LEO GPS Measurements to Study the Topside Ionospheric Irregularities

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ABSTRACT

GPS measurements from Precise Orbit Determination (POD) GPS antenna onboard Low Earth Orbit (LEO) satellites can be an effective tool for monitoring the occurrence of the topside ionospheric irregularities and may essentially contribute to the multi-instrumental analysis of the ground-based and in situ data. In the present study we analyze the occurrence and global distribution of ionospheric irregularities during the main phase of the geomagnetic storm of 29-31 August 2004 on the base of LEO GPS measurements, as well as in situ data from CHAMP and DMSP satellites. To study GPS fluctuation activity we used TEC-based indices ROT (rate of TEC change) and ROTI (rate of TEC Index), proposed by *Pi et al.* [1997]. Using the CHAMP GPS measurements, we created maps of GPS phase fluctuation activity and found two specific zones of the most intense irregularities: (1) the region of the auroral oval at high latitudes of both hemispheres and (2) the low latitudes/equatorial region between Africa and South America. At high latitudes, the topside ionospheric irregularities appeared to be more intensive in the southern hemisphere, which is, most likely, due to seasonal variations in the interhemispheric field-aligned currents system. An analysis of multi-instrumental observations reveals reinforcement of the equatorial ionization anomaly after sunset in Atlantic sector on 30 August and formation of the significant plasma depletions and irregularities over a large longitudinal range. Equatorial irregularities were also found in the morning sector at the recovery phase of the storm. For the first time, we show that a global distribution of ionospheric irregularities caused the phase fluctuations in GPS measurements from LEO CHAMP satellite. Application of ROTI technique to LEO GPS data shows its sensibility even to a rather moderate geomagnetic storm.

1. INTRODUCTION

Ionospheric irregularities generated mainly at the bottom-side ionosphere can develop in time and space, as a result the ionospheric irregularity region extends vertically to high altitudes, at least 2,000-3,000 km [e.g. *Phelps and Sagalyn*, 1976; *Su et al.*, 2006]. As it was stated by *Woodman* [1993], the topside irregularities are always originated in the linearly unstable bottom-side ionosphere. While the ionospheric irregularities of the bottom-side ionosphere and F-region in the equatorial and auroral regions have been extensively studied with the wide range of ground-based measuring facilities such as ionosondes, incoherent scatter radars, VHF/HF coherent backscatter radars, all-sky cameras, GPS stations, investigations of the topside ionospheric irregularities are mostly limited by ground-based radars and in-situ observations using probes carried by Low Earth Orbit (LEO) satellites. In the present paper we demonstrate that GPS phase fluctuations measurements from the GPS receiver onboard LEO satellites can be an effective tool for monitoring the occurrence of the topside ionospheric irregularities and may essentially contribute to the multi-instrumental analysis of the ground-based and in-situ data.

2. GEOMAGNETIC STORM OF 29-31 AUGUST 2004

Geomagnetic storm, occurred on 29-31 August 2004, was rather moderate one in comparison with other severe geomagnetic events during the years 2003-2004; however, it can be considered as an intensive storm according to the maximum Dst index variations below -100 nT. An interplanetary shock was observed at ~09:00 UT on 29 August by the Advanced Composition Explorer (ACE), which gives the time of sudden storm commencement (SSC) of 10:04 UT on the Earth (vertical dashed line in Fig. 1). With the shock arrival, an abrupt increase of the solar wind speed was observed, along with sudden changes in solar wind ram pressure and proton density (Fig. 1). The interplanetary magnetic field (IMF) Bz component showed a smooth rotation, indicating a magnetic cloud. The geomagnetic storm had a long and monotonic development before the peak of SYM-H, which occurred at 22:00 UT on 30 August (minimum SYM-H excursion of -128 nT). The auroral electrojet (indicated by A_E index) showed a small short-term increase ~4 h after the shock arrival on 29 August. However, much more prominent enhancement in the AE-activity was observed from ~5 UT to 23 UT on 30 August, when the IMF Bz turned southward and remained that for many hours. Consequently, the substorm activity remained highly enhanced (with AE up to 1000-1200 nT) from 09 to 23 UT on 30 August and further continued during many hours on 31 August (Fig. 1). The recovery phase lasted almost 5 days.
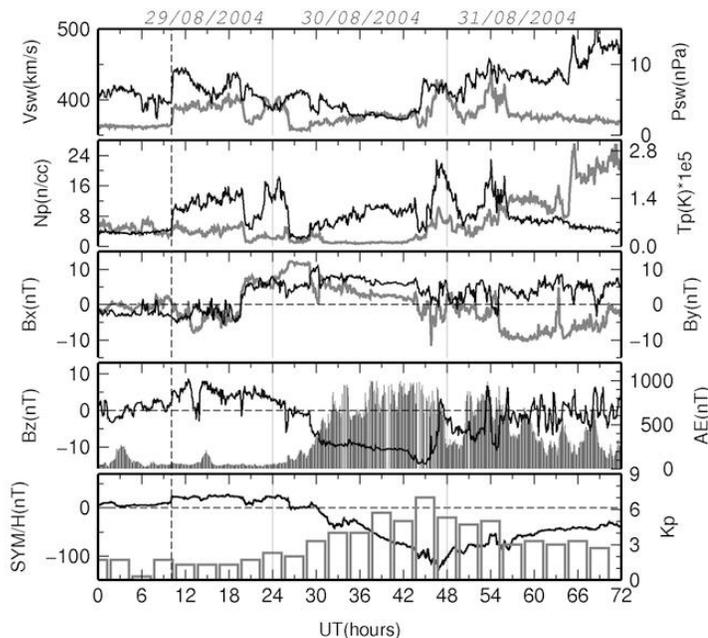
Figure 1. Variations of interplanetary and geomagnetic parameters during 29-31 August 2004 geomagnetic storm (from OMNIWeb Plus services, http://omniweb.gsfc.nasa.gov/).

3. DATABASE

Multi-instrumental dataset was used in this research. Most important results come from CHAMP measurements. The in-situ electron density at ~400 km height was obtained from CHAMP PLP measurements. The data of the POD antenna of the onboard GPS receiver were used to determine the total electron content (TEC) between CHAMP and GPS satellites, viz, topside ionosphere/plasmasphere electron content in the altitudinal range of 400-20,200 km. The ion

concentration Ni at ~840 km height was obtained from the in-situ plasma measurements by DMSP F15 satellite. GPS TEC from ground-based stations was obtained using IGS network.

4. GPS DATA ANALYSIS

Ionospheric irregularities can be characterized by measuring their impact on the amplitude and phase of the received GPS signal. In order to estimate slant TEC from the frequency-differenced GPS phase delay the well-known algorithms were used from [*Blewitt*, 1990]. During phase TEC processing, detection and correction of cycle slips, loss-of-lock and multipath were done.

Pi et al. [1997] proposed to use the time-derivative of TEC (ROT, rate of TEC change) as a measure of phase fluctuation activity and the Rate of TEC Index (ROTI) as a GPS-based index that characterizes the severity of the GPS phase fluctuations and detects the presence of ionospheric irregularities, as well as measures the irregular structures of TEC spatial gradient. ROT is calculated using the algorithm (Eq. 1):

$$ROT = \frac{TEC_k^i - TEC_{k-1}^i}{(t_k - t_{k-1})} \quad (1)$$

where i is a visible satellite and k is the time of epoch. The CHAMP RINEX files raw data are 10 seconds sampled. ROT is calculated in units of TECU/min, where 1 TECU=10^{16} el/m^2, for each visible GPS satellite at CHAMP position. The ROT values are then calculated and detrended for all individual satellite tracks for elevation angles over 50 degrees. Based on the retrieved values of ROT, the ROTI values are calculated over 1-minute period with running window (Eq. 2):

$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2} \quad (2)$$

Here we used a thin-layer model based on the assumption that all electrons are concentrated in an infinitely thin spherical shell at 450 km of height; locations of the phase fluctuations are related to the locations of the ionosphere piercing points. Along the satellite pass we use a grid of 1 deg x 5 deg resolution in latitude and longitude correspondingly. The value in every cell is calculated by averaging all ROTI values in the cell area.

It should noted that the ROT/ROTI technique by the ground-based GPS observations is widely used to track signatures of the ionospheric irregularities and their influence on the performance of navigation systems, whereas results of the ROTI technique applied to LEO GPS observations were not reported yet.

To estimate vertical TEC from CHAMP GPS measurements, firstly we calculate the slant TEC obtained from pseudorange measurements; then to obtain the absolute slant TEC we use a phase-leveling code algorithm described in [*Ma and Maruyama*, 2003]. The retrieved slant TEC should be calibrated from instrumental biases. Differential code biases (DCB) for GPS satellites are used from the final IGS GIMs product. To estimate the unknown DCB for CHAMP receiver we apply algorithm generally used in UCAR/CDAAC for LEO GPS data processing [*Yue et al.*, 2011]. Slant TEC values were scaled to estimate vertical POD TEC using a geometric factor derived by assuming the plasma occupies a spherical thin shell at the altitude of 450 km. The elevation angle cut-off was selected as 50 deg. In the case when several GPS satellites were above the cut-off angle the values of vertical TEC were averaged to obtain a single POD VTEC value for each epoch.

5. RESULTS

We examine spatial-temporal variation of the ionospheric irregularities observed in GPS phase fluctuations by using CHAMP GPS measurements. To the best of our knowledge, attention has never been paid on ROT/ROTI observations from GPS receiver onboard LEO satellite. Figure 2 presents global maps of the ROTI variability along CHAMP passes during 30-31 August 2004 and average ROTI maps for the evening post-sunset (left panel) and morning (right panel) sectors. All passes are shown in chronological order from right to left. Approximate time of the geographic equator crossing time in universal time (UT) is indicated at the top part of each graph, the equator crossing time in local time (LT) was about 21 LT for the evening sector and 09 LT for the morning sector. Maps are presented in geographic coordinates. The data gaps are due to either missing of GPS observations in RINEX file or no GPS satellites being above 50 deg elevation angle.

As a reference source for the quiet time, the top panel of Fig.2 presents the average maps calculated from CHAMP ROTI observations from the set of 14 quiet days in August 2004 before the considered event. The average ROTI map is constructed with grid sectors of 5 deg x 10 deg resolution in latitude and longitude correspondingly; the value in every cell is calculated by averaging all ROTI values covered by this cell area. Average ROTI map for the morning sector (Fig. 2d) illustrates very a low intensity of fluctuations activity with higher values observed at high latitudes; whereas, for the evening sector (Fig. 2a) one can observe more intense level of fluctuations activity with increased ROTI values at high and equatorial latitudes.

Next graphs (Fig.2b,c,e,f) illustrate maps with separate CHAMP ROTI passes during 30-31 August 2004. We observe a significant increase of the fluctuation activity level during the prolonged main phase of the storm, practically on the whole day of 30 August. As the CHAMP altitude was ~400 km, the detected GPS phase fluctuations were related to plasma irregularities at the topside ionosphere. The occurrence of the most intense ionospheric irregularities can be seen as regions with the very high ROTI (equal to 5 and higher) values. We can clearly observe two specific zones of the most intense irregularities – first is the region of the auroral oval at high latitudes of both hemispheres, the second one is the low-latitudes/equatorial region between Africa and South America. Comparison between the observed irregularities and the reference quiet-time maps reveals considerably higher level of the intensity as well as the expansion of the areas affected by the irregularities' occurrence. In the next sections we demonstrate the reliability of the ROTI-detected ionospheric irregularities by comparison with independent instruments' measurements.

6. CONCLUSIONS

For the first time, we show a global distribution of ionospheric irregularities caused the phase fluctuations in GPS measurements from LEO CHAMP satellite. Application of ROTI technique to LEO GPS data shows its sensibility even to a rather moderate geomagnetic storm. We show that the LEO ROTI technique allows to successfully detect the electron density irregularities at the topside ionosphere above the CHAMP orbit from GPS signal measurements under geomagnetically quiet and disturbed conditions. Due to the availability of GPS POD data derived from multi-satellite missions like FORMOSAT-3/COSMIC and Swarm, ROTI technique based on topside LEO GPS measurements could essentially contribute to a global space weather monitoring system and provide a valuable database to study the ionospheric irregularities occurrence.
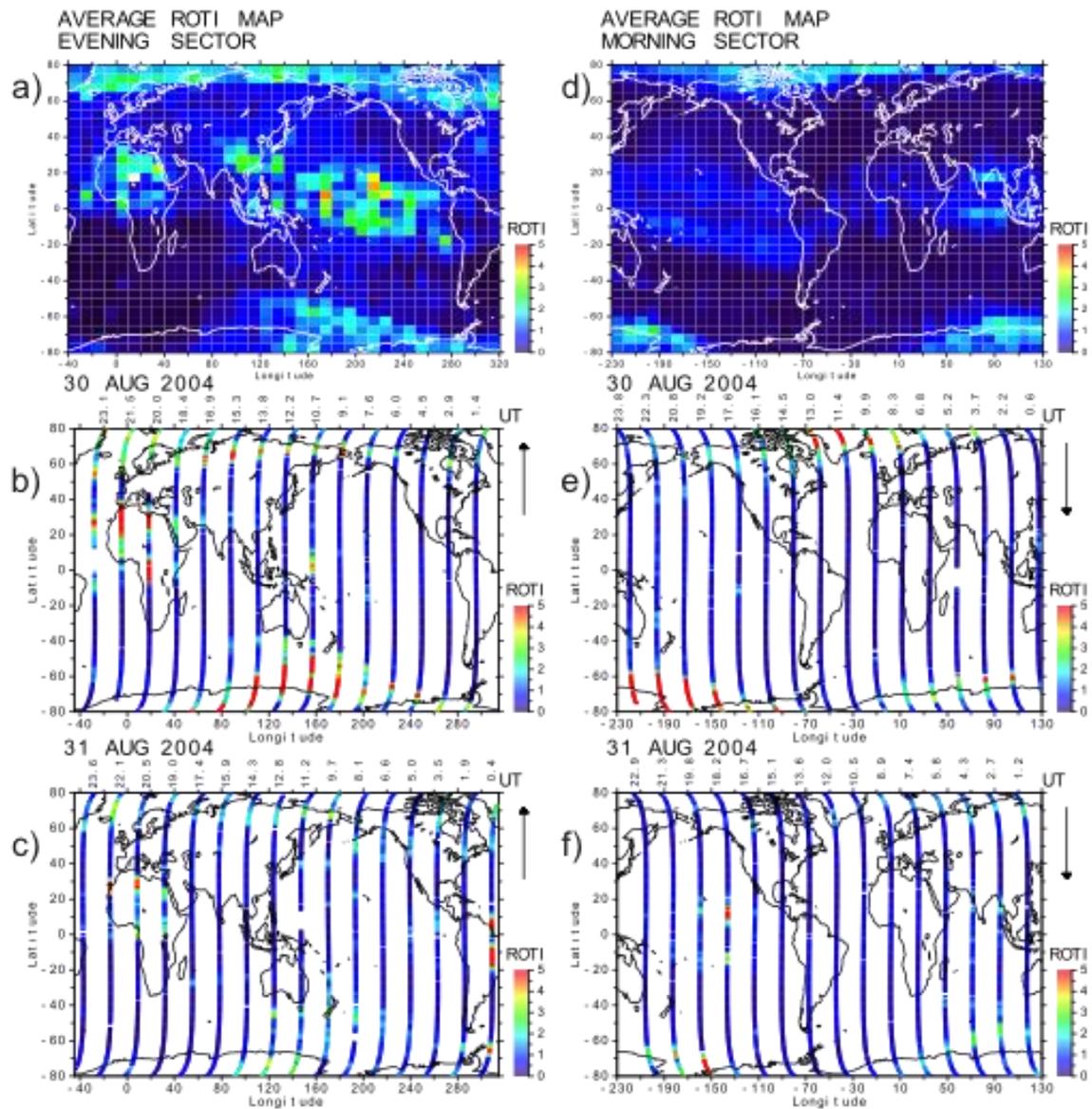
Figure 2. Global maps of CHAMP ROTI observations. Top panel presents average ROTI maps for quiet time period. Global maps of the ROTI variability along CHAMP passes on 30-31 August 2004 for evening (left panel) and morning (right panel) sectors. All passes are shown in chronological order from right to left. Approximate time of equator crossing time in UT is indicated at the top part of each graph, the equator crossing time in LT was about 21 LT for evening sector and 09 LT for morning. Maps are presented in geographic coordinates.

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www.cosmic.ucar.edu/cdaac/products.html). We are grateful to International GNSS Service (IGS) for GPS data and products (ftp://cddis.gsfc.nasa.gov/pub/gps/data/daily/).

REFERENCES

Blewitt, G. (1990), An automatic editing algorithm for GPS data, *Geophys. Res. Lett., 17*, 199-202.

Ma, G., & T. Maruyama (2003), Derivation of TEC and estimation of instrumental biases from GEONET in Japan. *Ann. Geophys.*, 2083–2093.

Phelps, A. D. R., & R. C. Sagalyn (1976), Plasma density irregularities in the high-latitude top side ionosphere, *J. Geophys. Res.*, 81(4), 515-523.

Pi, X., A. J. Mannucci, U. J. Lindqwister & C. M. Ho (1997), Monitoring of global ionospheric irregularities using the worldwide GPS network, *Geophys. Res. Lett.*, 24, 2283.

Su, S.-Y., C. H. Liu, H. H. Ho, & C. K. Chao (2006), Distribution characteristics of topside ionospheric density irregularities: Equatorial versus midlatitude regions, *J. Geophys. Res.*, 111, A06305, doi:10.1029/2005JA011330.

Woodman, R. F. (1993) Equatorial ionospheric irregularities as observed by Jicamarca radar, in *Low-Latitude Ionospheric Physics, COSPAR Colloq. Ser.,* vol.7, 83-95.

Yue, X., W. S. Schreiner, D. C. Hunt, C. Rocken, & Y.-H. Kuo (2011), Quantitative evaluation of the low Earth orbit satellite based slant total electron content determination, *Space Weather*, 9, S09001, doi:10.1029/2011SW000687.