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STORM-TIME OCCURRENCE OF TEC FLUCTUATIONS ASSOCIATED WITH POLAR PATCHES USING GPS MEASUREMENTS

Irk Shagimuratov, Ivan Efishov, Yurij Ruzhin, Nadezhda Tepenitsyna (*WD IZMIRAN, Kaliningrad, Russia, pcizmiran@gazinter.net*)

Abstract: The paper presents an analysis of the occurrence of strong phase fluctuations of GPS signals observed at Antarctic stations. The fluctuations caused large scales ionospheric irregularities which were associated with the occurrence of polar patches in TEC.

1. Introduction

The ionosphere irregularities are responsible for scintillations and phase fluctuations of GPS signals. The scintillations are caused by small irregularities with scale less than 50 km and phase fluctuations are caused by large scale irregularities. Because of the depressive nature of the ionosphere the dual-frequency GPS phase measurements provide useful information about variations of the ionospheric total electron content (TEC). The intensity of scintillation essentially increases during geomagnetic storms. Several studies used GPS observations to monitor TEC fluctuation caused irregularities [1,2]. The indices ROT and ROTI have been used [3] as a measure of the activity of phase fluctuations. Aarons et al. [1] using high-latitude GPS stations from IGS network showed the development of phase fluctuations for individual storms.

In this paper we describe the occurrence of GPS phase fluctuations during November 2004 events on the basis of Antarctic GPS observations. This study concerns the analysis of strong phase fluctuations which we associated with polar patch structures. Polar cap patches are regions of enhanced ionization which drift across the polar cap in an anti-sunward direction from the source region near the dayside auroral oval [4]. In the patches, the electron density can exceed a factor of 2-10 above the background. The horizontal dimensions of patches are 100 - 1 000 km. They drift through the ionospheric polar caps under the influence of high-latitude convection at speeds up to 1 000 m/s. Plasma density small-scale irregularities found within patches are responsible for scintillation of trans-ionospheric radio signals, and the TEC fluctuations produced by patches can also have adverse effects on communications and navigation systems [5].

The first observations of patch structures with the GPS technique were presented in [6]. The intensive TEC fluctuations observed along GPS satellite passes demonstrate a strong horizontal gradient of TEC. Fluctuation effects and TEC gradients connected with patches can have a different impact on GPS measurements and data processing for high-precision GPS positioning. They affect the phase ambiguity resolution, increase the number of undetected and uncorrected cycle slips and loss of signal lock [7].

The longitude and latitude picture of the storm-time occurrence of phase fluctuations are presented in detail for polar and auroral latitudes.

2. Analysis

2.1. Data source

GPS data from IGS network were used to study the development of phase fluctuations during a geomagnetic storm. The GPS observations covering auroral and polar ionosphere enable one to investigate the latitudinal occurrence of phase fluctuations depending on the geomagnetic activity. We used stations CAS1, DAV1, MAW1, MCM4 and SYOG in this study. The dual-frequency differential carrier phase L1 and L2 signals were examined to estimate the scintillation effects.

2.2. Estimation technique

Standard GPS observations carried out by IGS network provide TEC measurements with the interval of 30 sec. To estimate the phase fluctuations, TEC data with the rate of change of 1 min (ROT) were usually used:

$$ROT = 9.53 \cdot \left((\Phi_1 - \Phi_2)_{tj} - (\Phi_1 - \Phi_2)_{ti} \right),$$

where $\Delta t = t_j - t_i = 1$ min, Φ_1 and Φ_2 [m] denote the measured differential carrier phase observable of L1 and L2. A scaling factor converts the differential ionospheric delay to units of electrons/m2. When using ROT we avoid the problem of phase measurements biases.

The rate of TEC characterizes is relative to spatial changes of TEC along satellite passes. The absolute value of TEC in patches is a very important geophysical parameter. As known, the TEC measurements derive from phase measurements with integer ambiguities, as well as L1-L2 biases offsets at both transmitter and receiver biases and therefore intrinsically have unknown TEC biases. The TEC biases remain constant in the absence of cycle slips.

The absolute TEC and the instrumental biases were estimated using the single site algorithm [8]. To determine the ionospheric TEC a geometry-free linear combination of GPS observables was used. Usually the total vertical electron content (VTEC) is modeled. The vertical TEC is approximated by a spherical layer with infinitesimal thickness. The height of this layer, approximately 400 km, corresponds to the average latitudinal position of the electron density profile peak (hm). The value of the

TEC is the function of terrestrial longitude and latitude.
The slant TEC and vertical TEC with first-order approximation can be related by the geometrical factor

$$VTEC = TEC \times \cos z' \quad ,(1)$$

where z' is the zenith angle of the satellite on the layer height.
For the zenith angles less than 800 the error of the approximation is small and vanishes at zenith.
The biases were determined for every individual station using the GPS measurements for all satellite passes over station during a 24 hour period. Using this procedure an absolute TEC for all satellite passes observed over single station during 24 hour period is calculated.

2.3. Geomagnetic conditions

The day of November 2004 consisted of several geomagnetic active periods. Variations of Kp and Dst indexes are presented in Fig.1.

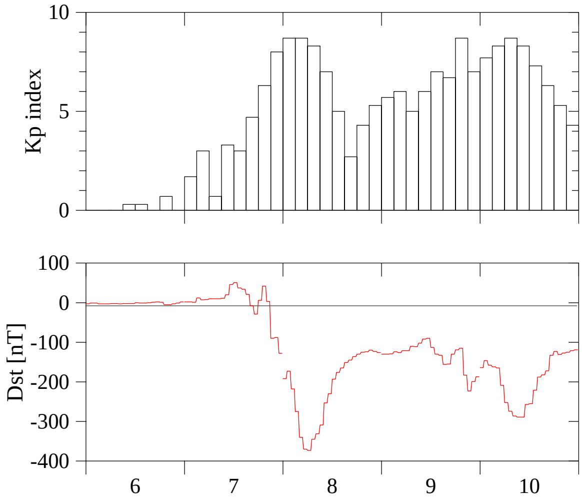

Fig.1. Kp and Dst variations during November 6-10, 2004

Dst variations show that the period under consideration consisted of sequence of magnetic storms. The sudden commencement (SC) occurred on November 7. The most disturbed days was November 10 (ΣKp=56), the maximal disturbance of the geomagnetic field took place on November 8, when Dst variations reached -370 nT and Kp reached the maximal value of 9. The detailed picture of the development of the geomagnetic disturbance show the variations of the geomagnetic field. In the analysis we used the geomagnetic data observed at auroral station of Mawson (64°N, 114°E).

2.4. Variations of TEC and phase fluctuations activity

The spatial and temporal development of TEC fluctuations is clearly observed in time variations in the dual frequency carrier phase along satellite passes. For example TEC variations for PRN 30 and PRN4 observed at polar Antarctic stations CAS1 and MCM4 during 17-23 UT on 6 and 9 November 2004 respectively are presented in Fig. 2a (right panel). November 6 was a very quiet day in contrast to the disturbed day of November 9.

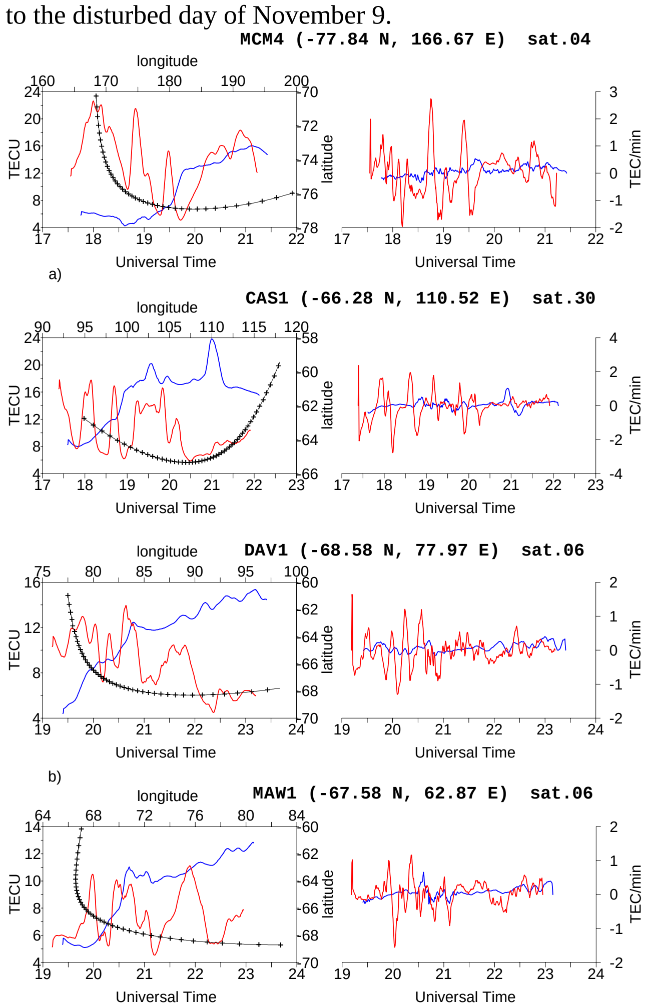

Fig2. Temporal TEC variations (left column) and raw phase fluctuations along individual satellite passes during the disturbed (red line) and quiet days (blue) observed at different stations. The subionospheric trajectories of satellite traces are also presented in the left column in geographic coordinates (dashed curves).

This figure also shows satellite ionospheric tracks at an altitude of 400 km, in geographic coordinates. Strong TEC fluctuations are exceptional features of the polar ionosphere. TEC eruptions are recognized as the structure with enhancements relative to the background. The increase in TEC can exceed the factor of 2-4, and the enhancement of TEC can exceed 10 TECU relative to the background.
The rate of changes of TEC for PRNs 30 and 4 at the same stations are presented on the left panel of Fig. 2. for November 6 and 9. During disturbance the fluctuations of TEC were essentially increased relative to quiet condition, the maximal values of ROT (3 TEC/min) were reached. In Fig 2b the variations of TEC for PRN 6, observed simultaneously at the nearest located stations: DAV1

and MAV1, longitudinally spaced about 15°, for quiet and disturbed days are presented. During the storm booth stations on edge of polar cup are ordered. During quiet conditions the stations were in auroral region of the ionosphere. Above both stations the intensity of phase fluctuations was less pronounced than in the polar ionosphere. It is seen in Figures 2b for DAV1 and MAV1. The TEC fluctuations demonstrate a similar structure for PRN 6.The time lag (about 40 min) between similar structures shows the TEC variations, demonstrates traveling of those inhomogeneous. For such a similarity of structures we can estimate the minimal speed drift. The time delay between the similar discrete structures corresponds to the propagation velocity of the patches (about 700 m·s-1).

2.5. Storm-time development of phase fluctuations

The occurrence of TEC fluctuations was analyzed using the rate of changes of TEC. ROT can be successfully applied to process large data files, because ROT eliminates phase ambiguities. Figure 3 presents the development of TEC fluctuations, using ROT, for the geomagnetic active period of 8-10 November 2004. The pictures illustrate the occurrence of TEC fluctuations for all passes of satellites observed at CAS1, MCM4, DAV1 MAW1 and SIOG over a 24 hour interval on quiet and disturbed days. The top panel demonstrates variations of in the geomagnetic field at Mawson which is located on the equatorial edge of the polar cap - Φ=70°. The occurrence of TEC fluctuations correlates very well with geomagnetic activity and the Bz component of the Interplanetary Magnetic Field. During the storm, the intensity of fluctuations strongly increased relative to quiet conditions.

At the polar stations CAS1 and MCM4 weak and moderate TEC fluctuations are detected all the time during a quiet day of November 6. During the storm the intensity of TEC fluctuations increased essentially.

At lower latitudes stations MAV1 and DAV1 (those stations located in the auroral region) the fluctuations during quiet conditions were detected only between 00UT and 06UT. At SYOG stations the activity of phase fluctuations was less pronounced because it remained all the time in the auroral region. The maximal activity of fluctuations took place on November 9. The analyses show that the occurrence of TEC fluctuations depends on the substorm activity which was maximally observed in the afternoon of November 9 (see behavior of Dst variations). During the previous and next days of 8 and 10 November activity phase fluctuations were less strong though the sum Kp amounted to 52 and 56, respectively. In [9] it was shown that patches occurrence depended weakly on the sum Kp value. At the same time, other authors showed that polar patches occurred during disturbed magnetic conditions. Our analysis of TEC fluctuations during a severe geomagnetic storm of March 31, 2001 shows that a strong TEC fluctuation was observed, when Kp reached 7-8 [10].

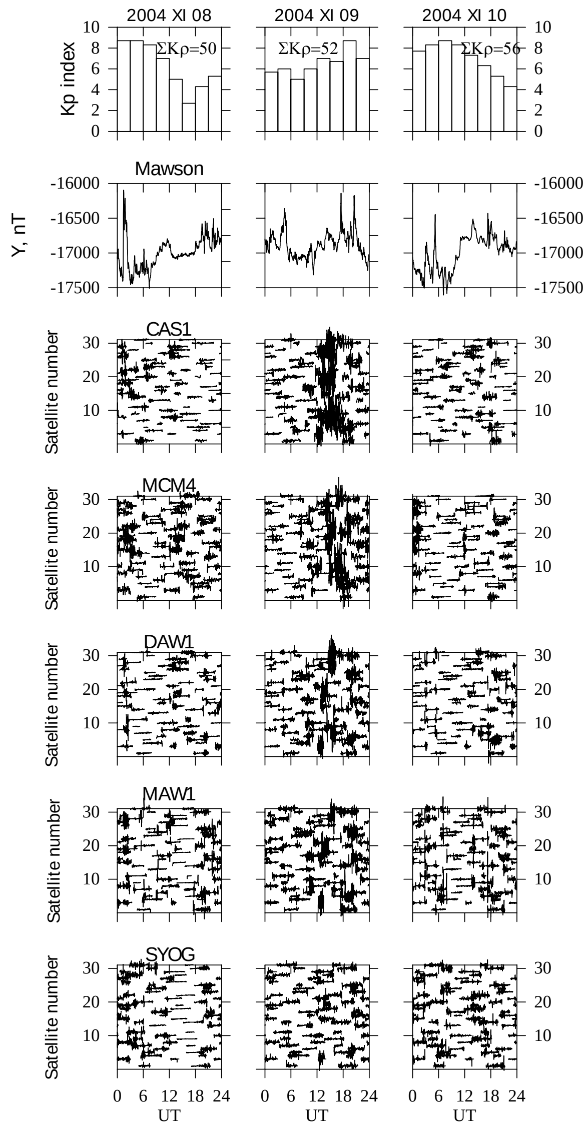

Fig.3. Magnetic activity at Mawson and the phase fluctuations occurrence at different stations on November 8-10 2004. The plots show the phase fluctuations for individual satellites.

The pictures clearly demonstrate that the patch activity on the disturbed days was controlled by UT. Over different stations, spaced in longitude and latitude, the occurrence of TEC fluctuations took place at the same time of UT. Phase fluctuations correlated with behaviour of geomagnetic activity

2.6. Activity of polar patches during the storm

The strong and deep fluctuations of TEC presented in Fig. 2 were caused by the presence of large-scale ionospheric structures of enhanced electron density in the polar ionosphere. These structures were associated with the occurrence of polar patches. The numbers of patches were evaluated by counting peaks of TEC enhancement along single satellites' trajectories. A number of 6 to 8 patches of different

intensity can be observed along individual satellite passes.
To evaluate the absolute enhancement of TEC in a patch the background (base level) was computed. The procedure computing of TEC base level data was similar to the elaboration of f0F2 measurements [9]. As an example, Fig.4, demonstrates the procedure of estimating TEC enhancement in a patch. Taking into account the fact that background can change along the satellite pass the base level also varies in time.
The method had been used when estimating TEC in patches against the background. Fig.5 shows the number of patches detected at Antarctic stations with different intensity (weak 0-4 TECU, moderate 4.1-8.0 TECU and strong more than 8.0 TECU).
The weak patches are registered all day at polar stations. The intensity of polar patches was maximal in the afternoon of November 9 when substorm activity was maximal and geomagnetic field at Mawson varied strongly

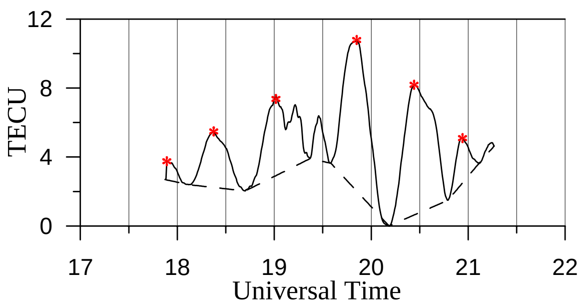

Fig.4 Procedure estimating of TEC enhancement in patches. The variation of TEC along satellite pass (solid), base TEC level (dashed).The patch structures are indicated by asterisk.

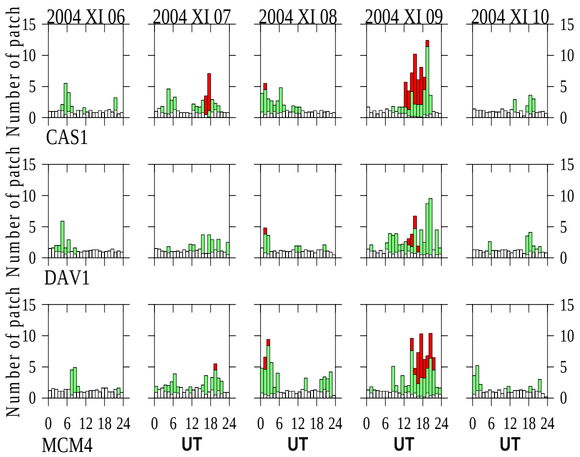

Fig.5.Diurnal variations of patch activity at different Antarctic stations over November 6-10, 2004 (white- intensity of patches less than 4 TECU, green- less than 8 TECU; red- more than 8 TECU).

3. Conclusion

Deep TEC fluctuations are regularly detected in phase measurements along individual GPS satellite passes at Antarctic stations. These fluctuations were associated with polar patches. The intensity of patch structures increased during geomagnetic disturbances, TEC fluctuations during the storm reached 10TECU. The enhancement of TEC exceeded 2-4 times the relative background. Storm-time occurrences of phase fluctuations were controlled by UT. The occurrence of patch structures depended little on the sum Kp index and was maximal during the substorm activity.

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