Ionospheric imaging using various radio tomographic systems

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Abstract

Radio Tomography (RT) based on low-orbital (LO), high-orbital (HO) satellite navigational systems and radio occultation sounding (FormoSat-3/COSMIC system) is considered. Examples of ionospheric RT imaging in different regions of the world (Russia, South-East Asia, North America) illustrating separate and combined use of LORT and HORT are given. Validation of ionospheric imaging with various RT systems is carried out using ionosondes data. Ionospheric images are compared with DMSP data and model data (IRI, GAIM). General problems of ionospheric radio tomography of the near-Earth environment, problems of the uniqueness and limitations of ionospheric imaging are considered.

1. Introduction

Radio tomographic studies of the ionosphere employing radio transmissions from low-orbital navigational satellite systems (like the American "Transit" and Russian "Tsikada") are actively progressing since early 90-ies. Nowadays about a dozen of LO receiving networks (chains) operating in different regions of the world are used widely for research purposes. In recent years receiving networks of high orbital satellite systems such as the Americal GPS and Russian GLONASS has got rapidly advancing; the European system "Galileo" is being deployed. More than a thousand HO receivers are currently available all over the world. Two years ago a new satellite system FormoSat-3/COSMIC has come into operation. FormoSat-3/COSMIC satellites, inter alia, are realizing measurements of radio transmissions from GPS satellites. Using the FormoSat-3/COSMIC radio occultation data it is possible to retrieve electron density profiles. In the presentation we describe and discuss the results of studying the structure and dynamics of the ionosphere based on the data from different radio tomographic systems.

2. Ionospheric imaging based on low-orbital satellite navigational systems

Development of ionospheric research based on the data from LO navigational satellite systems got started more than 15 years ago. Ionospheric RT techniques allow imaging of spatial distribution of electron density from the data of ionospheric radio sounding. In RT experiments reception of two coherent 150- and 400-MHz satellite transmissions is carried out at a set of ground receiving sites arranged along the ground projection of the satellite path and spaced by a few hundred kilometers from each other. Such systems make it possible to obtain 2D RT cross-sections of ionospheric electron density distribution in a plane containing the satellite path (altitude-latitude) within 1-3 thousand kilometer range for 10-15 minutes time interval. Horizontal resolution of ionospheric LORT is 20-30 km and vertical resolution is 30-40 km. RT methods enable detailed investigation of various ionospheric irregularities (troughs, crests of equatorial anomaly, travelling ionospheric disturbances, spots of ionization, wavelike structures, etc.) and high-resolution identification of low-contrasting structures [1-5]. LORT method allows also determintion of ionospheric plasma flows [6].

In the presentation, examples of LORT cross-sections of subauroral and auroral ionosphere (Alaska region) upon different solar-geomagnetic conditions are shown. Ionization of the upper atmosphere estimated from LORT data is compared with the fluxes of ionizing particles measured at DMSP satellites. Ionization by corpuscular fluxes from the magnetosphere was usually lower than the ionization by electromagnetic radiation; however, its contribution may prove notable during geomagnetic disturbances (especially strong enough) and in the night-time with no solar electromagnetic radiation. As an example, a LORT ionospheric cross-section over Alaska during the period of Halloween storm is shown in Fig.1 in contours of 10^{12} m^{-3} units. A wavelike structure of ionization with multiple extrema is clearly seen in the image at 59N-69N latitudes. Figure 2 shows the energy fluxes for electrons (solid line) and ions (dashed line) obtained from DMSP F13 measurements.

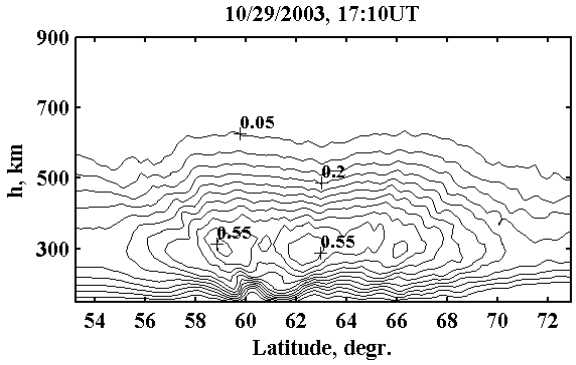

Fig.1. RT image of the ionosphere in the Alaska region during geomagnetic storm at 17:10UT on 29.10.2003

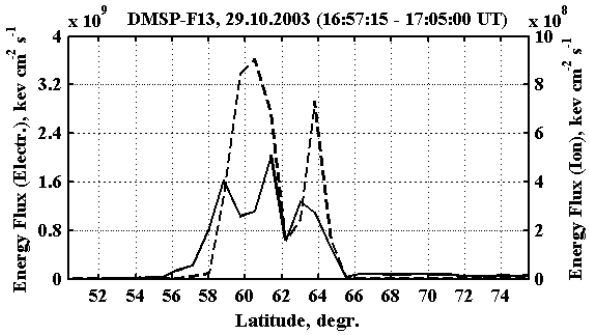

Fig.2. Electron and ion energy fluxes measured at DMSP F13 satellite at 16:57-17:05UT on 29.10.2003

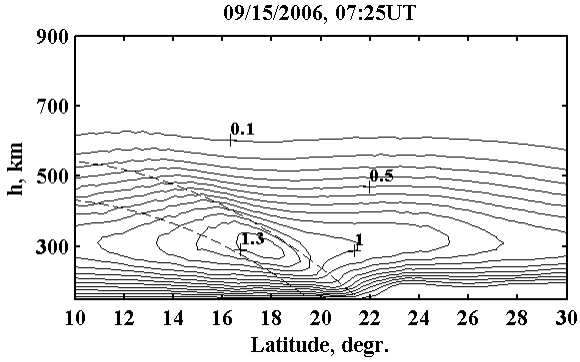

Fig.3. RT image of equatorial anomaly at 07:25UT on 09/15/2006 as obtained from LITN data

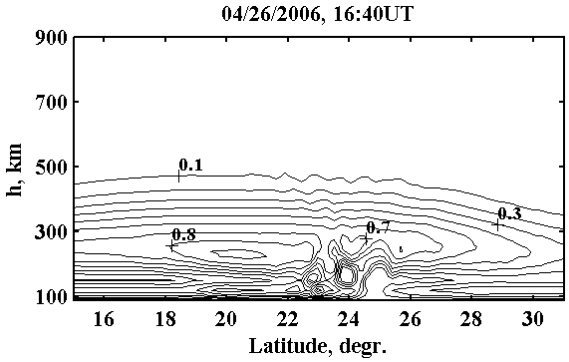

Fig.4. RT image of the night-time ionosphere at 16:40UT on 04/26/2006 as obtained from LITN data

In 1994-1996 first RT experiments were carried out in the Sout-East Asia at the Shanghai-Manila low-latitude ionospheric tomography network (LITN) [1, 3-5]. In 2006 LITN had been modified: currently the systematic ionosphere tomography network can receive triple-band beacon signals from NNSS-like and FormoSat-3 satellites and include six ground-based stations at ChungLi (25.14°N, 121.54°E), TasoTun (23.98°N, 120.70°E), CheCheng (22.73°N, 120.54°E), Manila (14.57°N, 120.99°E), Itu Aba Island (10.06°N, 114.35°E), and Pontianak (0.03°S, 109.35°E), and ongoing sites in China and Japan. In the presentation examples of LORT images of equatorial anomaly are shown. As an illustration, a typical LORT cross-section of equatorial anomaly is displayed in Fig. 3: the well-matured core of the anomaly is oriented in the direction of geomagnetic field (the field lines are shown by dashes); the asymmetry of equatorial anomaly and variations in the thickness of the ionospheric layer are clearly seen. An untypical RT cross-section (Fig.4) was observed in the night on 26 April 2006 at 16:40 UT (04/27/2006, 00:40LT) likely reflecting the stage of equatorial bubbles formation at 23°N, 24°N and 25°N latitudes. Results of LORT ionospheric images comparison with the IRI and GAIM model data in different latitudal regions are shown in the presentation as well.

3. Ionospheric imaging based on high-orbital satellite navigational systems

A new research tool appeared with the deployment of global navigational systems like GPS, GLONASS and Galileo. Due to low angular velocity of high-orbital satellites it becomes essentially necessary to take into account temporal changes of the ionosphere, which implies a 4D statement of RT problem (three spatial coordinates and time). Main specific features of the 4D problem are its high dimensionality and essential incompleteness of data. Unlike 2D RT, here an additional procedure is required to interpolate the found solutions in the region of missing data [7]. Spatial resolution of HORT is much lower than the LORT resolution; as a rule, horizontal resolution in Europe and USA is not better than 100 km. In the presentation examples of 4D ionospheric imaging based on GPS data measured during periods of different solar-geomagnetic activity are shown. Illustrating VTEC distributions (TECU contours with 2.5 TECU step) calculated from 4D ionospheric images obtained for 13 December 2006 above

the eastern (at 09:00 UT) and western (at 19:00 UT) hemispheres under quiet geomagnetic conditions are shown in Figures 5 and 6. The northern and southern crests of equatorial anomaly are distinctly apparent in the figures. Results of HORT images comparison with the ionosondes data and LORT reconstructions are presented. The analysis showed that wavelike ionospheric structure is reproduced with high accuracy. Ionosphere containing irregularities is worse reconstructed: not all maxima of the real ionosphere are reflected in the cross-section. In Figures 7 and 8 an example is shown illustrating the comparison between HORT and LORT imaging of Alaska region ionosphere at 19:10UT of 29 October 2003 during the period of an extra strong geomagnetic storm. As seen from the figures, the maxima of electron density are close to each other but the wavelike structures observed in LORT images are not resolved in HORT cross-sections.

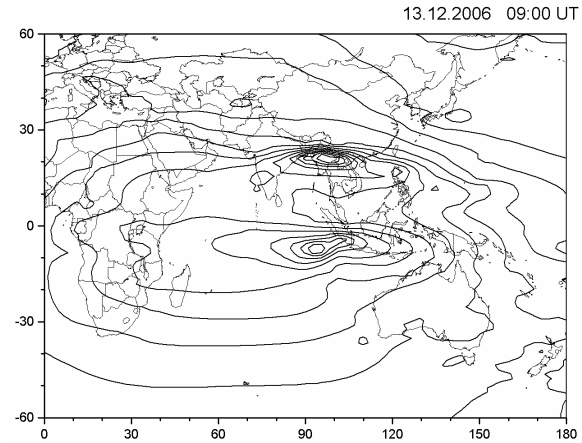

Fig.5. Contours of VTEC (eastern hemisphere) on 13.12.2006 at 09:00UT as obtained from HORT data

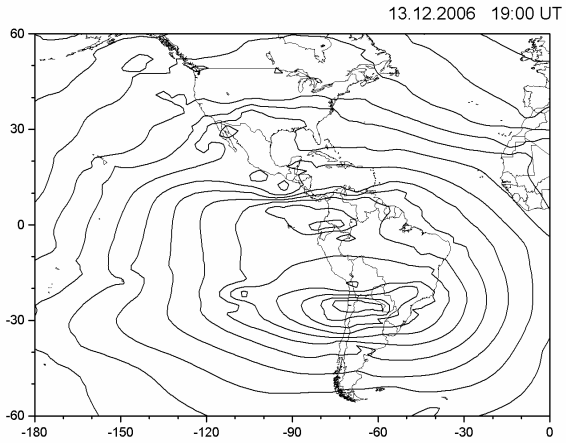

Fig.6. Contours of VTEC (western hemisphere) on 13.12.2006 at 01:00UT as obtained from HORT data

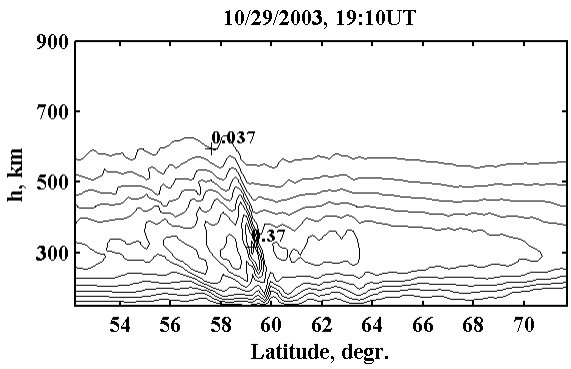

Fig.7. RT image of the ionosphere over Alaska obtained by LORT on 10/29/2003 at 19:10 UT

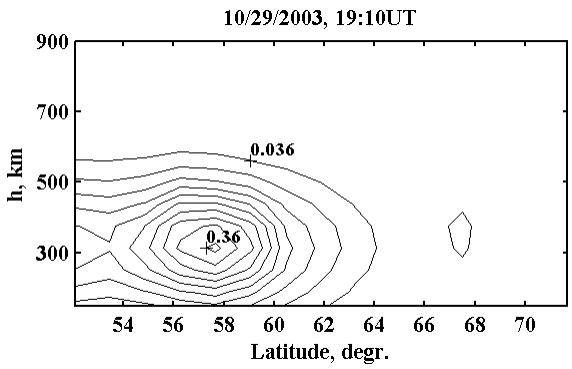

Fig.8. RT image of the ionosphere over Alaska obtained by HORT on 10/29/2003 at 19:10 UT

4. Radio Tomography and Radio occultation

In April 2006 a new satellite system FormoSat3/COSMIC (Taiwan's Formosa Satellite Mission #3 and Constellation Observing System for Meteorology, Ionosphere and Climate) had been put into operation. The system comprises 6 low-orbital satellites flying at about 800 km heights. FormoSat-3/COSMIC satellites are payloaded with triple-band radio beacons suitable for low-orbital tomography; also measurements of GPS signals are carried out at these satellites. A method is developed for calculating radio occultation electron density profiles from FormoSat-3/COSMIC data allowing for the effects of large-scale gradients and ionospheric plasma irregularities [8-12]. On average, it is possible to obtain about 1800 radio occultation profiles per day to be used for calculating ionospheric parameters including ionospheric plasma frequencies (e.g., *foF2* and *foE*), ionospheric top heights (e.g., h_mF2 and h_mE) and other. Radio tomography with ground measurements of satellite transmissions implies that ionospheric sounding is carried out with a wide range of different locations of receiving/transmitting systems. In this sense the RO method providing additional data at a set of tangential rays (along satellite-to-satellite paths) is a particular case

of radio tomographic technique. Examples of RO profiles comparison with electron density profiles obtained from LORT and HORT ionospheric images are shown in the presentation.

5. Conclusion

LORT and HORT combination provides significant advantages such as a possibility to obtain 3D ionospheric images within large regions (owing to HORT) and to considerably improve the resolution (owing to LORT). Combined use of RT and RO methods implying that the RT data measured by ground receivers are supplemented with the satellite-to-satellite sounding data (RO data) makes it possible to achieve noticeably higher vertical resolution of RT imaging and to to realize an effective global and regional monitoring of ionospheric plasma.

6. Acknowledgments

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7. References

1. V.E.Kunitsyn and E.D.Tereshchenko, Ionospheric Tomography. Springer-Verlag. 2003.
2. S.E.Pryse, "Radio tomography: A new experimental technique", *Surveys in Geophysics*, 2003, **24**, pp.1-38.
3. E.S.Andreeva, S.J.Franke, K.C.Yeh and V.E.Kunitsyn, "Some features of the equatorial anomaly revealed by ionospheric tomography", *Geophys. Res., Lett.*, **27**, 2000, pp. 2465-2468.
4. K.C.Yeh, S.J.Franke, E.S.Andreeva and V.E.Kunitsyn, "An investigation of motions of the equatorial anomaly crest", *Geophys. Res., Lett*., **28**, 2001, pp. 4517-4520.
5. S.J.Franke, K.C.Yeh, E.S.Andreeva and V.E.Kunitsyn, "A study of the equatorial anomaly ionosphere using tomographic images", *Radio Sci*., **38**, 2003, 1011, doi:10.1029/2002RS002657
6. V.E.Kunitsyn, E.S.Andreeva, S.J.Franke and K.C.Yeh, "Tomographic investigations of temporal variations of the ionospheric electron density and the implied fluxes", *Geophys. Res. Lett*., **30**, 2003, 1851-1854.
7. V.E,Kunitsyn, E.S.Andreeva, M.A.Kozharin and I.A,Nesterov, "Ionosphere radio tomography using high-orbit navigation system", *Moscow University Physics Bulletin*, **60**(1), 2005, pp.94-108.
8. L.-C. Tsai, W. H. Tsai, W. S. Schreiner, F. T. Berkey, and J. Y. Liu, "Comparisons of GPS/MET retrieved ionospheric electron density and ground based ionosonde data", *Earth Planets Space*, **53**, 2001, pp.193-205.
9. L.-C.Tsai, C.H.Liu, W.H.Tsai, and C.T.Liu, "Tomographic imaging of the ionosphere using the GPS/MET and NNSS data", *J. Atmos. Sol. Terr. Phys*., **64**, 2002, pp.2003-2011.
10. L.-C.Tsai, W. H. Tsai, "Improvement of GPS/MET ionospheric profiling and validation with Chung-Li ionosonde measurements and the IRI", *Terrestrial, Atmospheric and Oceanic Sciences*, 2004, V.15(4),P.589-607.
11. L.-C.Tsai, W. H. Tsai, J. Y. Chou, and C. H. Liu, "Ionospheric tomography of the reference GPS/MET experiment through the IRI model", *Terrestrial, Atmospheric and Oceanic Sciences*, **17**(1), 2006, pp.263-276.
12. L.-C.Tsai, C.H. Liu, and T. Y. Hsiao, "Profiling of ionospheric electron density based on the FormoSat-3/COSMIC data: results from the intense observation period experiment", *Terrestrial, Atmospheric and Oceanic Sciences*, in press, 2007.
13. http://www.haarp.alaska.edu/haarp/data.fcgi.