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Geomagnetic Disturbances and Operation of the GPS Navigation System

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Abstract—During strong magnetic storms, the relative rate of phase glitches in midlatitude GPS measurements exceeds by at least one or two orders of magnitude the corresponding level for magnetically quiet days, and can be as high as several percent and even (for some GPS satellites) several tens percent of the total number of observations, which may be unacceptable for certain important navigation tasks. The glitch rate is three to five times higher for GPS satellites on the Earth's dayside than for those located on the opposite side. The glitch rate is found to increase abruptly after SSC in the case of isolated major magnetic storms. A high positive correlation between the increase in the phase glitch rate and the intensity of ionospheric irregularities during geomagnetic disturbances suggests that the increase in the glitch rate can be due to the scattering of GPS signals by ionospheric irregularities.

INTRODUCTION

The GPS satellite navigation system has become a powerful factor of technological progress and is now widely used in various fields of human activity. Much attention has therefore been paid to the continuous improvement of the GPS system and the expansion of its application to navigation and development of higher precision time and frequency measurement systems. Joint operation of the GPS and Russian GLONASS system should open up much more opportunities in the nearest future.

In the last few years, GPS has been widely used in geodynamics and physics of the Earth's atmosphere, ionosphere, and plasmasphere [Davies and Hartmann, 1997; Klobuchar, 1997]. Such investigations are not just of purely scientific interest but are also important for the improvement of GPS itself. To solve these problems, a global network of GPS receiving stations has been set up, which included at least 900 sites by August 2001, feeding data to the Internet.

Dual-frequency multichannel receivers of the GPS global navigation system allow high-precision measurements of the line-of-sight group and phase delays between a ground receiver and GPS satellite transmitters in the reception area to be made simultaneously at two coherently linked frequencies $f_1 = 1575.42$ and $f_2 = 1227.60$ MHz. These data, converted to the total electron content (TEC) values, are now being widely used to study the regular ionosphere and natural and man-made disturbances. Due to the lack of space, we omit here the corresponding references, which include now thousands of publications.

The study of deep and fast TEC variations due to strong scattering of satellite signals by small-scale irregularities of the ionospheric F_2 layer at equatorial and polar latitudes [Aarons and Lin, 1999; Aarons *et al.* 1996, 1997; Klobuchar, 1997; Pi *et al.* 1997]) holds a special place among ionospheric investigations. Applied interest in this problem can be explained by the fact that such scattering produces amplitude-fading events, which can result in phase glitches at GPS operating frequencies.

To increase the efficiency of detection of disturbances in the near-Earth space, the Institute of Solar–Terrestrial Physics, Siberian Division, Russian Academy of Sciences, has developed a new global detector technology (GLOBDET) and the corresponding software, which makes it possible to automatize the acquisition, filtering, and primary reduction of GPS data obtained via the Internet [Afraimovich, 2000]. This technology is used to detect, on global and regional scales, the ionospheric effects of powerful magnetic storms [Afraimovich *et al.*, 2000], solar flares [Afraimovich, 2000], solar eclipses [Afraimovich *et al.*, 1998], rocket launches, earthquakes, etc.

However, RINEX-format GPS data obtained via the Internet also contain information on glitches in phase delay measurements [Hoffmann-Wellenhof *et al.*, 1992]. In TEC measurements, these data are, as a rule, used to assess data quality and reconstruct lost and distorted TEC information. In this work, we applied the previously developed GLOBDET technology to a global analysis of the glitch rate in phase measurements made with the GPS navigation system during disturbed periods in near-Earth space.

GEOMETRY OF THE EXPERIMENT AND GENERAL INFORMATION ABOUT THE DATABASE IN USE

This study used the data from the global network of GPS receiving stations available on the Internet. For different events, we used slightly different sets of GPS stations. However, the experiment geometry was virtually the same for all events. For short, we omit here the coordinates of the stations. This information is available at http:/lox.ucsd.edu/cgi-bin/allCoords.cgi?

The GPS global network rather densely covers North America and Europe and, much rarer, Asia. Less GPS stations are located in the Pacific and Atlantic. However, the present-day coverage of the Earth's surface by GPS stations makes it possible to globally detect disturbances with an unprecedented spatial data accumulation. Thus, the corresponding numbers of stations and satellite rays in the Western Hemisphere can already exceed 500 and 2000–3000, respectively.

We selected for our analysis four days from the period 1999–2000 with daily averaged indices of geomagnetic field disturbance, $\langle Dst \rangle$, ranging from –4 to –70 nT and $\langle Kp \rangle$ varying from 2.38 to 6.38. The general data of these events are presented in the table.

Figures 1 and 2 show the measured variations in (a) soft X-ray emission in the 0.1–0.8 nm wavelength interval; proton fluxes at energies (b) >1 MeV and (c) >5 MeV, measured at the geostationary orbit by the GOES 10 satellite (135° W) with a temporal resolution of 5 min; (d) H component of the Earth's magnetic field recorded at Irkutsk station (52.2° N, 104.3° E), and (e) Dst index during the magnetic storms of April 6 and July 15, 2000.

The table summarizes the statistical parameters of the data used in this paper: for each of the days analyzed, it gives the number m of stations in use, the total number n of satellite passes, and the total number Σl of 30-s measurements. The total volume of data exceeds 11.3×10^6 30-s observations.

DATA PROCESSING TECHNIQUE

The aim of primary data processing is to estimate the rate of glitches in the measurements of the phase difference $L1$–$L2$. The estimates of the intensity of TEC variations, made at the same stations and within the same time intervals as glitches, also proved to be very useful for identifying the causes of the increased rate of glitches.

We now briefly describe the procedure of data processing. Our primary data series consist of TEC levels, elevations and azimuths of the ray connecting the receiver and the satellite, computed using our own CONVTEC code that transforms standard RINEX files obtained from the Internet (RINEX files are available at http://lox.ucsd.edu/cgi-bin/dbSimpleDailyDataBrowser.cgi).

In addition, these files contain information on glitches in phase delay measurements in the special Lost of Lock Indicator (LLI) (a description of the RINEX format can be found at http://igscb.jpl.nasa.gov:80/igscb/data/format/rinex2.txt). This code allows one to identify glitches due to phase losses at one or two operating frequencies f_1 and f_2. In this paper, we use LLI only to record phase glitches independently of their types.

We needed the TEC series inferred from the phase differences $L1$–$L2$ using a well-known technique [Afraimovich, 2000] in order to confirm the fact of each phase-difference glitch. We also use the TEC series without glitches in the phase difference $L1$–$L2$ and reading gaps to estimate the intensity of TEC variations for the same sets of stations and time intervals as were used to estimate the rate of phase glitches. To exclude variations in the regular ionosphere and trends introduced by the satellite motion, we apply a procedure for trend elimination with preliminary smoothing of the initial TEC series with a time window of about 60 min. We then use the rms deviations of TEC variations thus filtered as estimates of the intensity $A(t)$ of TEC variations.

Thus, the result of the primary processing of RINEX files is the number of phase glitches within the given unit time interval $dT = 5$ min and the corresponding number of measurements required for data normalization. We adopted such a time interval length in order to reduce the volume of data analyzed without losing the time resolution required for an analysis (the standard time step for RINEX files (30 s) would require a higher storage capacities).

We then averaged these data for each GPS satellite over all selected stations, and this allowed us to compute the mean densities $M(t)$ and $S(t)$ of observations and glitches, respectively. At the midpoint of the satel-

Statistics of the experiment

No.	Date	Day no.	m	n	$\Sigma l \times 10^6$	$\langle P \rangle$, %	$\langle Dst \rangle$, nT	$\langle Kp \rangle$
1	July 29, 1999	210	160	2267	1.5	0.005	–17.9	2.38
2	Jan. 9, 2000	009	323	3736	2.12	0.06	–4.79	–
3	Apr. 6, 2000	097	243	3414	1.75	0.53	–67.42	4.5
4	July 15, 2000	197	306	4938	2.9	0.33	–58.38	6.38

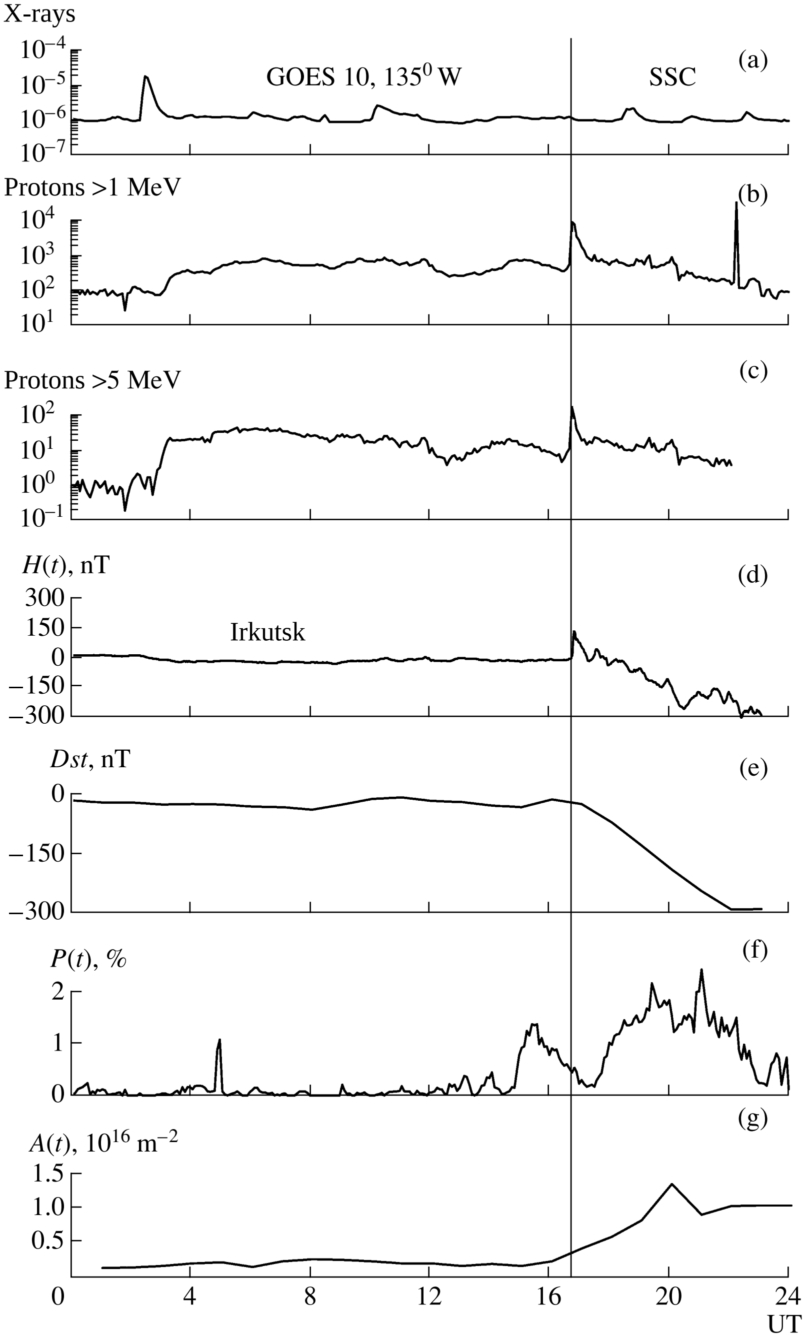

Fig. 1. Variations in (a) 0.1–0.8 nm soft X-ray radiation; flux of protons with energies (b) >1 and (c) >5 MeV measured at a geostationary orbit by the GOES 10 satellite (135° W) with a time resolution of 5 min; (d) H-component of the Earth's magnetic field recorded at Irkutsk station (52.2° N, 104.3° E); and (e) *Dst* index during the magnetic storm of April 6, 2000. Panel (f) shows the UT dependence of the mean relative glitch rate $P(t)$ obtained for dayside midlatitudes 30°–60° N after averaging the data of all GPS satellites. Panel (g) shows for comparison the dependence $A(t)$ of the intensity of TEC variations obtained at the same set of stations. The time of SSC (1642 UT) is indicated by a thin vertical bar in all panels.

lite pass, the rate $M(t)$ of observations is, on the average, equal to 10 ± 1 of 30-s counts; it can decrease at the beginning and end of the pass, because the time intervals, when a given satellite is observed at elevation angles greater than a certain level, do not coincide at different stations. We then computed the mean relative glitch rate $P(t) = S(t)/M(t)$ in percent. Moreover, the daily averaged relative glitch rate $\langle P \rangle$ averaged over all satellites and GPS stations proved to be useful for an analysis.

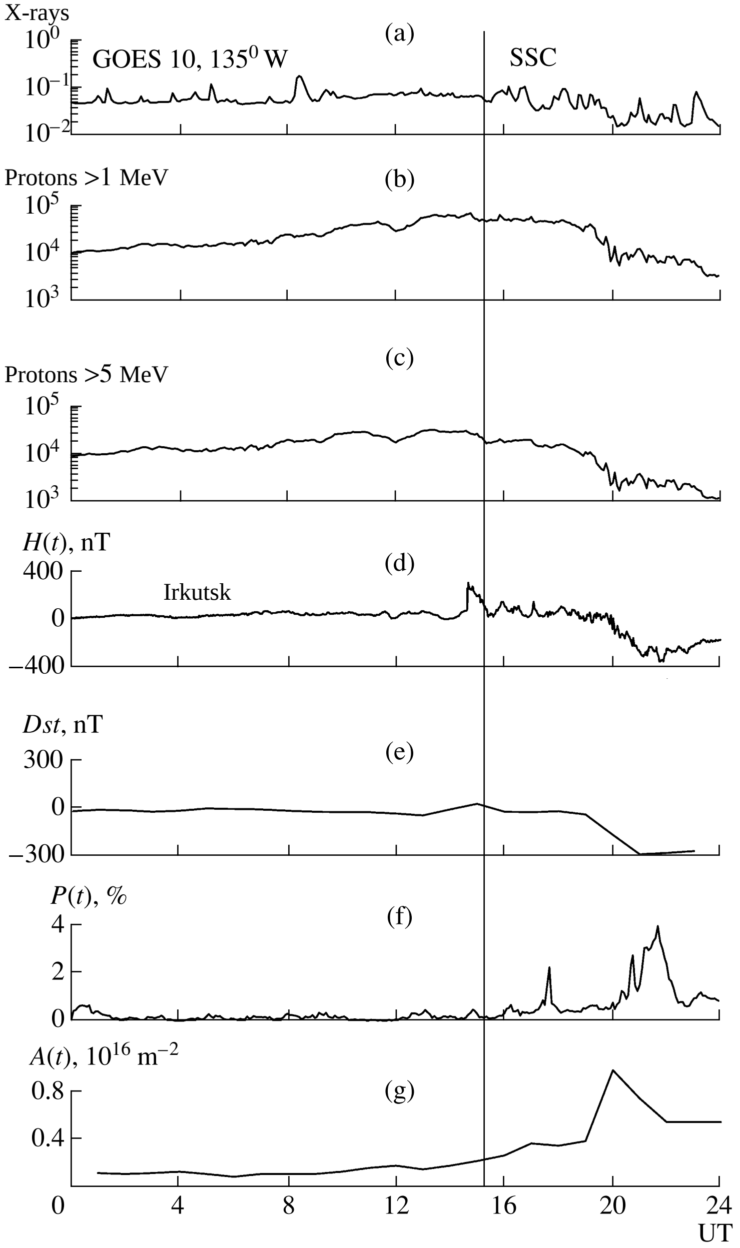

Fig. 2. Same as in Fig. 1 but for the magnetic storm of July 15, 2000. The time of SSC (1437 UT) is indicated by a thin vertical bar in all panels.

Glitches in phase measurements can be due to the conditions of signal reception near a receiver (thunderstorm discharge and radio interferences), refraction, and tropospheric absorption and scattering, which is especially pronounced at low elevation angles θ. To eliminate the influence of signal reception conditions, we used only observations at satellite elevation angles θ (t) greater than 30°.

Since we had globally averaged the number of glitches for all rays and stations, the weight of midlatitude stations located in North America and, to a lesser degree, in Europe is predominant due to the nonuniform distribution of stations (see above). Therefore, all results reported below refer to the 30–60° N midlatitude belt.

RELATIVE GLITCH RATE ANALYSIS

Magnetically Quiet Days

Left-hand panels in Fig. 3 show how the rate of observations, $M(t)$, that of glitches, $S(t)$, and the relative glitch rate, $P(t)$, varied with universal time UT on the magnetically quiet day of July 29, 1999 (Figs. 3a, 3b). Figures 3c and 3d show the variations in the same

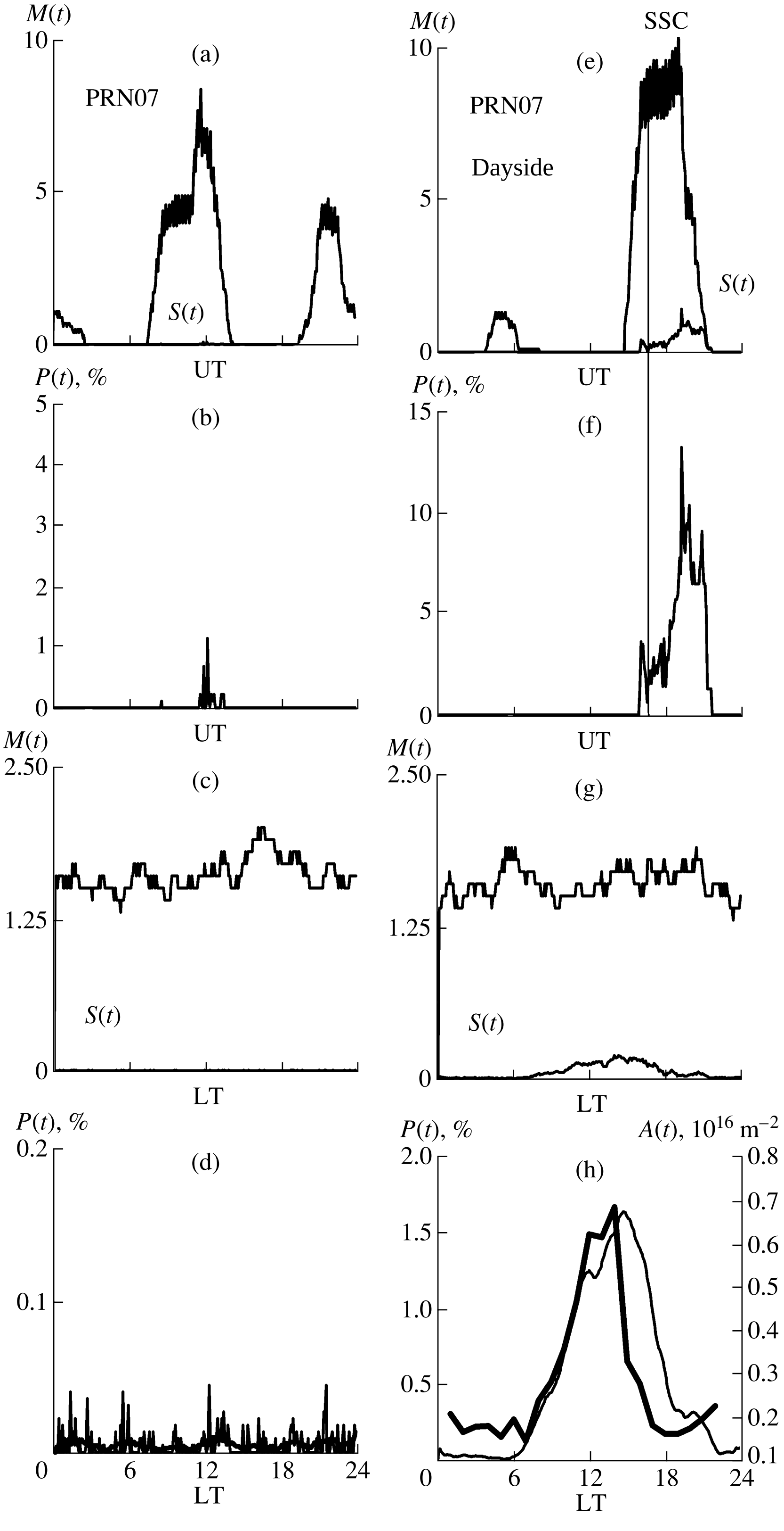

Fig. 3. Mean rates of observations ($M(t)$) and glitches ($S(t)$) and the mean relative glitch rate $P(t)$ for individual satellites as functions of universal time UT (a, b, e, f). Panels (c, d, g, h) show the same quantities averaged over all observed satellites and smoothed with a time window of 2 h as a function of local time. The left-hand side represents the magnetically quiet day of July 29, 1999, and the right-hand side shows the major magnetic storm of April 6, 2000 (dayside). The vertical bars in panels (e, f) indicate the time of SSC (1642 UT). Thick line in panel (h) shows for comparison the dependence $A(t)$ of the intensity of TEC variations obtained from the same set of stations as the $P(t)$ dependence.

quantities, averaged over all observed satellites, as functions of local time LT. We computed local times for each GPS station based on its geographic longitude.

As expected, the mean rate of observations, $M(t)$, for a particular satellite, varies in the course of a day from 0 to 8, depending on the satellite orbit (a). When averaged over all satellites, $M(t)$ has virtually no significant minima but decreases, on the average, to 1.7 (c). On the scale adopted in Fig. 3, the curve $S(t)$ for July 29, 1999, runs virtually in unison with the x axis (Figs. 3a, 3c).

As evident from Figs. 3b and 3d, the glitches during a magnetically quiet day are sporadic and asynchronous at different stations (i.e., they are likely to be due to signal reception conditions at individual stations). For the magnetically quiet day of July 29, 1999, the daily averaged relative glitch rate $\langle P \rangle$ averaged over all satellites and GPS stations was equal to 0.005% (row 1 in the table).

Figure 4 shows the local time (LT) variation in the relative mean glitch rate $P(t)$ computed by averaging the data of all GPS satellites observed simultaneously at the network of GPS stations at elevation angles exceeding 30°. The dependences $P(t)$ are smoothed with a time window of 2 h. The corresponding dates are indicated near the $P(t)$ curves. On the scale adopted in Fig. 4, the curve $P(t)$ for July 29, 1999 (the unsmoothed curve is shown in Fig. 3d), runs virtually in unison with the x axis.

However, the mean $\langle P \rangle$ value on the other magnetically quiet day of January 9, 2000, was higher by one order of magnitude and equal to 0.06% (row 2 in the table). We can note that the daily average $P(t)$ on January 9, 2000, nonuniformly depends on local time (LT).

The Magnetic Storms of April 6 and July 15, 2000

A totally different behavior was observed on April 6, 2000, during a huge magnetic storm with a pronounced sudden commencement. The right-hand panels of Fig. 3 show the variations in the mean rates of observations, $M(t)$, and glitches, $S(t)$, and in the mean glitch rate $P(t)$ for PRN07 versus the universal time UT (Figs. 3e, 3f). The time of SSC (1642 UT) is indicated by vertical bars in Figs. 3e and 3f.

In this case, we selected only the GPS stations that were located on the Earth's dayside during SSC in order to more reliably detect the effect of sudden storm commencement on $P(t)$.

The same quantities averaged over all satellites and longitudes are shown as functions of LT in Figs. 3g, 3h and 4 (dotted line).

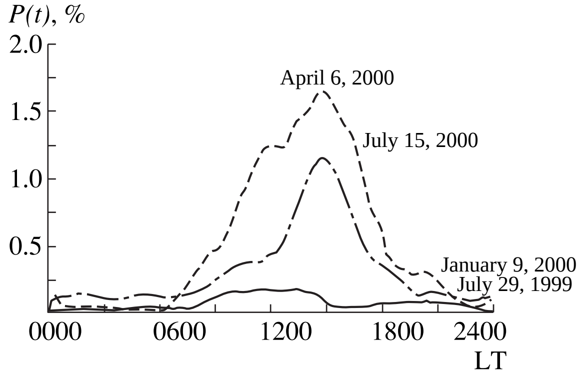

Fig. 4. Local-time (LT) variation in the mean relative glitch rate $P(t)$ obtained by averaging the data over all GPS satellites observed simultaneously by the GPS station network at elevation angles exceeding 30°. The dependences $P(t)$ are smoothed with a time window of 2 h. The corresponding dates are indicated near curves $P(t)$ (the thin line merging with the x axis corresponds to July 29, 1999; the thick line, to January 9, 2000; the dashed line, to July 15, 2000, and the dotted line, to April 6, 2000).

First, we should note that, in this case, the relative glitch rate $P(t)$ is higher than on magnetically quiet days by one (compared to January 9, 2000) or even two (compared to July 29, 1999) orders of magnitude, and reaches several percent and (for some GPS satellites) even several tens percent of the total rate of observations (Fig. 3f). The mean $\langle P \rangle$ for this storm is equal to 0.53% (row 3 in the table), which is 100 and 10 times as high as the $\langle P \rangle$ value for July 29, 1999, and January 9, 2000, respectively.

The mean glitch level averaged over all GPS satellites on the Earth's dayside proved to be three to five times higher than for the satellites located on the opposite side (Figs. 3h, 4).

We can also mention the effect of abrupt increase in the glitch rate after SSC (Fig. 3f). To synchronize this effect with the data illustrating the variations in the magnetic field and fluxes of energetic particles at the geostationary orbit, we show in Fig. 1f the $P(t)$ dependences averaged over all satellites and stations located on the Earth's dayside.

A similar result corroborating all the above-mentioned specific features of the storm of April 6, 2000, was obtained for another magnetic storm on July 15, 2000. The results of measurements at geostationary orbit and at the magnetic observatory Irkutsk (Fig. 2 and the local-time (LT) variation in the relative glitch rate $P(t)$ were obtained by averaging the data of all GPS satellites (dot-and-dash line in Fig. 4)).

The mean value $\langle P \rangle$ for this storm was equal to 0.33% (row 4 in the table) and also exceeds significantly the glitch level for magnetically quiet days.

The glitch rate also abruptly increases after the SSC of the storm in question. Figure 2f shows the variations in the relative glitch rate $P(t)$, averaged over all satellites and stations located on the dayside, versus UT. The vertical bar indicates the time of the sudden storm commencement (1437 UT).

Phase glitches could be caused, as mentioned in INTRODUCTION, by deep and rapid TEC variations due to strong scattering of satellite signals by intense small-scale irregularities of the ionospheric F_2 layer at equatorial and polar latitudes [Aarons and Lin, 1999; Aarons *et al.*, 1996, 1997; Klobuchar, 1997; Pi *et al.*, 1997]. However, the midlatitude ionosphere becomes more nonuniform during the active phase of a magnetic storm [Afraimovich *et al.*, 2000; Ho *et al.*, 1998], and, therefore, a similar mechanism can also result in appreciable GPS signal scintillations at midlatitudes. To verify this hypothesis, we determined the dependences $A(t)$ of the intensity of TEC variations obtained for the same set of stations that was used to determine $P(t)$.

The $A(t)$ variations versus UT (Figs. 1g, 2g) and LT (thick line in Fig. 3h) were obtained by averaging the rms of TEC variations (over all satellites and GPS stations) for 2.5-h time intervals shifted by 1 h. We thus obtain for a day-long interval a total of 24 counts of the $A(t)$ variation, which include the data of the preceding and following days.

Figure 2g shows the $A(t)$ dependence of the intensity of TEC variations, obtained for all satellites at midaltitudes (30°–60° N) located on the Earth's dayside during the strong magnetic storm of July 15, 2000. As is evident from this figure, the $A(t)$ variation correlates, on the whole, rather well with the UT-variation in the relative glitch rate $P(t)$ computed for the same set of stations.

A similar result for the UT-variation was obtained for the great magnetic storm of April 6, 2000 (Fig. 1g). The correlation between the increases in the glitch rate $P(t)$ and intensity $A(t)$ of TEC variations is more evident in the LT-variation for the magnetic storm of April 6, 2000, (Fig. 3h, thick line).

DISCUSSION AND CONCLUSIONS

The principal results of this work are as follows.

(1) We found that the relative rate of phase glitches in the GPS navigation system measurements depends strongly on the disturbance level of the Earth's magnetosphere.

(2) During strong magnetic storms, the relative rate of phase glitches exceeds the corresponding level on magnetically quiet days by at least one to two orders of magnitude, and can be as high as several percent or even (for some GPS satellites) several tens percent of the total rate of observations. Such a level may be unacceptable for certain important navigation tasks.

(3) For the GPS satellites located on the Earth's dayside, the glitch level is three to five times higher than for the satellites located on the opposite side of the Earth.

(4) We found that the glitch rate abruptly increases after sudden storm commencements of huge isolated magnetic storms.

(5) The strong positive correlation between the increases in the phase glitch rate $P(t)$ and the intensity $A(t)$ of TEC variations during geomagnetic disturbances suggests that the increase in $P(t)$ could be due to the scattering of GPS signals by ionospheric irregularities. The glitches recorded by us are most likely to be caused by strong scattering of satellite signals by small-scale irregularities of the ionospheric F_2 layer, which are most often observed at equatorial and polar latitudes [Aarons and Lin, 1999; Aarons *et al.*, 1996, 1997; Klobuchar, 1997; Pi *et al.*, 1997]. However, at certain stages of strong geomagnetic disturbances, the midlatitude ionosphere acquires the features of the auroral ionosphere. In this case, scattering mechanisms, similar to the those operating at high and equatorial latitudes, can materialize.

Of course, phase measurements are more vulnerable to instrument failures and interference in the GPS satellite–receiver channel than group delay measurements, which are directly used for positioning. Therefore, it is necessary to monitor coordinate determination errors for the stationary sites of the global GPS network, using RINEX-format data available on the Internet, and to analyze these data series in combination with the data on the state of the nearest space.

Our aim was to study the effect of magnetospheric disturbances on the operation of GPS. A detailed analysis of the causes of phase glitches in GPS is a very difficult task and lies beyond the scope of this paper. We are aware that this work shows only the principal averaged patterns of this effect and hope that our paper will provide impetus for setting up an entire series of more detailed studies.

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