Arctic Ionosphere Imaging and GNSS Tomography

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Abstract— For better understanding the nature and mechanisms of the physical processes that occur in the Arctic atmosphere and ionosphere, it is vital to have the adequate experimental input for the research. Global Navigation Satellite Systems (GNSS) can be used as one of the sources of these data, whose processing and analysis enables the structure and dynamics of the ionosphere to be explored by different methods including ionospheric radio tomography. We present and discuss a series of examples of radio tomographic reconstructions to illustrate a variety of ionospheric features observed above the Arctic. These radio tomographic images illustrate various structures, events, and processes associated with convection and other phenomena. We observed the characteristic ring-shaped irregularities encircling the North Pole, the tongues of ionization, the ionization patches moving from the dayside to the night-side ionosphere, etc.. The results of comparison between Global Ionospheric Maps and radio tomographic reconstructions are presented and discussed.

1. INTRODUCTION

The Arctic upper atmosphere is an active link in the solar-terrestrial coupling system. It is just the polar region that accommodates a series of unique physical phenomena associated with the configuration of interplanetary magnetic field, penetration of solar wind plasma into the upper atmosphere, etc.. The complexity and global character of the processes in the Arctic ionosphere require non-local methods to diagnose the spatiotemporal structure of ionospheric disturbances. Satellite radio tomography (RT) based on Global Navigation Satellite Systems (GNSS) is one of the most efficient methods for doing this. GNSS include first-generation low-orbiting (LO) systems (Transit, Parus, etc.) and second-generation high-orbiting systems (GPS and GLONASS, currently in operation, and Galileo, BeiDou, QZSS, under development in Europe, China, and Japan). The satellite constellations together with the networks of ground receivers enable probing the ionosphere along a set of rays and applying tomographic approaches to reconstruct the distributions of ionospheric parameters by the methods of low- and high-orbiting radio tomography (LORT and HORT).

2. METHODS

RT methods based on LO navigation satellite systems have been actively developed for more than two recent decades [1–4]. In LORT experiments, coherent 150/400 MHz radio transmissions from satellites are recorded by a set of ground receivers aligned with the satellite path and spaced by a few hundred km apart from each other. LO satellites move sufficiently fast (~ 7.9 km/s) compared to the characteristic times of the ionospheric processes and cross the studied ionospheric region in a very short time, providing virtually instantaneous ($\sim$ 5–10 min) 2D (latitude-height) snapshots of the ionosphere. The typical spatial resolution of HORT (20–30 km) can be increased up to 10 km by considering the refraction of the rays. The time interval between the neighboring LORT reconstructions depends of the number of operating satellites and, with the current satellite configuration, is 30–240 min. HORT problems are distinct by high dimensionality and essential incompleteness of data. Relatively low angular velocities of GPS/GLONASS satellites make necessitate temporal variability of the ionosphere to be taken into account. This leads to the 4D statement of the tomographic problem in three spatial and one time coordinates. Here, we have to introduce an additional procedure of interpolating the obtained solutions into the areas of missed data or to seek for a smoothed averaged solution [5]. The coverage of the studied territories by receiving networks is typically nonuniform, which limits the vertical and horizontal resolution of HORT to at best 100 km with a time interval of 60–20 min between the successive reconstructions. Dense networks in Europe, continental U.S., and Alaska provide higher resolution (30–50 km) with a time step of 30–10 min. Resolutions as high as 10–30 km with a time step of 2 min can only be achieved in the regions covered by extremely dense networks in California and Japan. The main results of LORT and HORT investigations of the ionosphere are described in [1–4, 6–10].

3. OBSERVATIONS AND RESULTS

RT imaging of the Arctic region revealed a variety of ionospheric structures including wavelike disturbances, ionization troughs, plasma distributions with numerous enhancements and depletions, local features, etc.. Figures 1–4 exemplify the structures reveled by RT in the Alaska region during geomagnetically quiet periods ($Kp < 3$). The raw data from the American LORT system were provided for our analysis by courtesy of NWRA (Northwest Research Associates, USA). A narrow trough at $\sim 59°$N and wavelike disturbances north of the trough are observed on March 30, 2001 at 15:47UT (07:47LT) (Figure 1). High electron concentrations in the central part and in the north of the region, untypical of the morning ionosphere, are remarkable: the observed values are rather characteristic of the daytime equatorial ionosphere. One hour later (Figure 2), the trough becomes less pronounced and almost disappears; intense wavelike disturbances are observed at 60°–64°N. Many LORT images show enhanced ionization in the evening and nighttime ionosphere above Alaska in the southern and northern segments of the studied region. For example, a wavelike "dual-core" structure at 60°–64°N is observed against the southwardly increasing ionization in the LORT reconstruction on October 2, 2003 at 05:44UT (October 1, 20:44 LT) (Figure 3). The trough is identified at about 65°N. In the RT image for nearly the same time on the next day (Figure 4), the situation is opposite: the electron density increases northwards, and wavelike disturbances with a spatial scale from fractions of degree to 1.5–2° in latitude are present in the northern part of the reconstruction. HORT reconstructions demonstrate a broad variety of large-scale structures including patches of enhanced ionization reaching 10000 km lengthwise and 1500 km crosswise, with sharp gradients of concentration at their edges, observed in the high-latitude and polar ionosphere.

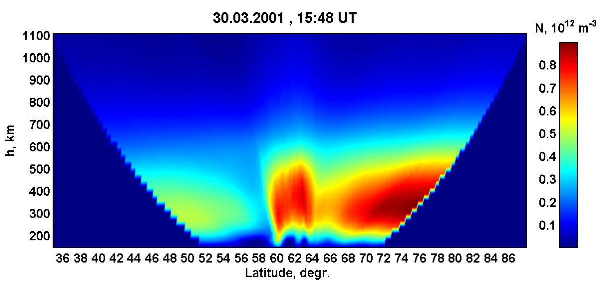


Figure 1: Example of LORT image above Alaska, March 30, 2001, 15:48 UT.

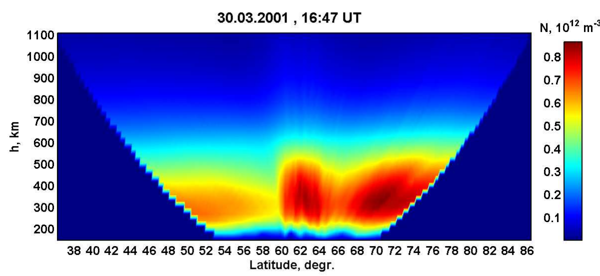


Figure 2: Example of LORT image above Alaska, March 30, 2001, 16:47 UT.

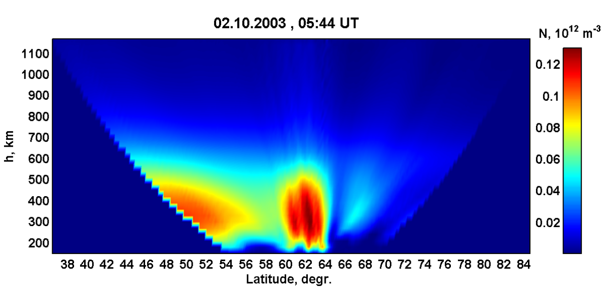


Figure 3: Example of LORT image above Alaska, October 2, 2003, 05:44UT.

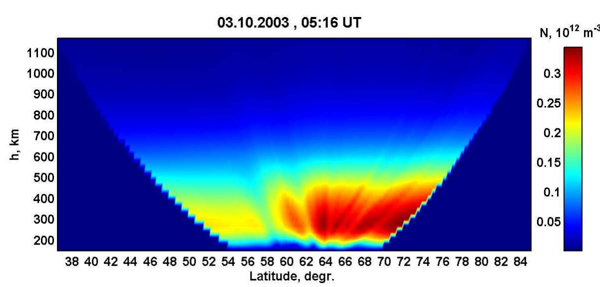
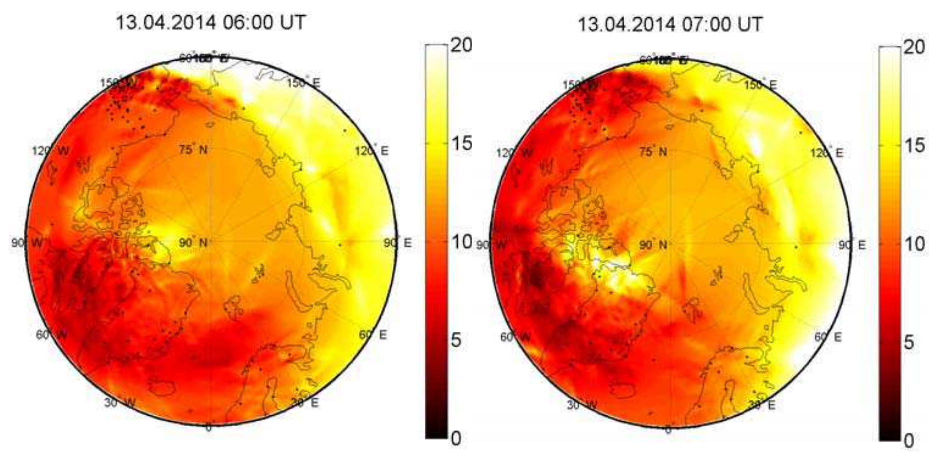


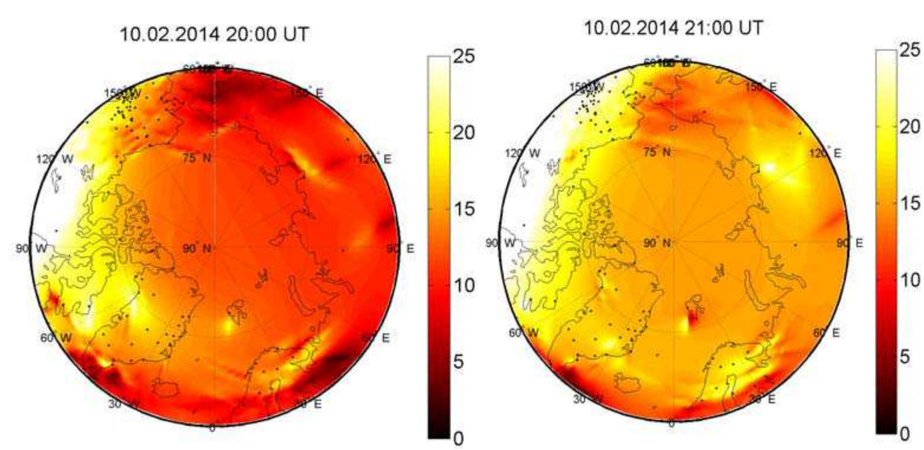
Figure 4: Example of LORT image above Alaska, October 3, 2003, 05:16UT.

Figure 5 shows the example of vertical TEC maps calculated from HORT reconstruction of the Arctic ionosphere on April 13, 2014 at 06:00 and 07:00UT ($Kp = 4$ and 3, respectively). In the map at 06:00UT there is a spot of increased TEC (> 15 TECU) in the polar region above the Canada Islands and northern Greenland. High TEC (~ 20 TECU) in the European sector are due to the ionization of the daytime ionosphere by the radiation from the Sun. An hour later (07:00 UT), the polar spot of high TEC expands compared to the previous reconstruction. Many HORT images display the structures which can probably be identified with tongues of ionization (TOI) — the large flows of enhanced daytime ionospheric plasma, extending antisunwards along the convection lines from the dayside to the nightside ionosphere through the polar cap. TOIs are structured into patches. The examples are presented in Figure 6 for 20:00 and 21:00UT on February 10, 2014 ($Kp = 4$). The bands of high TEC are seen extending from the dayside ionosphere into the night side. In the map on the left panel, high TEC (> 20 TECU) form a wide elongated zone above the northern Canada and Greenland. The nightside ionosphere at that time is structured into numerous smaller features (e.g., the spot in the region of Svalbard and enhanced ionization above the northern Europe and northeast Russia). The general pattern of ionization at 21:00 is similar to that observed at 20:00; however, a noticeable increase in ionization is observed in the arc-shaped zone above Scandinavia and West Europe (probably related morphologically to the auroral oval boundary). In the both structures, the maximal TEC exceed 20 TECU, which is untypical of the nighttime European ionosphere. Yet another example of TOIs is shown in Figure 7 for April 14, 2014 (21:00 and 22:00UT). The both TEC maps display high TEC above Greenland, which are observed as a flow of enhancements separated by linear zones of lower TEC. The figure illustrates the evolution of this high-TEC area, which has moved from central Greenland (21:00UT) to Scandinavia (22:00UT) in one hour. Recently, the ionospheric studies have started to widely use the 2D global ionospheric maps (GIM) of total electron content calculated with the thin sheet model of the ionosphere. In the presentation, we compare these maps with RT reconstructions. Our analysis shows that GIM TEC maps generally provide smoothed (averaged) plasma distributions and are incapable of resolving highly structured Arctic ionosphere during the disturbed periods.



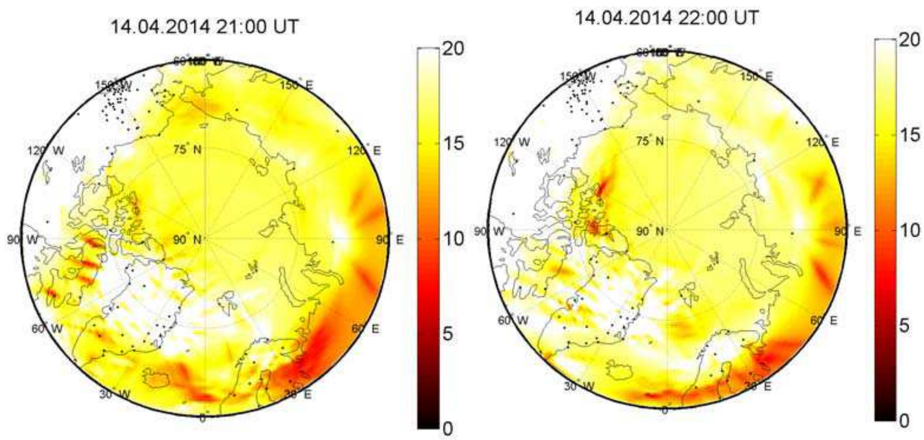
(a) (b)

Figure 5: TEC maps for April 13, 2014, (a) 06:00 UT and (b) 07:00.



(a) (b)

Figure 6: TEC maps for February 10, 2014, (a) 20:00 UT and (b) 21:00.



(a) (b)

Figure 7: TEC maps for April 14, 2014, (a) 21:00 UT and (b) 22:00.

4. CONCLUSIONS

Our reconstructions reveal a broad variety and high dynamics of plasma distributions in the Arctic region. RT methods efficiently image the troughs in ionization, wavelike disturbances, local irregularities, tongues of ionization, patches, specific ring structures encircling the North Pole, etc.. Combination of the LORT and HORT approaches appears to be most promising for studying the structural features and evolution of high-latitude ionospheric irregularities on different spatiotemporal scales.

ACKNOWLEDGMENT

We thank the team of the Kyoto World Data Center for Geomagnetism [11] and Space Physics Interactive Data Resource [12] for providing the geomagnetic indices. We are deeply grateful to NWRA for providing the data for LORT analysis. The work was supported by the Russian Science Foundation (grant 14-37-00027). The part of the analysis of the wave structures of the ionosphere by the RT methods was supported by the Russian Foundation for Basic Research (grant 14-05-00855).

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