A Case Study of The Mid-Latitude GPS Performance at Nighttime During The Magnetic Storm of July 15, 2000

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Abstract

Using the geomagnetic storm of July 15, 2000 as an example, we investigated the dependence of GPS navigation system performance on the nightside at mid-latitudes on the level of geomagnetic disturbance. The investigation was based on the data from the global GPS system available through the Internet. It was shown that the number of GPS phase slips increases with the increasing level of disturbance and that there is a good correlation between the rate of $Dst$-variation and the frequency of slips. It was further shown that the relative frequency of slips has also a clearly pronounced aspect dependence. Phase slips of the GPS signal can be caused by the scattering from small-scale irregularities of the ionospheric E-layer. Phase slip characteristics are indicative of Farley-Buneman instabilities as a plausible physical mechanism that is responsible for the formation of geomagnetic field-aligned irregularities. Using simultaneous measurements of backscatter signal characteristics from the Irkutsk incoherent scatter
radar and existing models for such irregularities, we estimated the order of magnitude of the expected phase fluctuations of the GPS signal at a few degrees.

1 Introduction

The satellite navigation GPS system has become a powerful factor of scientific and technological progress worldwide, and enjoys wide use in a great variety of human activity. In this connection, much attention is given to continuous perfection of the GPS system and to the widening of the scope of its application for solving the navigation problems themselves, as well as for developing higher-precision systems for time and accuracy determinations. Even greater capabilities are expected in the near future through the combined use of the GPS with a similar Russian system (GLONASS). The operation of the GPS is considerably affected by characteristics of the medium lying along the path of signal propagation. Because of this it is important to analyze the GPS performance during strong geomagnetic disturbances that change the characteristics of one of the regions having the greatest influence on GPS signals, the ionosphere. Failures in the GPS operation in the polar and equatorial regions are frequently discussed (in, e.g., Skone et al., 2000). However, the presence of failures at mid-latitudes is scantily discussed in the literature (Afraimovich et al., 2000), in spite of reasonably complete spatial coverage and the extensive practical applications of GPS receivers just in the mid-latitude region.

This paper considers the dependence of the time and space distribution of phase slips (PS) of the mid-latitude GPS receivers on the nightside of the Earth based on using data from the Irkutsk incoherent scatter (IS) radar and time-coincident two-frequency phase measurements from the mid-latitude GPS receivers in the Earth’s northern hemisphere obtained during the geomagnetic disturbance on July 15, 2000 (17-24 UT (July 15, 2000), 00-07 of Irkutsk LT (July 16, 2000), with maximum values of Kp=9, and $Dst=-325$ nT) (Afraimovich et al., 2000).
2 Experimental layout

A preprocessing of the GPS data provided estimates of the normalized (to a total number of observations) relative density of phase slips (RDPS). Ascertaining the reason behind the increase in the slip density was also greatly facilitated by the intensity estimates of total electron content (TEC) variations for the same stations and time intervals determined by a standard technique of two-frequency measurements. The acquired data were used to derive the mean power spectrum \(< S^2(F) >\) of TEC variations - the result of an averaging of the energy spectrum of TEC variation for each path of the subionospheric point for all such paths. Throughout the text below, we shall use the TEC unit TECU equal to \(10^{16} \text{ m}^{-2}\) which is generally accepted in the literature.

We have also calculated the dependence of the RDPS as a function of line-of-sight (LOS) azimuth and elevation from the GPS receiver to the satellite. The azimuth was measured from the northward direction, and the elevation from the horizontal (is approximately equal to the cotangent of the ratio of the height of the subionospheric point to the range to it). For comparison, the data for the magnetically quiet day of July 29, 1999 were processed, during which the geomagnetic disturbance Dst index was on the order of \(-10 \text{ nT}\).

The Irkutsk IS radar is located at 120 km north of Irkutsk (53°N, 104°E); it is a monostatic facility for probing the mid-latitude ionosphere using the radio wave backscattering method at 154-162 MHz frequencies (Potekhin et al., 1999). The radar includes the linearly polarized receive-transmit antenna for making, based on the IS method (Evans, 1969), absolute measurements of the electron density from Faraday fadings of the received signal, as well as electron and ion temperatures and the plasma drift velocity in the ionospheric F-region (height range 170-750 km). During geomagnetic disturbances the radar can be used (Potekhin et al., 1999) to investigate the ionospheric E-layer (height range 100-120 km) using data on backscatter (BS) from small-scale irregularities extended along the Earth’s magnetic field (Haldoupis et al., 1997).

The antenna beam of the radar is such that when investigating the ionospheric F-region by the IS method, the scattered signal is received by the main lobe of the antenna beam. When investigating the E-layer by the BS method, the signal is received by the lower sidelobes of the beam, with a
power attenuation on the order of $10^{-11}$ with respect to the main lobe. The experiment under discussion involved measurements of the IS signal power, the BS signal power, and of the plasma drift velocity.

3 Description and discussion of the GPS data

The data presented in Fig. 1 clearly show a high correlation between the time derivative of the geomagnetic disturbance $Dst$-index and the number of PS. The number of phase slips exceeds one percent in the disturbance maximum, and the position of the maximum is closely time-coincident with maximum absolute values of $dDst/dt$. The data in Fig. 1a also intimate that on the magnetically quiet day of July 29, 1999, the number of PS decreases by several orders of magnitude (Fig. 1a, gray line with stars), compared with the number of PS during disturbed periods (Fig. 1a, black line). This suggests that the phase slips of the GPS receivers are associated with an increase of the level of geomagnetic disturbance and can be caused by phase distortions of GPS signals as they propagate through a disturbed region of the ionosphere that is abundant in irregularities of different scales.

Fig. 2 presents the spectral power $< S^2(F) >$ of TEC variations (Fig. 2a), and the dependence of the relative density of PS $P(N,E)$ on the position of the subionospheric point with respect to the GPS station’s location (Fig. 2b). It is evident from Fig. 2 that during the geomagnetic storm of July 15, 2000 (20-22 UT) the TEC variation power increases by 1-2 orders of magnitude, both in the low- and high-frequency parts of the spectrum. This suggests that the slips can be caused by phase distortions of GPS signals under the influence of small-scale irregularities (smaller than or on the order of the radius of the Fresnel zone), the amplitude of which increases with increasing geomagnetic disturbance level. Fig. 2b clearly shows a strong aspect dependence of the RDPS on the position of the subionospheric point (the direction of the beam to the satellite) - PS occur most commonly in the northward direction, at low elevations of the ”satellite-receiver” beam ($\alpha<300$).
4 Description and discussion of the Irkutsk IS radar data

One of the best-known types of small-scale irregularities, the scattering of which is characterized by a strong aspect dependence, are the geomagnetic field-aligned E-layer irregularities (Buneman, 1963; Farley, 1963).

Fig. 3 presents the data from the Irkutsk IS radar: the dependence of the scattered signal power and ionospheric plasma drift velocity as functions of time and radar range R. The measurements of the backscattered signal power were made with respect to the IS signal level corresponding in the figure to the 10 dB level. The drift velocity measurements were made from the frequency Doppler shift of the scattered signal (Haldoupis, 1997).

An analysis for a similar storm of September 25, 1998 showed that the strongest scattering occurring within the ranges of 550-1100 km corresponds to the scattering from the geomagnetic field-aligned ionospheric E-layer irregularities (Potekhin et al., 1999). Such irregularities are usually observed in the mid-latitude ionosphere during strong geomagnetic disturbances (Foster and Tetenbaum, 1991; Haldoupis, 1997). It is evident from Fig. 3b that between 22 and 24 UT the drift velocity exceeded the ion-sound velocity of 250 m/s; for that reason, the necessary conditions (Buneman, 1963; Farley, 1963) for the generation of such irregularities were satisfied. It was shown (Potekhin et al., 1999) that the signal that is scattered from E-layer irregularities is received by the lower sidelobes of the antenna beam in the direction northward of the radar; for that reason, the power of this BS signal is attenuated by 11 orders of magnitude due to the experimental geometry. The IS signal is received by the main beam lobe; therefore, it does not undergo such an additional attenuation.

A comparison of Fig. 3a and Fig. 1 reveals that the occurrence of an anomalously powerful scattering from geomagnetic field-aligned E-layer irregularities, maximum values of the derivative $dDst/dt$ and of the relative density of phase slips of GPS receivers are time-coincident.

The relation of the scattering cross-section of irregularities to the scattered signal power is defined by the radar equation (Isimaru, 1978) (within a factor that is unimportant for a further consideration):
\[ P_{rc}(\vec{R}) = \text{const} \cdot P_{tr} \frac{G^2(\vec{R})}{R^2} \sigma(\vec{R}) V \quad (1) \]

where \( P_{rc} \) and \( P_{tr} \) stand for the power of the scattered and sounded signals, respectively; \( G \) is the antenna power gain in the direction of the sounding volume; \( \sigma \) is the scattering section per unit volume; and \( V \) is the sounded volume.

The radar equation (1) can be used to estimate the relative scattering cross-section of irregularities, from which the scattering occurs (taking into consideration that the values of \( R, V \) and \( P_{tr} \) are of the same order of magnitude for the two different scattering mechanisms):

\[ \sigma_{BS} \sim P_{rc,BS} \frac{G^2_{IS}}{P_{rc,IS} G^2_{BS}} \sigma_{IS}. \quad (2) \]

The power of the backscattered signal \( P_{rc,BS} \) exceeds that of the incoherently scattered signal \( P_{rc,IS} \) by three orders of magnitude \( (P_{BS}/P_{IS}=10^3, \text{Fig. 3a}) \). The antenna gain in the two cases under consideration are related by the relation \( G^2_{IS}/G^2_{BS}=10^{11} \). The scattering section of the IS signal is known (Evans, 1969): \( \sigma_{IS} \sim 10^{-19} \text{ m}^{-1} \). Therefore, from (2) one can estimate the scattering section of geomagnetic field-aligned ionospheric E-layer irregularities at the mean frequency of 154 MHz of the Irkutsk IS radar.

\[ \sigma_{BS} \sim 10^{-5} \text{m}^{-1}. \quad (3) \]

5 The possible cause of phase slips of GPS receivers

One conceivable reason for PS of GPS receivers on the nightside can be the phase distortions of the GPS signal caused by the scattering from small-scale irregularities of ionospheric plasma.

The distribution \( P(\gamma) \) of the relative density of \( P \), constructed as a function of the angle \( \gamma \) between the propagation direction of the GPS signal and the geomagnetic field, has a pronounced tendency for an increase in relative density of PS as \( \gamma \) approaches \( 90^\circ \) (Fig. 4a). This result is also in good agreement with the feature pointed out in Section 3, the increase in the slip
density in the case of the northward directed LOS to the satellite at low elevations \( \alpha \).

We carried out a numerical simulation of the scattering from geomagnetic field-aligned irregularities using the international reference model of the magnetic field (IGRF) and the well-known model of irregularities (Uspensky and Starkov, 1987) that has an approximate form:

\[
\sigma_{BS}(\vec{R}) = \sigma_0 e^{-(h(\vec{R})-110)/10} 10^{-|\gamma(\vec{R})-90^\circ|/10}
\]  

(4)

where \( h(\vec{R}) \) and \( \gamma(\vec{R}) \) are the altitude of the point \( \vec{R} \) above ground level (in km) and the angle with the magnetic field (in degrees), respectively. To obtain \( P(\gamma) \), the expression (1) was integrated with respect to all directions of the vector \( \vec{R} \) in view of (4) and the directional pattern of the Irkutsk IS radar \( G(\vec{R}) \). The simulation showed that the strongest scattering occurs in the region close to the region of the experimentally observed maximum of the RDPS (Fig. 3b, 4b). This suggests that it is the scattering from the geomagnetic field-aligned E-layer irregularities which causes phase slips of GPS receivers.

Let us now estimate the level of phase distortions in terms of the proposed mechanism. By approximating the scattering section of the oriented irregularities by the experimental law \( \ln(\sigma_{BS}(k_1)) = a_0 + a_1 k^{-2.25} \) obtained in (Moorcroft, 1987), from (3) we can estimate the absolute scattering section per unit volume at the frequency \( f_1 = 1575.42 \) MHz of GPS performance:

\[
\sigma_{1575} = \sigma_{BS} \left( \frac{150}{1575} \right)^{2.25} \sim 10^{-8} - 10^{-7} \text{m}^{-1}.
\]

(5)

In accordance with Rytov’s method (Isimaru, 1978), phase distortions of the signal in a medium with the irregularity section \( \sigma \) per unit volume and with the propagation path length \( L \) in this medium, are defined by the expression:

\[
< \Delta \varphi^2 > = L \sigma / 2.
\]

(6)

Taking into account the thickness of the E-layer \( L \sim 10^4 \) m, it is possible to estimate minimum phase distortions of the GPS signal:

\[
\Delta \varphi \sim 3 \sqrt{< \Delta \varphi^2 >} \sim 10^{-1} - 10^{-2} \text{rad},
\]

(7)
taking into account the oblique propagation through the E-layer, $\Delta \varphi$ will be still larger.

Thus, in accordance with the proposed model, phase distortions of the signal can exceed a few degrees and lead, even in the case of such a noise-stable system as the GPS, to phase slips with a standard pretreatment of the GPS signal.

6 Conclusion

In this paper we have considered some of the space and time characteristics of phase slips of mid-latitude GPS receivers on the nightside of the Earth during the strong geomagnetic disturbance of July 15, 2000.

It has been shown that the number of PS increases with the increasing rate of $Dst$-variation with the time, and has a clearly pronounced aspect dependence - the relative frequency of phase slips is the largest in the northward direction at small elevations. We have suggested a plausible mechanism that is responsible for PS - phase distortions of the GPS signal propagating through the ionosphere that are caused by the scattering from the geomagnetic field-aligned E-layer irregularities. Using the data from the Irkutsk IS radar we have estimated the order of phase distortions of the GPS signal that are caused by this mechanism and amounting to several degrees.

To reliably explain the night-time phase slips of GPS receivers in terms of this mechanism alone requires a more detailed verification of the functioning of GPS receivers produced by different manufacturers, for such a level of phase distortions, and a relevant numerical simulation of the algorithms involved.

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