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Analysis of the ionosphere/plasmasphere electron content variability during strong geomagnetic storm

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Abstract

The ionosphere/plasmasphere electron content (PEC) variations during strong geomagnetic storms in November 2004 were estimated by combining of mid-latitude Kharkov incoherent scatter radar observations and GPS TEC data derived from global TEC maps. The comparison between two independent measurements was performed by analysis of the height-temporal distribution for specific location corresponding to the mid-latitudes of Europe. The percentage contribution of PEC to GPS TEC indicated the clear dependence from the time with maximal values (more than 70%) during night-time. During day-time the lesser values (30–45%) were observed for quiet geomagnetic conditions and rather high values of the PEC contribution to GPS TEC (up to 90%) were observed during strong negative storm. These changes can be explained by the competing effects of electric fields and winds, which tend to raise the layer to the region with lower loss rate and movement of the ionospheric plasma to the plasmasphere.

Keywords: Plasmasphere; Ionosphere; Total electron content, Electron density profiles; Incoherent scatter radar

1. Introduction

Specification and forecasting of the upper atmosphere plasma distribution are fundamental for mitigation of space weather effects for communication, radio propagation and GNSS applications. The characteristics of the Earth's upper atmosphere ionized part are responding to variations of solar and magnetic activity. Nowadays the measurements of Global Positioning System (GPS) are widely used by the scientific community for the Earth's atmosphere studies. The dense network of GPS receivers fulfills simultaneous coverage in global scale with high temporal resolution. The height of GPS/GLONASS orbits is about 20,200 km above the Earth's surface, and so most part of the propagation path of a radio signal from a GPS satellite to ground-based GPS receiver is mainly within the plasmasphere. As the electron densities in the plasmasphere are several orders of magnitude less than in the ionosphere (Gallagher et al., 2000), the plasmasphere is often ignored at analysis and estimation of GPS TEC data, however the plasmaspheric contribution to the GPS TEC can become significant under certain conditions, especially during geomagnetic disturbances. Actuality and timeliness of plasmasphere morphology and dynamics investigations is dictated by the urgent need to include plasmaspheric density into current empirical models of the ionosphere to make them proper for GPS TEC simulation and comparison, as well as for adjustment of GPS TEC into these models.

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The plasmasphere is filled by the plasma outflow from the underlying ionosphere along geomagnetic field lines (Lemaire and Gringauz, 1998). As an element of the Earth's space weather system, the plasmasphere is subject to substantial changes during geomagnetic disturbances in space induced by solar activity. Ionospheric responses to enhanced geomagnetic activity are often analyzed in terms of the electron density increases (positive ionospheric storm effects) or decreases (negative ionospheric storm effects). Understanding of positive and negative ionospheric storm changes is of particular interest because they can have significant effects on large regions of the upper atmosphere. The structure and dynamics of the plasmasphere are responding to the geomagnetic disturbance activity. The loss and refilling of the plasma density in the plasmasphere have been studied extensively in the past from the limited perspective of individual ground based measurements or satellite crossings of the plasmasphere. The outflow of plasma from the ionosphere is one of the main factors that determine size, shape and the dynamics of the plasmasphere, which vary strongly according to the level of geomagnetic activity (Rishbeth et al., 1978; Brunelli and Namgaladze, 1988; Lemaire and Gringauz, 1998).

There are in-situ and whistler measurements led to the discovery of the plasmasphere in the 1960s, the helium EUV emission was used to global imaging image the Earth's plasmasphere and several theoretical and empirical models of the plasmasphere were developed since then. But a number of unknowns still persist. The clarifications of them are essential for holding a predictive capability of the near-Earth space weather in the plasmasphere region (Ganguli et al., 2000).

In the past several decades, many new remote sensing methods have been developed and applied to the plasmasphere. In earlier studies the estimation of the plasmaspheric density factor was done by analysis of correlations of different TEC measurements for common ionospheric penetration points. Implicit in this formulation is the assumption that the plasmaspheric TEC contribution is nearly constant on a diurnal basis during quiet period of high solar activity (Lunt et al., 1999). Nowadays there are appeared the new opportunities for more detailed study of PEC distribution. TEC data derived from ground-based GPS receivers contain little information about the vertical structure of ionospheric electron density and satellite-borne TEC observation could be used to supplement the ground-based receivers. The total number of electrons along a ray path from GPS satellites to a ground-based receiver is called total electron content (GPS TEC), this value is composed by ionospheric electron content, IEC, and plasmaspheric electron content, PEC. So, the contribution of PEC to the GPS TEC can be estimated from the simultaneous measurements of GPS TEC and IEC. Estimates of IEC can be retrieved as a result of integration of the ionospheric electron density profiles (EDPs). For this aim one can use EDPs derived from satellite radio occultation (RO) or ground-based radio-physical measurements. GPS RO data establish the basis for a new remote sensing technique for vertical profile information on the electron density of the entire ionosphere from satellite orbit heights down to the bottom side (Heise et al., 2002; Kirchengast and Foelsche, 2004; Jakowski et al., 2005; Liou et al., 2010). Using data of the first successful RO mission CHAMP, Jakowski et al. (2002) carried out the detailed investigation of the Earth's plasmasphere 3D structure. Belehaki et al. (2004) combined ionosonde and GPS TEC measurements for plasmaspheric electron content estimation. The new RO mission FORMOSAT-3/COSMIC made a positive impact on a global ionosphere and plasmasphere study, providing essential information about the altitudinal electron density distribution; particularly over regions that are not accessible by ground-based measuring instruments such as ionosondes and GPS dual frequency receivers.

2. Measurements and data

The RO measurement is a very useful tool for climatologically study of regular PEC distribution on a global scale (Cherniak et al., 2012), but the number of EDPs provided by RO missions is still insufficient to study the daily behavior of the ionosphere over any specified location. Possible data sources for the investigations of the rapid PEC changes are incoherent scatter (IS) radars that are able to provide electron density profiles of both bottomside and topside parts of the ionosphere with rather high temporal resolution during their measurement campaigns. The IS method is one of the most efficient ground-based radio-physical methods to investigate the ionosphere. The IS radars use operating frequencies which are much higher than the critical frequencies of the ionosphere's maximum and the method provides a possibility to study topside ionosphere from the ground. It allows to measure the ionospheric EDPs in a wide range of altitudes and estimate their behavior during perturbation of various origins. Besides the electron density distributions, IS radars also provide several other physical parameters (such as plasma velocities, electron and ion temperatures, etc.), that are extremely valuable in understanding the physical processes and mechanisms affecting the large-scale ionospheric density distribution.

The combination of two independent measurement sources was used in order to estimate the ionosphere and plasmasphere height-temporal distribution for European mid-latitudes location, corresponding to Kharkov incoherent scatter radar coordinates (geographic: 49.6°N, 36.3°E, geomagnetic: 45.7°N, 117.8°E, McIlwain parameter $L = 1.9$). For the Kharkov IS radar, located on 36.3°E longitudes the local time corresponds to LT $\approx$ UT + 2 h.

The EDPs on Kharkov IS radar were obtained by using of double-frequency measuring channel with the compound sounding signal developed by the author (Cherniak and Lysenko, 2013). This method based on transmitting of a two-frequency composite signal with