Magnetospheric disturbances, and the GPS operation

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Short title: MAGNETOSPHERIC DISTURBANCES, AND THE GPS OPERATION
**Abstract.** We have investigated a dependence of the relative density of phase slips in the GPS navigation system on the disturbance level of the Earth’s magnetosphere. The study is based on using Internet-available selected data from the global GPS network, with the simultaneously handled number of receiving stations ranging from 160 to 323. The analysis used four days from the period 1999–2000, with the values of the geomagnetic field disturbance index $Dst$ from 0 to -300 nT. During strong magnetic storms, the relative density of phase slips on mid latitudes exceeds the one for magnetically quiet days by one-two orders of magnitude as a minimum, and reaches a few and (for some of the GPS satellites) even ten percent of the total density of observations. Furthermore, the level of phase slips for the GPS satellites located on the sunward side of the Earth was by a factor of 5-10 larger compared with the opposite side of the Earth. The high positive correlation of an increase in the density of phase slips and the intensity of ionospheric irregularities during geomagnetic disturbances as detected in this study points to the fact that the increase is slips is caused by the scattering of the GPS signal from ionospheric irregularities.
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).

Recently the GPS system has also gained wide-spread acceptance in research in the field of geodynamics, in the physics of the Earth’s atmosphere, ionosphere and plasmasphere, etc. [Davies and Hartmann, 1997; Klobuchar, 1997]. Investigations of this kind are not only of purely scientific interest but are also important for perfection of the GPS system itself. To address these problems, a global network of receiving GPS stations was set up, which consisted, by November 2000, of no less than 757 points, the data from which are placed on the Internet.

Using two-frequency multichannel receivers of the global navigation GPS system, at almost any point on the globe and at any time simultaneously at two coherently-coupled frequencies $f_1 = 1575.42$ MHz and $f_2 = 1227.60$ MHz, highly accurate measurements of the group and phase delays are being underway along the line of sight (LOS) between the receiver on the ground and the transmitters on-board the GPS system satellites which are in the zone of reception.

These data, converted to values of total electron content (TEC), are of considerable current use in the study of the regular ionosphere and of disturbances of natural and technogenic origins (solar eclipses, flares, earthquakes, volcanoes, strong thunderstorms,
auroral heating; nuclear explosions, chemical explosion events, launches of rockets). We do not cite here the relevant references for reasons of space, which account for hundreds of publications to date.

The study of deep, fast variations in TEC caused by a strong scattering of satellite signals from intense small-scale irregularities of the ionospheric $F_2$-layer at equatorial and polar latitudes has a special place among ionospheric investigations based on using satellite (including GPS) signals \cite{Aarons et al., 1996, 1997; Klobuchar, 1997; Pi et al., 1997; Aarons and Lin, 1999}. The interest to this problem as regards the practical implementation is explained by the fact that as a result of such a scattering, the signal undergoes deep amplitude fadings, which leads to a phase slip at the GPS working frequencies.

To achieve a more effective detection of disturbances in the near-terrestrial space environment, we have developed a new technology of a global detector GLOBDET, and a relevant software which makes it possible to automate the acquisition, filtering and pretreatment process of the GPS data received via the Internet \cite{Afraimovich, 2000b}. This technology is being used to detect, on a global and regional scales, ionospheric effects of strong magnetic storms \cite{Afraimovich et al., 2000a}, solar flares \cite{Afraimovich, 2000b, 2000c}, solar eclipses \cite{Afraimovich et al., 1998}, launches of rockets \cite{Afraimovich et al., 2000d}, earthquakes, etc.

In this paper we have used an earlier GLOBDET technology in a global analysis of the relative density of phase slips in the GPS system during disturbances of the near-terrestrial space environment. The experimental geometry and general information about the data base used are presented in Section 2. The determination of the relative density of phase slips, and the method of processing the data available from the Internet are briefly outlined in Section 3. Section 4 describes the results obtained for magnetically
quiet and disturbed conditions. Results are discussed in Section 5.

2. Experimental geometry and general information about the data base used

This study is based on using the data from a global network of GPS receiving stations available from the Internet. For a number of reasons, slightly differing sets of GPS stations were chosen for the various events under investigation; however, the experimental geometry for all events was virtually identical. The analysis used a set of stations (from 160 to 323) with a relatively even distribution across the globe. For reasons of space, we do not give here the stations coordinates. This information may be obtained from [http://lox.ucsd.edu/cgi-bin/allCoords.cgi](http://lox.ucsd.edu/cgi-bin/allCoords.cgi).

The set of stations, which we selected out of the part of the global GPS network available to us, covers rather densely North America and Europe; Asia has much poorer coverage. The number of GPS stations in the Pacific and Atlantic oceans is even smaller. However, such coverage over the globe is already presently sufficient for a global detection of disturbances with spatial accumulation unavailable before. Thus, in the western hemisphere, the corresponding number of stations can, already today, reach at least 500, and the number of beams to the satellites no less than 2000-3000.

The analysis involved four days of the period 1999-2000, with the values of the geomagnetic field disturbance index \( Dst \) ranging from 0 to -300 nT and \( Kp \) from 2 to 9. These events are summarized in Table 1.

Figure 1 presents the measured variations of the \( H \)-component of the geomagnetic field at station Irkutsk (52.2°N; 104.3°E –a, e), and \( Dst \) (b, f) during major magnetic storms on April 6, and July 15, 2000; a correlative analysis of the data is made in
Sections 4.

The statistic of the data used in this paper for each of the days under examination is characterized by the information in Table 1 about the number of stations used $m$, and in Tables 2, 3 about the total number $n$ of satellite GPS passes (LOS). The total amount of data exceeds $10^7$ 30-s observations.

3. The method of processing the data from the Internet

The purpose of a preprocessing of the GPS data in this paper is to obtain slip density estimates in measuring the phase difference $L1 - L2$, and slips of phase measurement at the fundamental frequency $L1$. Ascertaining the cause of the increase in slip density was also greatly facilitated by estimating the TEC variation intensity for the same stations and time intervals.

The GPS technology provides the means of estimating TEC variations on the basis of phase measurements of TEC $I$ in each of the spaced two-frequency GPS receivers using the formula [Afraimovich et al., 1998]

$$I_o = \frac{1}{40.308} \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} [(L1\lambda_1 - L2\lambda_2) + const + nL]$$  \hspace{1cm} (1)

where $L1\lambda_1$ and $L2\lambda_2$ are phase path increments of the radio signal, caused by the phase delay in the ionosphere (m); $L1$ and $L2$ are the number of full phase rotations, and $\lambda_1$ and $\lambda_2$ are the wavelengths (m) for the frequencies $f_1$ and $f_2$, respectively; const is some unknown initial phase path (m); and $nL$ is the error in determination of the phase path (m).

Phase measurements in the GPS can be made with a high degree of accuracy corresponding to the error of TEC determination of at least $10^{14}$ m$^{-2}$ when averaged on 30-s intervals.
This makes possible detecting ionization irregularities and wave processes in the ionosphere over a wide range of amplitudes (up to $10^{-4}$ of the diurnal TEC variation) and periods (from 24 hours to 5 min). The TECU (Total Electron Content Units), which is equal to $10^{16}$ m$^{-2}$ and is commonly accepted in the literature, will be used throughout the text.

Primary data include series of "oblique" values of TEC $I_o(t)$, as well as the corresponding series of elevations $\theta(t)$ and azimuths $\alpha(t)$ along LOS to the satellite calculated using our developed CONVTEC program which converts the GPS system standard RINEX-files on the Internet [Gurtner, 1993].

3.1. The relative density of difference phase $L1 - L2$ slips and of phase $L1$ slips

We hold fixed a slip of the phase difference $L1 - L2$ in the case where the modulus of the TEC increment for a time interval of 30 s (which is a standard one for the GPS data placed on the Internet) that is calculated by formula (1), exceeds the specified threshold of order, for example, 100-200 TECU. A slip of phase $L1$ is also fixed in a similar manner but with a much larger threshold and with due regard for the time varying distance to the satellite.

As a result of a pretreatment of the RINEX-files, we have the number $S$ of phase slips within a single selected time interval $dT=5$ min, as well as the corresponding number $M$ of observations that is required for normalizing the data. Our choice of such an interval was dictated by the need to reduce the amount of the data analyzed without decreasing the time resolution that is required for the analysis (a standard time step for the RINEX-files equal to 30 s would require a larger memory capacity).

These data for each of the GPS satellites were then averaged for all the stations
selected in order to infer the mean density of observations $M(t)$ and the mean density of phase slips $S(t)$. In the middle of the observed satellite pass, the density of observations $M(t)$ averages $10 \pm 1$ (30-s counts); at the beginning and end of the pass it can decrease because the time intervals of observation of a given satellite at elevations larger than that specified do not coincide at different stations. Subsequently, we calculated the mean relative density of phase slips $P(t) = S(t)/M(t)$, %. Furthermore, the daily mean value of the relative number of phase slips $\langle P \rangle$ that was averaged over all GPS satellites and stations was useful for our analysis.

Figure 2 (at the left) gives an example of the observation density $M(t)$ --a, heavy line; the slip density $S(t)$--a, thin line; b - ratio $S(t)/M(t)$ for one of the PRN07 passes as recorded at station CHB1 (the geographic coordinates are $45.6^\circ$N, $275.5^\circ$E) during the magnetic storm of April 6, 2000. Dependencies $M(t)$, $S(t)$ and of the relative slip density $P(t)$ for PRN07, averaged over the mid-latitude stations of North America as a function of universal time (UT), are plotted in panels (e,f). The SSC (sudden storm commencement) time 16:42 UT is shown in panels e) and f) by a vertical bar. The number $n$ of satellite PRN07 passes used to carry out an averaging is marked in panel f. In this paper we are using the term PRN (pseudo random noise) to designate the satellite number [Hofmann-Wellenhof et al., 1992].

As would be expected the mean observation density $M(t)$ for a single satellite exhibits a diurnal variation that is determined by the satellite’s orbit, and varies over the range from 0 to 8.

3.2. Estimation of the TEC variation intensity

We have used the series $I_o(t)$, containing neither slips of the phase difference $L1 - L2$ nor gaps of counts, to estimate the TEC variation intensity for the same sets of stations
and time intervals as used in estimating the phase slip density.

Series of the values of elevations $\theta(t)$ and azimuths $\alpha(t)$ of the beam to the satellite were used to determine the coordinates of subionospheric points, and to convert the "oblique" TEC $I_o(t)$ to the corresponding value of the "vertical" TEC by employing the technique reported by [Klobuchar, 1986]

$$ I = I_o \cos \left( \arcsin \left( \frac{R_z}{R_z + h_{max}} \cos \theta \right) \right) $$

(2)

where $R_z$ is the Earth’s radius, and $h_{max}=300$ km is the height of the $F_2$-layer maximum.

To exclude the variations of the regular ionosphere, as well as trends introduced by the motion of the satellite, we employ the procedure of removing the linear trend by preliminarily smoothing the initial series with a selected time window of a duration of about 60 min. In a subsequent treatment, we use the standard deviation of the TEC variations $dI(t)$, thus filtered, as an estimate of the TEC variation intensity $A$ (see Section 4).

Figure 2c gives an example of a typical weakly disturbed variation in "oblique" TEC $I_o(t)$ for station WES2 (satellite number PRN04) on July 15, 2000 for the time interval 14:00-16:00 UT, preceding the onset of a geomagnetic disturbance near the WES2 station ($42.6^\circ$N, $288.5^\circ$E). For this same series, Figure 2d presents the $dI(t)$ variations that were filtered out from the $I_o(t)$ series by removing the trend with a 60-min window (rms of $dI(t)$ is smaller then 0.2 TECU).

Strong variations in TEC variation intensity occurred near station WES2 literally within 6 hours. Figure 2g and Figure 2h presents the dependencies $I(t)$ and $dI(t)$ for station ALGO ($46^\circ$N, $282^\circ$E), July 15, 2000, for the time interval 20:00-22:00 UT.
(PRN15). As is evident from the figure, the TEC variations increased in intensity at least by a factor of 40-50 when compared with the time interval 14:00–16:00 UT (Figure 2c and Figure 2d).

### 3.3. Conditions and limitations of a data processing

Slips of phase measurements can be caused by reception conditions for the signal in the neighborhood of the receiver (interference from thunderstorms, radiointerferences), which is particularly pronounced at low elevations $\theta$. To exclude the influence of the signal reception conditions, in this paper we used only observations with satellite elevations $\theta$ larger than $30^\circ$.

Another possible reasons for the phase slips, as has been pointed out in the Introduction, is due to deep, fast changes in TEC because of a strong scattering of satellite signals from intense small-scale irregularities of the ionospheric $F_2$-layer at equatorial and polar latitudes [Aarons et al., 1996, 1997; Klobuchar, 1997; Pi et al., 1997; Aarons and Lin, 1999].

However, since we are using a global averaging of the number of phase slips for all beams and stations, as a consequence of the uneven distribution of stations the proportion of mid-latitude stations of North America and, to a lesser extent, of Europe is predominant (see above). At the same time the number of stations in the polar region of the northern hemisphere and in the equatorial zone was found to be quite sufficient for a comparative analysis. To compare the results, we chose 3 latitude ranges: high latitudes $50 – 80^\circ$N; mid-latitudes $30 – 50^\circ$N; and equatorial zone $30^\circ$S–$30^\circ$N.

We selected also the data according to the types of two-frequency receivers, with which the GPS global network sites are equipped (the relevant information is contained in the initial RINEX format).
4. Results derived from analyzing the relative density of phase slips

4.1. Magnetically quiet days

Figure 3 plots the local time LT-dependence of the relative mean slip density $P(t)$ obtained by averaging the data from all satellites in the latitude range $0 - 360^\circ$E irrespective of the type of GPS receivers for the magnetically quiet days of July 29, 1999 (at the left) and January 9, 2000 (at the right). The local time for each GPS station was calculated, based on the value of its geographic longitude. The number $n$ of satellite passes used to carry out an averaging is marked in all panels.

As is evident from Figure 3b, the phase slips on a magnetically quiet day at mid latitudes have a sporadic character. The daily mean value of the relative density of phase slips $\langle P \rangle$, averaged over all GPS satellites and stations, was 0.017 % for the magnetically quiet day of July 29, 1999 (the line 2 in the Table 2). Similar data were also obtained for high latitudes (Figure 3a and the line 1 in the Table 2).

In the equatorial zone, however, even on a magnetically quiet day, the density of phase slips exceeds the latitudinally mean value of $P(t)$ at least by a factor of 15, and shows a strongly pronounced LT-dependence, with a maximum value of 1.52 % (Figure 3c and the line 3 in the Table 2).

For the other magnetically quiet day of January 9, 2000, however, the mean value of $\langle P \rangle$ at mid-latitudes was already larger 0.06 % (Figure 3e and the line 2 in the Table 2). For the diurnal $P(t)$-dependence on January 9, 2000, one can point out the irregularity of the mean density of phase slips as a function of local time LT.
4.2. Magnetic storms of April 6 and July 15, 2000

A totally different picture was observed on April 6, 2000 during a strong magnetic storm with a well-defined SSC.

Figure 1d presents the variations of the UT-dependence of the relative mean slip density $P(t)$ obtained for the territory of North America at mid-latitudes $30 - 50^\circ$N by averaging the data from all satellites. In this case, with the purpose of achieving a clearer detection of the effect of the magnetic storm SSC influence on the $P(t)$-dependence, we chose only those GPS stations which were on the dayside of the Earth at the SSC time (North America region). Noteworthy is a well-defined effect of an increase in the density of phase slips that occurred after SSC.

A maximum mean slip density $P_{\max}=2.4\%$ is attained 3-4 hours after an SSC. For a separate satellite, PRN07, $P_{\max}$ can even exceed 10\% (see Figure 2f). The same values, averaged over all observed satellites and mid-latitude stations ($0 - 360^\circ$E) but as a function of local time LT, are plotted in Figure 4b).

First of all, it should be noted that the relative density of phase slips $P(t)$ exceeds that for magnetically quiet days by one (when compared with January 9, 2000) or even two (when compared with July 29, 1999) orders of magnitude, and reaches a few and (for some of the GPS satellites) even ten percent of the total observation density (Figure 2f). The mean value of $\langle P \rangle$ for this storm is 0.67\% (the line 5 in the Table 2), which is by a factor of 40 larger than that of $\langle P \rangle$ for July 29, 1000, and by a factor of 10 larger than that for January 9, 2000.

It was also found that the averaged (over all satellites) level of phase slips for the GPS satellites on the subsolar side of the Earth is by a factor of 10 larger than that on the opposite side of the Earth (Figure 4b).
Similar dependencies with a maximum slip density $P_{\text{max}}=3.37\%$ and a sharply pronounced diurnal dependence were also obtained for equatorial latitudes (Figure 4c and the line 6 in the Table 2). On the other hand, although the high latitudes show a 10-fold increase of $\langle P \rangle$ as against a magnetically quiet day, no LT-dependence is observed (Figure 4a and the line 4 in the Table 2).

A similar result confirming all of the above-mentioned features of the April 6, 2000 storm was also obtained for the other magnetic storm of July 15, 2000 (see the measurements at magnetic observatory Irkutsk in Figure 1e, the universal time UT dependence in Figure 1h and the local time LT dependencies of the relative mean density of phase slips $P(t)$ obtained by averaging the data from all GPS satellites, in Figure 4d, e, f.

The mean value of $\langle P \rangle$ for this storm at mid-latitudes is 0.34 % (the line 5 in the Table 2), which is also in appreciable excess of the level of phase slips for magnetically quiet days. The effect of an increase in the density of phase slips after SSC is clearly pronounced for this storm as well (Figure 1h; see below).

4.3. **Correlation of the increase in slip density and TEC variation intensity**

It is known that equatorial latitudes are characterized by strong scintillations of the transionospheric signal caused by the scattering from $F_2$-region ionization irregularities [Aarons et al., 1996, 1997; Klobuchar, 1997; Pi et al., 1997; Aarons and Lin, 1999]. This is in reasonably good agreement with our data on the diurnal dependence of the phase slip density at the equatorial chain of stations (Figures 3c, 4c).

Since during the active phase of the magnetic storm the mid-latitude ionosphere becomes increasingly inhomogeneous, it might be anticipated that a similar mechanism is able to cause appreciable scintillations of the GPS signal at mid-latitudes as well.
To verify this hypothesis, we determined the dependencies $A(t)$ of the TEC variation intensity obtained for the same set of stations as in the case of $P(t)$ (see Section 3).

The dependencies $A(t)$ as a function of UT (Figure 1d, h - thin line) and LT (Figure 4b, e– thin line) presented below by averaging (over all GPS satellites and stations) the standard deviation of the variations $dI(t)$ for time intervals of 2.5 hours with a shift of 1 hour. Thus, 24 counts of the dependence $A(t)$ are obtained for a 24-hour period with due regard for the data from the preceding and next days.

In Figure 1h, the thin line represents the dependence $A(t)$ of the TEC variation intensity obtained for all satellites and for the territory of North America at mid-latitudes $30 - 50^\circ$N during the magnetic storm of July 15, 2000. As is apparent from this figure, the dependence $A(t)$ correlates quite well with the UT-dependence of the relative mean slip density $P(t)$ calculated from the same set of stations as in the case of $A(t)$.

A similar result on the UT-dependence was also obtained for a major magnetic storm of April 6, 2000 (Figure 1d, thin line). A correlation of the increase in slip density and in TEC variation intensity is shown as clearly by the LT-dependencies $A(t)$ for the magnetic storms of April 6 and July 15, 2000, presented in Figure 4b, e (thin line).

It was found that an increase in the level of geomagnetic activity is accompanied by an increase in total intensity of $A(t)$; however, it correlates not with the absolute level of $Dst$, but with the value of the time derivative of $Dst$ (a maximum correlation coefficient reaches -0.94 – Figure 1c, g). The derivative $d(Dst)/dt$ was obtained from the dependence $Dst(t)$ (Figure 1b, f) that was smoothed with a 7-hour time window.

This result is in reasonably good agreement with the conclusions drawn in [Ho et al.,1998]; [Afraimovich et al., 2000a].
4.4. The dependence of the slip density of phase measurements $L_1 - L_2$ and $L_1$ on the type of GPS receivers

The sample statistic of phase slips for the main types of two-frequency receivers (ASHTECH, TRIMBLE, AOA), installed at the global GPS network sites, is presented in Table 3. An analysis of slips in measuring the phase difference $L_1 - L_2$ and of the phase $L_1$ was carried out for the magnetically quiet day of July 29, 1999, and for the magnetic storms of April 6 and July 15, 2000. Lines 1, 5, 9 and 13 reproduce the data derived from analyzing the slips obtained for all stations irrespective of the type of receivers, and given in lines 2, 3 and 5 of Table 2.

Figure 5 plots the LT-dependencies of the relative mean slip density $P(t)$ of phase measurements of $L_1 - L_2$ (at the left) and phase measurements of $L_1$ only (at the right) obtained by averaging the data from all satellites in the longitude range $0 - 360^\circ$E at the mid-latitudes $30 - 50^\circ$N for major magnetic storm on April 6, 2000.

The data from Table 3 and Figure 5a suggest that for the ASHTECH receivers, the slip density of phase measurements at two frequencies $L_1 - L_2$ is by a factor of 5-20 smaller than that for the other types of receivers. These slips have a sporadic character, and show no clearly pronounced diurnal dependence. These estimates are only slightly exceeded by the slip density for the TRIMBLE receivers (Figure 5b).

The AOA receivers are the most susceptible to slips of $L_1 - L_2$ measurements (Figure 5c). The mean and maximum values of $P(t)$ exceed the respective values for the ASHTECH receivers during the magnetic storm of April 6, 2000, at least by a factor of 20-50. Furthermore, the LT-dependence is the most pronounced. It should also be noted that even on the magnetically quiet day of July 29, 1999, the level of slips for this receiver in the equatorial zone is an order of magnitude higher when compared with
mid-latitudes.

On the other hand, the level of slips of $L1$ phase measurements at the fundamental GPS frequency (see Table 3 and Figure 5, at the right) has a clearly sporadic character, is virtually independent of the type of receivers, the geomagnetic activity level, and of the time of day, and is at least one order of magnitude lower than that in $L1 - L2$ measurements. This leads us to conjecture that the slips of $L1 - L2$ measurements are most likely to be caused by the high level of slips of $L2$ phase measurements at the auxiliary frequency. According to our data, these slips are observed at equatorial latitudes under quiet conditions as well, and at mid-latitudes they increase with increasing geomagnetic activity.

5. Discussion and Conclusions

The main results of this study may be summarized as follows:

1. We have detected a dependence of the relative density of phase slips in the navigation system GPS on the disturbance level of the Earth’s magnetosphere during major magnetic storms. Hence, not only can the disturbances in the near-terrestrial space environment (caused by corresponding processes in the “Sun-Earth” system) be detected in TEC measurements by processing the GPS data, as has now been demonstrated in a large number of studies, but they also affect the operation of the navigation system GPS itself.

2. During major magnetic storms the relative density of phase slips at mid-latitudes exceeds that for magnetically quiet days at least by one or two orders of magnitude, and reaches a few and (for some of the GPS satellites) even ten percent of the total observation density.
3. The level of phase slips for the GPS satellites on the sunward side of the Earth is by a factor of 5–10 times than that on the opposite side of the Earth.

4. The high positive correlation of an increase in the density of phase slips $P(t)$ and the intensity of ionospheric irregularities $A(t)$ during geomagnetic disturbances as detected in this study points to the fact that the increase is slips $P(t)$ is caused by the scattering of the GPS signal from ionospheric irregularities.

It is most likely that our recorded phase slips at mid-latitudes are due to a strong scattering of satellite signals from small-scale ionospheric $F_2$-layer irregularities which are most frequently observed at equatorial and polar latitudes [Aaron et al., 1996, 1997; Klobuchar, 1997; Pi et al., 1997; Aarons and Lin, 1999].

This results in a decrease of the ”signal/noise” ratio, which has a particularly strong effect when receiving the signal of the auxiliary frequency $f_2$, whose power at the GPS satellite transmitter output is an order of magnitude smaller compared with the fundamental frequency $f_1$ ([Langley, 1998]; Interface Control Document ICD 200c; [http://www.navcen.uscg.mil/pubs/gps/icd200/]). Different types of GPS receivers respond to this differently; on the whole, however, the picture of the dependence on the local time, latitude range, and on the level of geomagnetic activity remains sufficiently stable.

Our intention was to investigate how magnetospheric disturbances accompanying magnetic storms affect the operation of the GPS system. A detailed analysis of the factors responsible for the phase slips in the GPS system is a highly difficult task, and is beyond the scope of this paper.

Of course, phase measurements are more sensitive to equipment failures and to anomalies in the GPS ”satellite-receiver” channel than group delay measurements and thus are of more importance.
measurements which are directly used in solving navigation problems. Therefore, it is necessary to have a monitoring of the errors of determining the coordinates of stationary sites of the global GPS network, based on the data in the RINEX-format available from the Internet, and to analyze these series in conjunction with the data on the conditions of the near-terrestrial space environment.

We are aware that this study has revealed only the key averaged patterns of this influence, and we hope that it would give impetus to a wide variety of more detailed investigations.

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Figure 1: Variations of the $H$-component of the geomagnetic field record at station Irkutsk ($52.2^\circ N; 104.3^\circ E$ – a), $Dst$ – b) and the dependence of the time derivative $d(Dst(t))/dt$ – c) during the magnetic storm of April 6, 2000. The UT-dependence of the relative mean slip density $P(t)$, obtained for the territory of North America at the mid-latitudes $30 - 50^\circ N$ by averaging the data from all GPS satellites - d. The same dependencies for a magnetic storm of July 15, 2000 - e, f, g, h. The SSC times 16:42 UT and 14:37 UT are shown by a vertical bar. For comparison, the thin line in panels d and h plots the dependencies $A(t)$ of the TEC variation intensity obtained for the same set of stations as in the case of $P(t)$.
Table 1: Statistics of experiments

| N  | Date      | Day number | m  | $Dst_{max}$, nT | $K_{p_{max}}$ |
|----|-----------|------------|----|----------------|---------------|
| 1  | 29.07.1999| 210        | 160| -40            | 3             |
| 2  | 9.01.2000 | 009        | 323| -13            | -             |
| 3  | 6.04.2000 | 097        | 243| -293           | 8             |
| 4  | 15.07.2000| 197        | 306| -295           | 9             |
Figure 2: Observation density $M(t)$ - a, heavy line; slip density $S(t)$ - a, thin line; b - ratio $S(t)/M(t)$ for one of the PRN07 passes as recorded at station CHB1 (45.6°N, 275.5°E) during the magnetic storm of April 6, 2000. Dependencies $M(t)$, $S(t)$ and of the relative slip density $P(t)$ for PRN07, averaged over the mid-latitude stations of North America as a function of the universal time UT - (e, f). The SSC time 16:42 UT is shown in panels e) and f) by a vertical bar. Time dependencies of the "oblique" TEC $I(t)$, measured at station WES2 (42.6°N, 288.5°E - c) prior to the onset of the geomagnetic disturbance of July 15, 2000, and at station ALGO (46°N, 282°E - g) thereafter. The $dI(t)$ variations filtered from the $I(t)$ series by removing the trend with a 60-min window for this stations - d); h). Panels b and f show the number $n$ of satellite passes used to perform the averaging.
Table 2: The relative density of phase slips

| N | Region         | $n_{\text{LOS}}$ | $\langle P \rangle \%$ | $P_{\text{max}} \%$ | $n_{\text{LOS}}$ | $\langle P \rangle \%$ | $P_{\text{max}} \%$ |
|---|----------------|------------------|------------------------|------------------|------------------|------------------------|------------------|
|   |                |                  |                        |                  |                  |                        |                  |
| 1 | 50 - 80°N      | 1109             | 0.028                  | 0.12             | 765              | 0.079                  | 0.66             |
| 2 | 30 - 50°N      | 1653             | 0.017                  | 0.17             | 4330             | 0.06                   | 0.25             |
| 3 | 30°S - 30°N    | 879              | 0.28                   | 1.52             | 694              | 0.5                    | 2.13             |
|   |                |                  |                        |                  |                  |                        |                  |
| 4 | 50 - 80°N      | 920              | 0.23                   | 0.81             | 1356             | 0.15                   | 0.53             |
| 5 | 30 - 50°N      | 1949             | 0.67                   | 2.40             | 4114             | 0.34                   | 1.49             |
| 6 | 30°S - 30°N    | 783              | 1.16                   | 3.37             | 892              | 0.39                   | 1.27             |
Figure 3: Local time LT-dependence of the relative mean slip density $P(t)$, obtained by averaging the data from all GPS satellites in the longitude range $0 - 360^\circ$E irrespective of the type of GPS receivers for the magnetically quiet days of July 29, 1999 (at the left), and January 9, 2000 (at the right): a, d – high latitudes $50 - 80^\circ$N; b, e – mid-latitudes $30 - 50^\circ$N; and c, f – equatorial zone $30^\circ$S-$30^\circ$N. The number $n$ of satellite passes used to carry out an averaging is marked in all panels.
Table 1: The slip density of phase measurements $L1 - L2$ and $L1$

| N  | Receivers | $n$ LOS | $\langle P \rangle$ % | $P_{max}$ % | $n$ LOS | $\langle P \rangle$ % | $P_{max}$ % |
|----|-----------|---------|----------------------|-------------|---------|----------------------|-------------|
|    |           |         | 1999, July 29; 30 - 50°N |             |         | 2000, April 6; 30 - 50°N |             |
| 1  | All       | 1653    | 0.017                | 0.17        | 1658    | 0.015                | 0.2         |
| 2  | Ashtech   | 153     | 0.015                | 0.65        | 153     | 0.017                | 0.65        |
| 3  | Trimble   | 428     | 0.03                 | 0.46        | 428     | 0.018                | 0.441       |
| 4  | AOA       | 434     | 0.002                | 0.28        | 460     | 0.02                 | 0.36        |
| 5  | All       | 1949    | 0.67                 | 2.4         | 3447    | 0.017                | 0.11        |
| 6  | Ashtech   | 595     | 0.03                 | 0.36        | 817     | 0.036                | 0.28        |
| 7  | Trimble   | 606     | 0.15                 | 1.2         | 1721    | 0.007                | 0.07        |
| 8  | AOA       | 546     | 1.57                 | 6.5         | 650     | 0.017                | 0.29        |
| 9  | All       | 4114    | 0.34                 | 1.49        | 4085    | 0.026                | 0.27        |
| 10 | Ashtech   | 1007    | 0.07                 | 0.8         | 1030    | 0.034                | 0.47        |
| 11 | Trimble   | 2144    | 0.36                 | 2.0         | 2144    | 0.025                | 0.29        |
| 12 | AOA       | 841     | 0.67                 | 2.46        | 841     | 0.026                | 0.31        |
Figure 4: Same as in Figure 3, but for the magnetic storms on April 6 (at the left) and July 15, 2000 (at the right). For comparison, the thin line in panels b and e plots the dependencies $A(t)$ of the TEC variation intensity obtained for the same set of stations as in the case of $P(t)$. 
Figure 5: LT-dependencies of the relative mean slip density $P(t)$ of $L1 - L2$ phase measurements (at the left) and phase measurements of $L1$ only (at the right), obtained by averaging the data from all satellites in the longitude range $0 - 360^\circ E$ at the mid-latitudes $30 - 50^\circ N$ for a major magnetic storm of April 6, 2000 (ASHTECH - a, d, TRIMBLE - b, e, and c, f - AOA receivers). The number $n$ of satellite passes used to carry out an averaging is marked in all panels.