Space Weather Variations and Corpuscular Ionization

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Abstract— Space weather manifestations in the northwest Russia are analyzed from the ionospheric images reconstructed by low-orbiting (LO) satellite radio tomography (RT). The Russian LORT chain installed in a wide latitudinal sector from Sochi to Svalbard approximately along the geomagnetic meridian and parallel to the descending ground tracks of the Russian navigational low-orbiting satellites. The two-dimensional (2D) distributions of electron density in the vertical plane above the chain reflect the response of the ionosphere to different space weather events. The geomagnetic storms belong to the most striking phenomena impacting the space weather. A variety of complicated ionospheric patterns resulting from the interplay between different space weather factors were revealed by LORT during the geomagnetic storms. Some features are common of the most storms, and the others are event-specific traits. The LORT images of the disturbed ionosphere demonstrate plasma distributions with numerous enhancements and depletions on various scales, rapid rearrangement of the ionospheric structures, uplifting of the ionospheric F-layer, variations in the position and shape of the main ionization trough, waves and wavelike disturbances, increased ionization in the night-time ionosphere, etc.. Many LORT images during the space weather perturbations show highly structured ionospheric patterns with isolated plasma irregularities ranging in size from a few tens to a few hundred km. The character of these features suggests their probable link to corpuscular ionization. We compared a series of such LORT images with the DMSP data on ionizing particle fluxes observed within a reasonably narrow band ($\sim 300\,\mathrm{km}$) along the RT chain. Corpuscular injections widely vary from a few to ten degrees along the latitude. Our comparison revealed the cases when the spatial pattern of ionization observed by LORT qualitatively agreed with the latitudinal profile of the fluxes of ionizing particles.

1. INTRODUCTION

Space weather is controlled by a variety of factors. Ionization of the upper atmosphere by X-ray and UV radiation from the Sun is one of the key impacts. Additional ionization is provided by corpuscular ionization, which causes energy rearrangement in the atmosphere and ionosphere, affects current systems, and structures the distributions of ionization in the ionospheric plasma. Ionization by corpuscular fluxes is typically lower than the ionization by EM radiation. However, its contribution can be very significant during the geomagnetic storms and in the night time, when EM radiation from the Sun is absent.

Diagnostics of corpuscular precipitation is an important field of present-day research in the ionospheric physics. The interest in this problem is associated with the fact that precipitations, as a proxy for the state of magnetospheric-ionospheric-atmospheric interactions, are important element in fundamental description of the space weather. On the other hand, precipitations are vital in many practical applications due to the effects produced in the ionosphere and atmosphere — parts of living environment. In particular, an important question in the study of corpuscular impacts as a space weather factor is the relationship between the precipitations and their effects in the distributions of ionospheric plasma. This relationship can be efficiently studied by the remote sensing methods and, primarily, by the ionospheric satellite radio tomography. RT reconstructions during space weather disturbances often reveal complicated patterns of ionospheric electron density with isolated narrow local high-gradient features. The spatiotemporal character of these ionospheric structures suggests their probable relation to corpuscular ionization. In this study, we compare a series of distributions of ionospheric electron density above the Russian RT system with the DMSP data on the structure of the ionizing particle fluxes.

2. METHODS

The ionospheric images analyzed in this work were reconstructed by the methods of low-orbiting (LO) radio tomography for the periods of disturbed space weather conditions during the 23rd and 24th solar cycles. The LORT method is described in detail in [1–6]. It provides two-dimensional

(2D) distributions of ionospheric electron density in the height interval from 100 to 1000 km above the chain of ground receivers with the horizontal resolution of 20–30 km and vertical resolution of 30–40 km. LORT is efficient in diagnostics of a broad range of ionospheric structures including ionospheric effects of particle precipitation. We have compared the LORT images with the corresponding data on ionizing particle fluxes provided by DMSP satellites. These satellites fly in sun-synchronous nearly polar (orbital inclination 98.7°) orbits about 850 km above the Earth. A DMSP orbit is completed in 102 min. The SSJ/4 (Precipitating Plasma Monitor) onboard DMSP spacecraft measures the electron and ion fluxes in 20 channels in the energy band from 30 eV to 30 keV with 1-s sampling interval.

The DMSP data on ionizing particle fluxes are available on the Internet [7, 8]. In our study, we used the DMSP data for the LO navigation satellites whose paths fall within 300 km of the RT chain. The existing geometry of RT systems and DMSP constellation fundamentally limits the DMSP precipitation data suitable for comparison with RT images (by the duration, spatial scales, dynamics, etc. of the precipitation events. The duration of precipitation events varies from a few min to a few hours; the spatial scales also vary significantly, from a few degrees to a few ten degrees in latitude [8–11], and the existing geometry cannot provide continuous and uniform precipitation monitoring in the studied region. Therefore, we can only qualitatively compare the RT cross sections with the corpuscular fluxes data.

3. OBSERVATIONS AND DISCUSSION

LORT reconstructions often record local ionization enhancements whose structure suggests their probable relation to precipitations. Below we present the examples of LORT reconstructions from the Russian RT system. The RT image in Figure 1 shows local maxima in electron density and wavelike disturbances in the interval of 67°–69° ($Kp = 4.3$). The DMSP satellites recorded the increase in the fluxes of precipitating electrons in the same interval of latitudes (Figure 2).

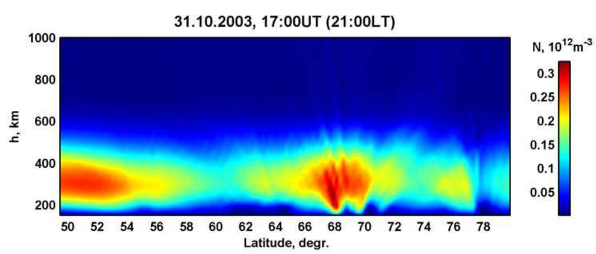

Figure 1: RT image of the ionosphere on October 31, 2003 at 17:00 UT (Northwest Russia).

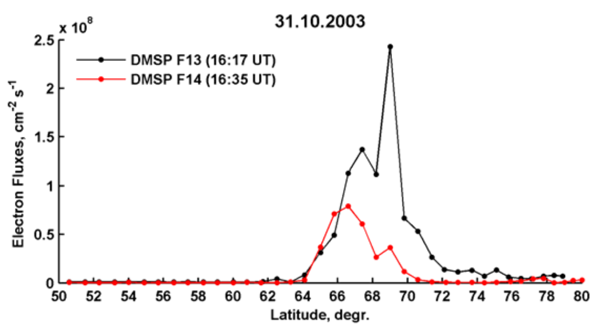

Figure 2: Electron fluxes according to DMSP measurements. October 31, 2003 (16:17 UT, 16:35 UT).

Examples of RT images of the ionosphere during the geomagnetic storm of April 24, 2012 at 17:41UT and 18:11UT ($Kp = 5$) are shown in Figures 3 and 4. In Figure 3, a vertical high-gradient electron density feature (a "wall" structure) with a maximum at a height of ~ 200 km is observed at 68°–69°N. Wavelike disturbances diverging from this structure are seen north and south of it. The ionization responsible for the observed pattern of electron density has probably occurred earlier in the underlying E-layer. Half an hour later (Figure 4), the "wall" structure rises upwards and splits in the vicinity of 68° N and 69°N into thin "slices" (with a cross-size of ~ 20 km) extending to a height of ~ 400 km along the magnetic field lines.

Figure 5 shows the spectrogram of precipitating electrons and ions from DMSP F18 satellite recorded on April 24, 2012 at 17:35–17:39 UT in the region of the Russian RT chain. Enhanced precipitations are observed at $\sim 68°$–69°N.

We note that due to the geometry of DMSP constellation and RT system, which do not provide spatially uniform and continuous in time coverage of the studied territory, and due to the very nature of precipitations, highly varying in space and time, the RT reconstructions and DMSP data are by no means always suitable for comparison. However, our RT data show that the structures similar to those described above (for which their relation to the precipitation events appears to be established quite reliably) are quite frequent.

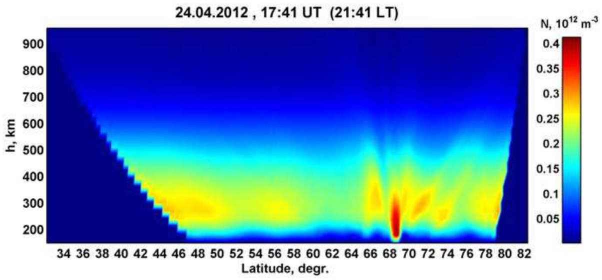

Figure 3: RT image of the ionosphere, April 24, 2012, 17:41UT (Northwest Russia).

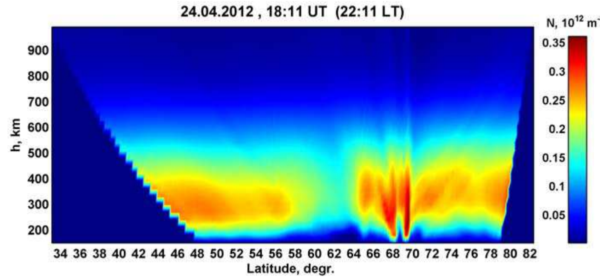

Figure 4: RT image of the ionosphere, April 24, 2012, 18:11UT (Northwest Russia).

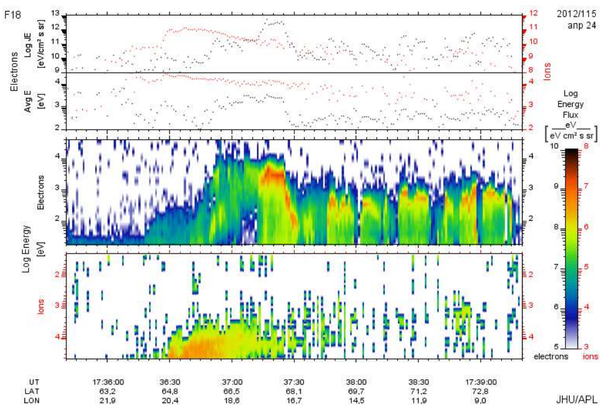

Figure 5: DMSP F18 spectrogram of precipitating particles, April 24, 2012, 17:35–17:39 UT.

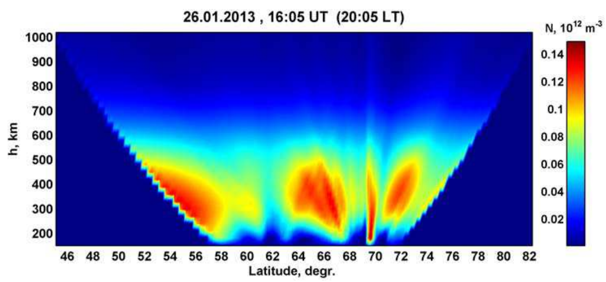

Figure 6: RT image of the ionosphere, January 26, 2013, 16:05UT (Northwest Russia).

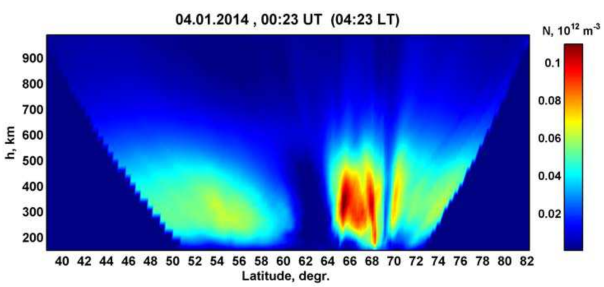

Figure 7: RT image of the ionosphere, January 4, 2014, 00:23UT (Northwest Russia).

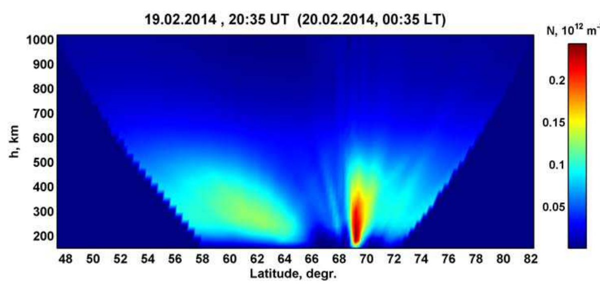

Figure 8: RT image of the ionosphere, February 19, 2014, 20:35UT (Russia).

The examples of such structures are presented in Figure 6–8. Isolated spots, narrow "walls," and wavelike features occur under different space weather conditions. Many of these structures are likely to result from the precipitation. Figure 6 displays the example of rather complicated electron density distribution along the Moscow-Svalbard path with the ionization trough at 62°–63°N and wavelike disturbances north of it ($Kp = 4$). In our opinion, the narrow vertical zone of enhanced ionization with a maximum at $\sim$ 190–200 km and cross-size $\sim$ 50 km near 69°N could have been formed by corpuscular ionization. The examples in Figures 7 and 8 show a number of similar local features, also probably related to the ionization by precipitating particles. In particular, precipitation could have contributed to the structuring of the ionospheric plasma in Figure 7 ($Kp = 1$), where a sharp polar edge of the ionospheric trough (60°–65°N) is followed farther north by vertical pillars of ionized plasma and wavelike disturbances north of the narrow trough at 69°N. The vertical plasma feature at 68°–69°N with a maximum at a height of $\sim$ 200 km and diverging wavelike structures north and south of it (Figure 8) is also likely to be modulated by corpuscular ionization.

4. CONCLUSIONS

The joint analysis of LORT images and satellite data on the fluxes of precipitating particles during space weather disturbances in the 23rd and 24th solar cycles demonstrates qualitative agreement between the latitudinal profiles of ionospheric ionization derived by LORT and corpuscular injections recorded by DMSP satellites. Along with the other factors, corpuscular ionization can modulate the distribution of ionospheric plasma on different spatial and time scales, e.g., affect the positions and shapes of polar and equatorial walls of the ionospheric troughs, structure the high-latitude plasma flows into patches, and generate local ionization features. LORT methods can efficiently diagnose all these structures and provide important information on the current space weather conditions and, in some cases, on their probable future changes (on the short time scale).

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