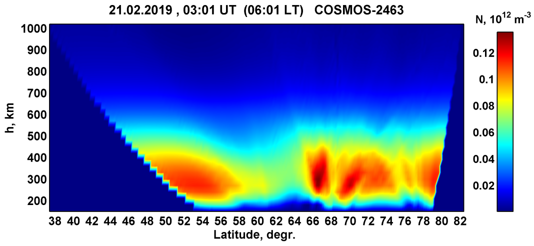

Figure 1. Example of LORT image above northwestern Russia, February 21, 2019, 03:01 UT

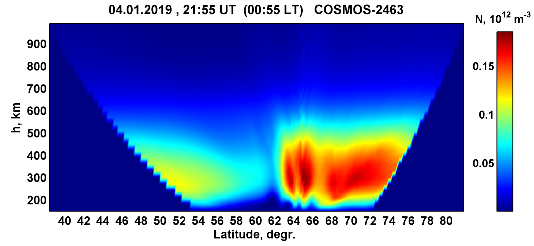

Figure 2. Example of LORT image above northwestern Russia, January 04, 2019, 21:55 UT

Along with the ionization troughs, also narrow isolated field-aligned structures quite frequently occur in the LORT reconstructions. For example, in Fig. 3, a narrow "wall" of highly ionized plasma which has a width of about 60 km is observed in the vicinity of latitude 68.5°N. Throughout the entire reconstruction region, quasi-wave disturbances are present in the LORT ionospheric cross section. This RT image refers to the moderately perturbed geomagnetic conditions (Kp = 3.3).

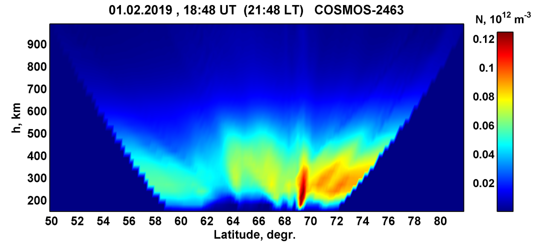

Figure 3. Example of LORT image above northwestern Russia, February 01, 2019, 18:48 UT

Figures 4-5 show the examples of the ionospheric LORT images reconstructed from the data of the RT receiving chain in the West Coast of the United States. A wide ionization trough in the interval from 44°N to 50°N and quasi-wave disturbances within the trough are clearly seen in Fig.4. These data were recorded during the disturbed perturbed period when Kp index was 4.3. In the LORT cross section in Fig.5, a narrow ionization trough is identified in the vicinity of 48°N during the geomagnetic storm at Kp = 5.7.

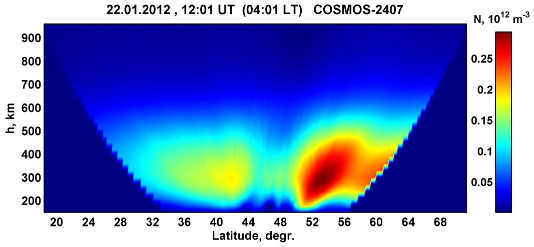

Figure 4. Example of LORT image above U.S. West Coast, January 22, 2012, 12:01 UT

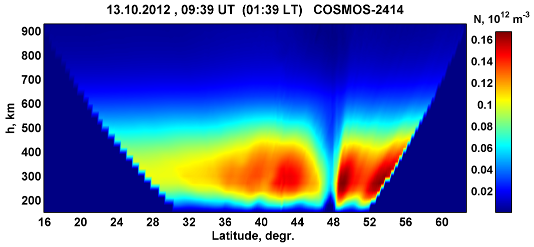

Figure 5. Example of LORT image above U.S. West Coast, October 13, 2012, 09:39 UT

The examples of LORT ionospheric reconstructions above Alaska during a moderately disturbed period with Kp = 3.7 are presented in Figs. 6 and 7. A rather highly structured distribution of electron density in Fig.6 demonstrates a deep and narrow ionization trough in the vicinity of 59°N and multi-extrema quasi-wave disturbances in the central part of the reconstruction about 60°–68°N. In Fig.7 which shows the RT snapshot of the ionosphere 50 minutes later, the trough almost disappears and the quasi-wave disturbances undergo visible transformation.

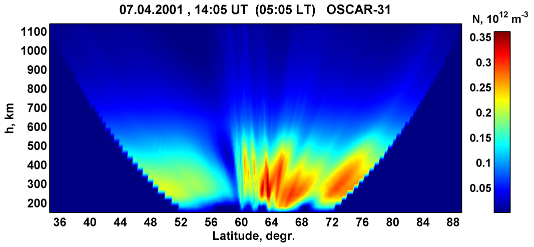

Figure 6. Example of LORT image above Alaska, April 07, 2001, 14:05 UT

The disturbed periods are typically marked with the enhancement of corpuscular precipitation. Corpuscular fluxes can have a modulating effect on the structure of the ionospheric plasma, for example, they can modulate the position and shape of the walls of the ionospheric trough and contribute to the formation of irregularities in the distribution

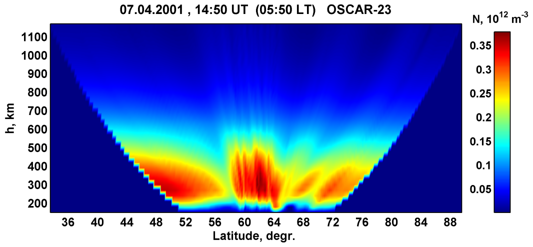

Figure 7. Example of LORT image above Alaska, April 07, 2001, 14:55 UT

of ionization [9]. For identifying the ionospheric response to particle precipitation, we qualitatively compared the results of LORT reconstructions with the DMSP satellite data on particle fluxes that directly cause ionospheric structuring. We only considered the LORT reconstructions for the evening and nighttime periods in order to exclude the contribution of the daytime ionization by the short-wave solar radiation. An example of this comparison for the northwestern Russia is presented in Figs. 8 and 9. The steep polar wall of the ionization trough with high gradients of electron density at 64°–68°N in the LORT cross section (Fig. 8) corresponds to the intensification of the fluxes of precipitating particles detected by the DMSP-F14 satellite (Fig. 9). In other words, the poleward wall of the main ionization trough is formed by the source of corpuscular ionization. These data were obtained during a moderately disturbed period (Kp = 4).

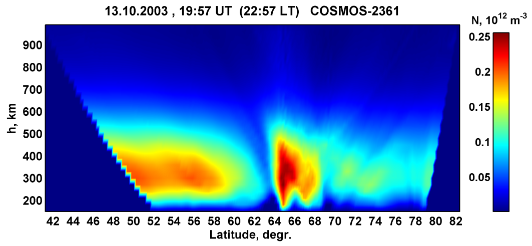

Figure 8. Example of LORT image above northwestern Russia, October 13, 2003, 19:57 UT

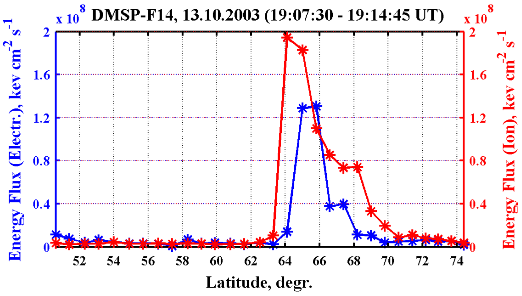

Figure 9. Electron and ion energy fluxes (DMSP-F14)

The HORT method makes it possible to study the dynamics of the ionospheric plasma both globally and above separate regions. Figures 10 and 11 show the example of the sequences of vertical TEC maps (in TECU units) above Europe and North America calculated based on the results of HORT reconstructions during the geomagnetic storm of May 14, 2019 when the Kp index reached 7. Figure 10 illustrates the evolution of the ionosphere with the ionization trough above Europe during three hours. Here, it can be seen how a clearly structured trough moves towards the south. A distinctly pronounced ionization trough stretching from the west to east coast is observed above North America (Fig. 11). Within four hours, the "bottom" of the trough becomes deeper, and separate bands with the "peaks" of ionization are observed north of the trough's poleward wall.

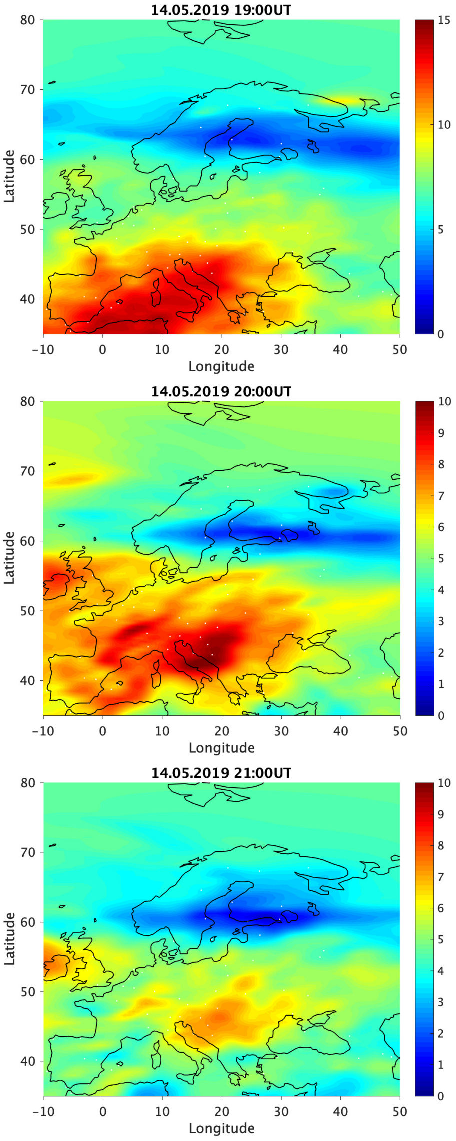

Figure 10. Evolution of the ionosphere above Europe according to HORT, 14.05.2019, 19–21 UT

4 Conclusions

The results of the RT reconstructions demonstrate a wide variety of structures in the high- and mid-latitude ionosphere: the troughs in electron concentration of the ionospheric plasma, the "stratification" of the trough, different "spots" of ionization and manifestations of the auroral oval, the isolated narrow features elongated in the direction of the geomagnetic field, the large-scale plasma density anomalies, multi-extrema quasi-wave disturbances, etc. The width and the shape of the main ionospheric trough widely vary in the different conditions of solar and geomagnetic activity. The corpuscular nature of the ionization that forms the poleward edge of the trough is supported by the comparison of the RT reconstructions with the observations by DMSP satellites. The radio tomographic results show high variability and complex structuring of the high-latitude ionosphere even in the quiet conditions. The radio tomographic results (LORT and HORT) can be used for analyzing various physical processes leading to the formation of the large-scale structure of the high- and mid-latitude ionosphere.

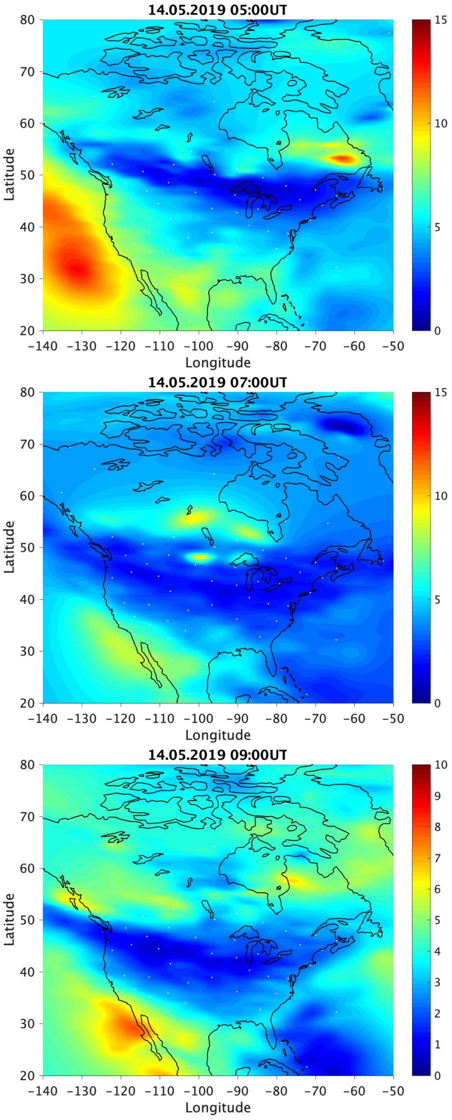

Figure 11. Evolution of the ionosphere above North America according to HORT, 14.05.2019, 05–09 UT

5 Acknowledgements

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References

[1] V. E. Kunitsyn, E. D. Tereshchenko, E. S. Andreeva, and I. A. Nesterov, “Satellite radio probing and radio tomography of the ionosphere“, *Physics Uspekhi*, **53**, 5, 2010, pp. 523–528, doi: 10.3367/UFNe.0180.201005k.0548.

[2] I. A. Nesterov and V. E. Kunitsyn, “GNSS radio tomography of the ionosphere: The problem with essentially incomplete data“, *Advances in Space Research*, **47**, 2011, pp. 1789–1803.

[3] G. S. Bust, and C. N. Mitchell, “History, current state, and future directions of ionospheric imaging“, *Rev. Geophys*, 2008, RG1003, doi:10.1029/2006RG000212.

[4] V. E. Kunitsyn, E. S. Andreeva, I. A. Nesterov and A. M. Padokhin, “Ionospheric Sounding and Tomography by GNSS“, in book: *Geodetic Sciences - Observations, Modeling and Applications*, InTech, 2013, pp. 223–252, doi: 10.5772/54589.

[5] I. A. Nesterov, E. S. Andreeva, A. M. Padokhin, Yu S. Tumanova, and M. O. Nazarenko, “Ionospheric perturbation indices based on the low- and high-orbiting satellite radio tomography data“, *GPS Solutions*, **21**, 4, 2017, pp. 1679–1694, doi: 10.1007/s10291-017-0646-1.

[6] E. S. Andreeva, M. B. Gokhberg, V. E. Kunitsyn, E. D. Tereshchenko, B. Z. Khudukon, S. L. Shalimov, “Radiotomographical Detection of Ionosphere Disturbances Caused by Ground Explosions“, *Cosmic Research*, **39**, 1, pp. 10–14, doi:10.1023/A:1002827609677.

[7] E. S. Andreeva, V. L. Frolov, V. E. Kunitsyn, A. S. Kryukovskii, D. S. Lukin, M. O. Nazarenko, and A. M. Padokhin, “Radiotomography and HF ray tracing of the artificially disturbed ionosphere above the Sura heating facility“, *Radio Science*, **51**, 2016, pp. 638–644, doi:10.1002/2015RS005939.

[8] H. G. James, V. L. Frolov, E. S. Andreeva, A. M. Padokhin, and C. L. Siefring, “Sura heating facility transmissions to the CASSIOPE/e-POP satellite“, *Radio Science*, **52**, 2017, pp. 259–270, doi:10.1002/2016RS006190.

[9] A. S. Rodger, L. H. Brace, W. R. Hoegy, and J. D. Winningham, “The poleward edge of the mid-latitude trough – its formation, orientation and dynamics“, *J. Atmos. Terr. Phys.*, **48**, 1986, pp. 715–728, doi: 10.1016/0021-9169(86)90021-8.