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Powerful solar radio bursts as a global and free tool for testing satellite broadband radio systems, including GPS–GLONASS–GALILEO

E.L. Afraimovich *, V.V. Demyanov, A.B. Ishin, G.Ya. Smolkov

Institute of Solar-Terrestrial Physics, Siberian Branch, Russian Academy of Sciences (ISTP SB RAS), P.O. Box 291, Irkutsk 664033, Russian Federation

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ABSTRACT

We investigated failures in the global positioning system (GPS) performance produced by solar radio bursts with unprecedented radio flux density during the X6.5 and X3.4 solar flares on 6 and 13 December 2006, respectively. The effect of these events on GPS was compared to that of the X17.2 solar flare of 28 October 2003. Significant experimental evidence was found that high-precision GPS positioning on the Earth's entire sunlit side was partially disrupted for more than 10–15 min on 6 and 13 December 2006. The high level of phase slips and count omissions resulted from the wideband solar radio noise emission. Our results provide serious grounds for revising the role of space weather factors in the functioning of modern satellite systems and for considering these factors more carefully in practice. Similar failures in the operation of satellite navigation systems (GPS, GLONASS, and GALILEO) can be fatal for operating safety systems as a whole and lead to great financial losses. Another important conclusion of our investigation concerns the continuous calibrated monitoring of the level of the solar radio emission flux. This monitoring involved a large number of solar radio spectrographs and allowed us to estimate the solar radio noise level in the range of the GPS–GLONASS–GALILEO frequencies.

1. Introduction

The X6.5 solar flare was registered on 6 December 2006. The flare is of particular interest not only to astronomers and radio astronomers, but to other scientists and engineers as well. In the X-ray and ultra-violet (UV) ranges, this flare was not the most powerful, but the broadband solar radio emission following the flare exceeded powerful solar radio bursts in all flares known up to now at least by two orders of magnitude. This led to fatal failures in the operation of broadband satellite radio systems, including the global positioning system (GPS). Operation failures and deep damping in the GPS signal were registered at some standard GPS receivers and specialized monitors of ionospheric scintillations in the L range (Cerruti et al., 2006a, b; Carrano et al., 2007; Carrano and Bridgwood, 2008; Kintner, 2008).

It was predicted by Klobuchar et al. (1999) that solar radio bursts could affect GPS performance, given the right-hand circular polarization (RHCP) (the polarization to which GPS antennas are receptive) and a sufficiently large solar flux in the L range. The direct interference from solar radio bursts has not been considered as a potential threat to GPS signal tracking, since flux densities of most bursts are below the GPS L_1 frequency threat threshold of 40,000 sfu proposed by Klobuchar et al. (1999). Therefore it is first of all important to know the data on solar radio flux with RHCP near the GPS frequency range.

Chen et al. (2005) found that a much lower threshold should be adopted for codeless or semi-codeless two-frequency GPS receivers. In that investigation, severe signal corruptions were detected by the International GPS Service receiver stations on the dayside during the large solar radio burst that accompanied the superflare of

* Corresponding author. Tel.: +7 8 3952 564554; fax: +7 3952 511675.
E-mail address: afra@iszf.irk.ru (E.L. Afraimovich).

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28 October 2003. Almost none of the GPS L_2 signals were being tracked during the solar flux peak for areas near the subsolar point. the rate of loss of lock on the GPS L_2 frequency was compared with the solar radio flux density in different bands. A correlation index of 0.75 was revealed in the 1415 MHz solar radiation band that was located between two GPS operating frequencies L_2 ($f_2 = 1227.60$ MHz) and L_1 ($f_1 = 1575.42$ MHz). The comparison indicated that GPS signal losses of lock are primarily caused by the microwave in-band interference, and the threat threshold of solar radio burst effects on the GPS system should be re-evaluated, since the burst flux density at 1415 MHz was just 4000–12,000 sfu. This threat threshold is far below the previously proposed one. The signal-tracking performance of different types of GPS receivers during such a super flare was also presented.

However, the global scale of the failure in all GPS positioning systems during this flare was unclear. Meanwhile, the problem is of doubtless scientific and practical interest in the estimation of the space weather effect on the operation of one of the most powerful reliable satellite systems considered practically impregnable. In this study, we investigate global failures in GPS performance produced by solar radio bursts with unprecedented radio flux density during the X6.5 and X3.4 solar flares on 6 and 13 December 2006, respectively. We compare the effect of these events on GPS with that of the X17.2 solar flare of 28 October 2003.

2. Method for GPS data processing

We use the GLOBDET software developed at ISTP SB RAS to process GPS data from the global network of two-frequency receivers (Afraimovich, 2000). Our database of GPS RINEX (the Receiver Independent Exchange Format) files consists of data from over 1500 GPS sites (http://sopac.ucsd.edu/other/services.html). For 6 December 2006 we use RINEX files from the CORS network (262 sites; website ftp://www.ngs.noaa.gov/cors/rinex/).

We also employ data from the Japanese GPS network GEONET (about 1225 stations in all) for 13 December 2006 (ftp://terras.gsi.go.jp/data/GPS_products/).

Fig. 1 shows the experimental geometry of GPS measurements during the solar flare on 6 and 13 December 2006. The GPS sites are marked by dots. The names of the sites are not given for reasons of space. Asterisks indicate the location of sunlit points for the solar flare on 6 and 13 December 2006.

We calculate the 30-s series of the L_1–L_2 phase difference at two GPS frequencies f_1 and f_2 along "receiver-satellite" lines of sight (LOS) to confirm a slip in measurements of the L_1–L_2 phase difference (Afraimovich et al., 2002a, b). These data for each GPS satellite are then averaged over a period of $dT = 5$ min at all chosen sites. This allows us to calculate the average observation density $M(t)$ and slip density $S(t)$ for all n LOSes. Further we calculate the average relative density of slips $P(t) = S(t)/M(t)$, %, and determine the maximum value P_{max}, %. If the next count in a RINEX file is absent, the number of slips is equated to that of expected observations; so the density of slips becomes equal to 100%.

Failures in L_1–L_2 imply the impossibility of a precision positioning in the two-frequency mode; thus coordinates in the single-frequency mode (L_1) may be determined incorrectly. However, the positioning in general is impossible if the signal on a GPS frequency is not registered at all. To estimate a possibility of such failures for all LOS, including L_1–L_2 failures, we define a relative number of missed counts $N(t)$ for a given 30-s interval with respect to the number of counts $M(t)$ expected in the 30-s interval $W(t) = N(t)/M(t)$, %. We also determine the corresponding maximum value W_{max}, %. The time resolution of $W(t)$ dependence, 30 s, allows a detailed comparison of $W(t)$ and $Q(t)$ values to those of the solar radio emission flux.

To compare different types of GPS receivers, we calculate the relative density $Q(t)$, % of measurement slips of main GPS signal parameters for f_1 and f_2: L_1 and L_2 are the phase delays, and P_1 and P_2 are the group delays. A measurement slip was registered when the current 30-s count of corresponding GPS parameters was zero

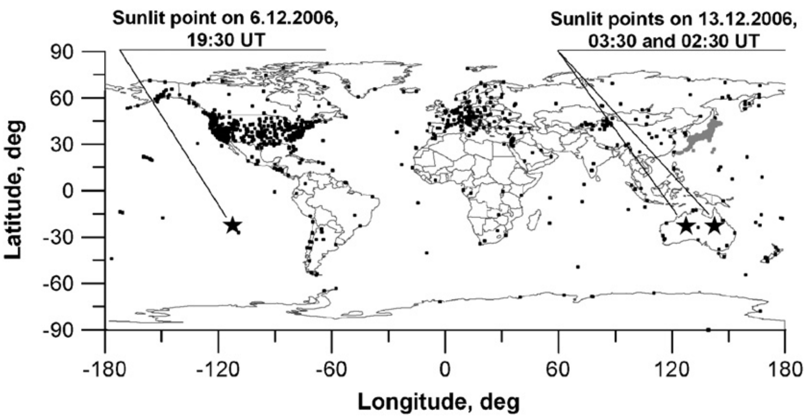

Fig. 1. Experimental geometry of GPS measurements during the solar flare on 6 and 13 December 2006. The GPS sites are marked by dots. The names of the sites are not given for reasons of space. Asterisks show the location of sunlit points for the solar flare on 6 and 13 December 2006.

or the current 30-s count of all parameters was absent as a whole.

3. Statistics of GPS phase slips and missed counts during powerful solar flares

3.1. 6 December 2006

According to data from the Owens Valley Solar Array (OVSA), the solar radio noise level in the GPS frequency range exceeded 10^6 solar flare units (sfu) (background noise is 10^2 sfu) on 6 December 2006. Fig. 2e shows the RHCP radio emission spectrum at 1.2–2.0 GHz, registered at the Solar Radio Spectrograph OVSA.

The planetary index of geomagnetic activity was $Kp\sim4$ (weakly disturbed ionosphere).

Fig. 2a presents the $P(t)$ dependences during the 6 December 2006 flare on the Earth sunlit side (200–300°E; −80 to +80°N). They were derived for $n = 12{,}793$ LOS's, for all observable GPS satellites with their pseudo-random noise (PRN) code number (Hofmann-Wellenhof et al., 1992) at the threshold elevation angle $\Theta > 10^\circ$ from 18:00 to 20:00 UT (heavy black line). $P(t)$ was observed to significantly exceed the background level $P_{max}\sim0.2$–0.3% typical of the weakly disturbed ionosphere (Afraimovich et al., 2002a, b) at 19:30–19:40 UT. This corresponded to an abrupt increase of the solar radio emission flux.

The maximum relative density value of slips $P_{max} = 18.5\%$ is ~50 times higher than the background

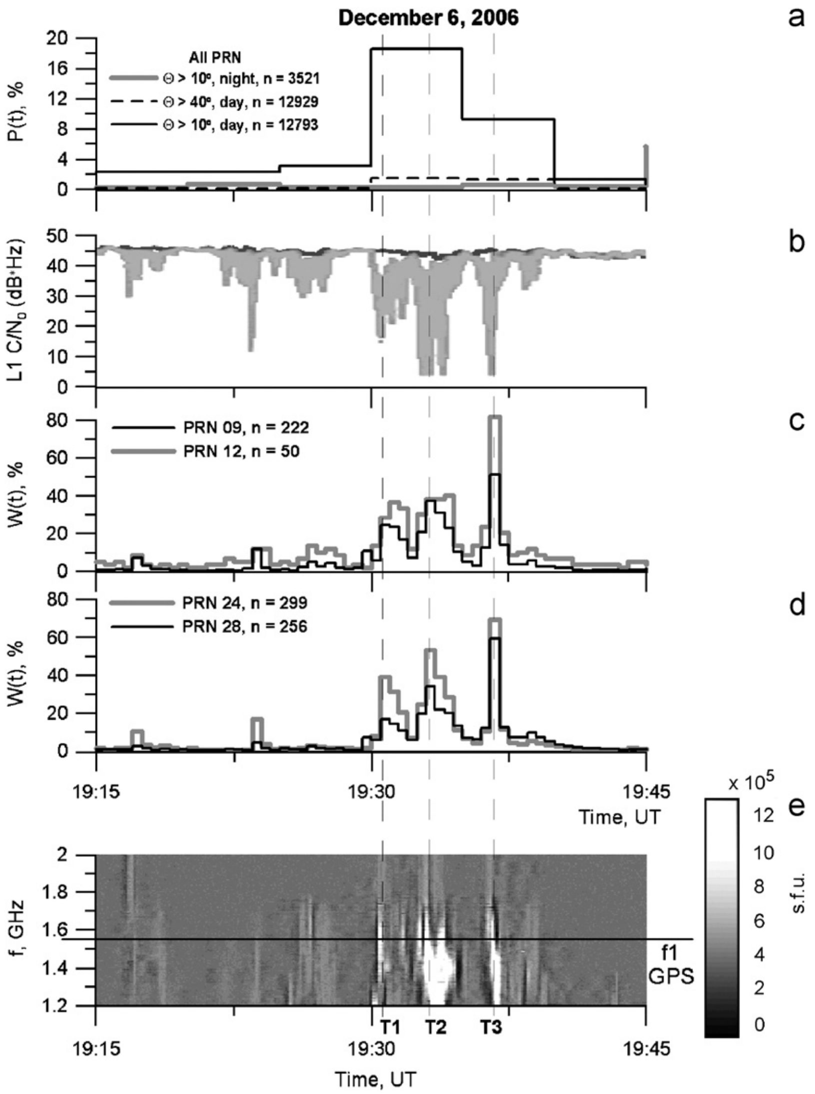

Fig. 2. GPS phase slips and count omissions during the 6 December 2006 solar flare. The relative density of phase slips $P(t)$ for elevations $\Theta > 10^\circ$ and $\Theta > 40^\circ$ on the Earth's sunlit side (the black and dashed lines, respectively (a)). The dependence of $P(t)$ for the Earth's dark side ($\Theta > 10^\circ$) is indicated by the gray line (a). The relative number of GPS sites $W(t)$ where the 30-s count omissions were observed for selected GPS satellites (PRN) (c), (d). The RHCP radio emission spectrum at 1.2–2.0 GHz, registered at the solar radio spectrograph OVSA (e). The signal-to-noise ratio at the $L1$ basic GPS frequency f_1 (b) registered on 6 and 5 December (the gray and black lines, respectively) by a specialized GPS receiver intended for monitoring scintillations (by Cerruti et al., 2006a, b).

one. At the same time, the slips average density on the Earth night side for $\Theta > 10^\circ$ ($n = 3521$ LOS) did not exceed the background one (Fig. 2a, gray line). Unfortunately, the time resolution of the $P(t)$ dependence ($dT = 5$ min) proved to be insufficient to display fine time structures of the radio emission flux (Fig. 2e), obtained with resolutions better than 1 s. Nevertheless, the similarity in the form of the envelopes of the phase slip distribution and solar radio flux can be noted.

Fig. 2c and d show the relative number of GPS sites $W(t)$, where missed 30-s counts were observed from 19:15 to 19:45 UT, for selected PRN. It is evident that maximum values W_{max} may reach 82% and 69% (PRN12, $n = 50$ GPS sites; and PRN24, $n = 299$ GPS sites). It is demonstrated that the sharp increase in phase slips and number of missed counts totally coincide with the moments of the most powerful solar radio bursts (moments T_1, T_2, T_3).

3.2. 13 December 2006

According to data from the Learmonth solar radio spectrographs, the total flux $F(t)$ of radio emission of

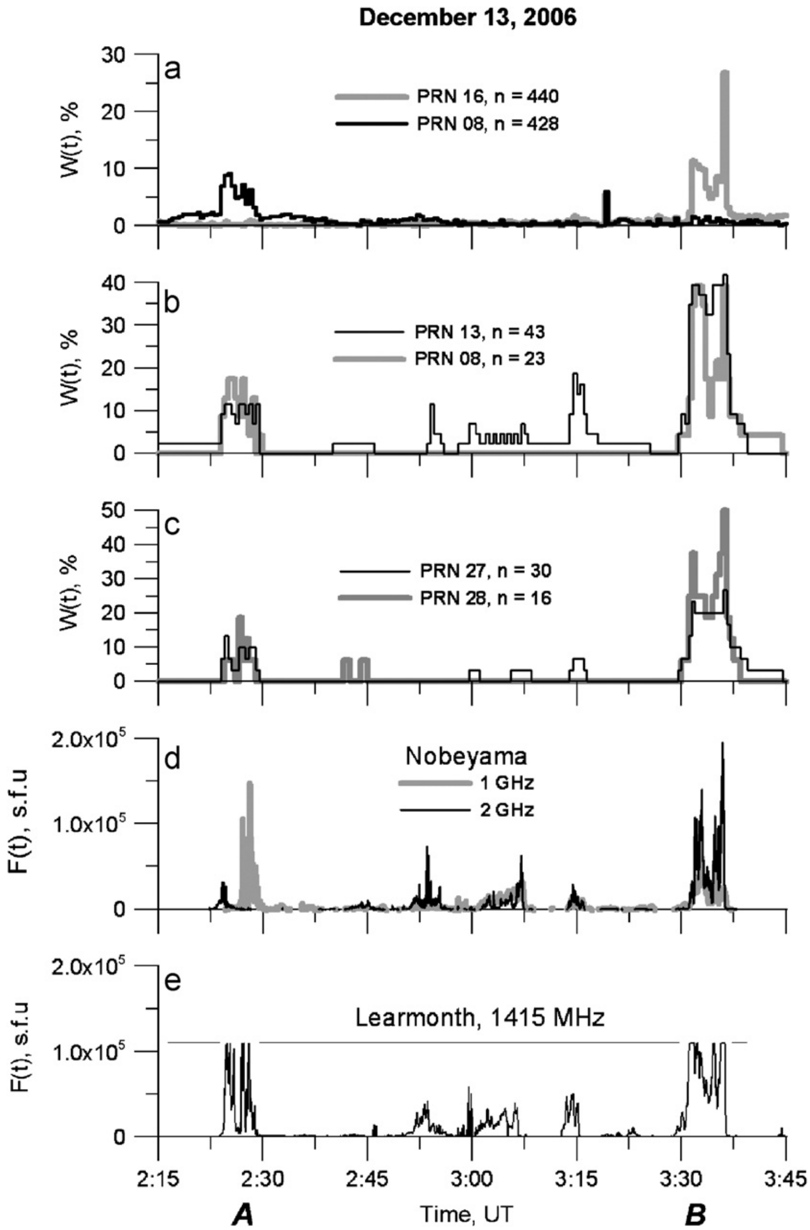

Fig. 3. GPS count omissions for selected GPS satellites (PRN) during the solar flare on 13 December 2006 in the sunlit hemisphere. The relative number of GPS sites $W(t)$ of the global GPS network where the 30-s count omissions were observed (b), (c); (a) for GEONET. The total flux $F(t)$ of radio emission (1415 MHz) registered by the Learmonth solar radio spectrograph (d). Horizontal line marks the level of spectrograph amplitude saturation (~110,000 sfu). The flux $F(t)$ of the RHCP radio emission at 1 and 2 GHz (the thick gray line and the black line, respectively), registered by the Nobeyama Radio Polarimeters (e).

13 December 2006 exceeded 10^5 sfu at 1415 MHz (Fig. 3e). Saturation can be noticed in the dependence of the solar radio flux from 02:20 to 02:28 UT (symbol *A*) and from 03:30 to 03:37 UT (symbol *B*). The horizontal line marks the spectrograph amplitude saturation level (~110,000 sfu).

Data from the Nobeyama Radio Polarimeters (http://solar.nro.nao.ac.jp/norp/html/event/20061213_0247/norp20061213_0247.html) show that the RHCP solar radio emission on 13 December 2006 exceeded 1.47×10^5 sfu at 1 GHz at 02:28:09 UT and 2.57×10^5 sfu at 2 GHz at 03:35:51 UT (Fig. 3d, the thick gray line and the black line, respectively). The sharp impulses of the solar radio flux coincided with the total radio emission flux $F(t)$, registered by Learmonth solar radio spectrographs.

For the 13 December 2006 flare on the Earth's sunlit side (40–200°E; −80 to +80°N) Fig. 3b and c present the relative number of GPS sites $W(t)$, where missed counts were registered, for all satellites with PRN observed from 02:15 to 03:45 UT. Obviously, the maximum values of W_{max} may reach 50% and 39% (PRN28, $n = 16$ GPS sites; and PRN08, $n = 23$ GPS sites). It is shown that the sharp increase in slips and count omissions completely coincides with the pulses of the solar radio emission during periods *A* and *B*, including the fine time structure of solar radio bursts.

There were too few GPS sites for the Earth's sunlit side (40–200°E; −80 to +80°N) on 13 December 2006 (http://sopac.ucsd.edu/other/services.html/). Therefore we use data from the Japanese GPS network GEONET consisting of 1225 GPS permanent stations. At present it is the largest regional GPS network in the world. Fig. 3a depicts the dependences $W(t)$ for the 13 December 2006 flare over Japan, for satellites with PRN observed from 02:15 to 03:45 UT. The maximum values of W_{max} may reach 27% (PRN16, $n = 440$ GPS sites). The sharp increase in count omissions coincides with the pulses of the solar radio emission during time intervals *A* and *B*.

3.3. 28 October 2003

It is interesting to estimate the GPS operation failures caused by the solar radio burst of 28 October 2003. The power of the burst was 2–3 orders of magnitude less than that of the solar radio bursts on 6 and 13 December 2006.

According to data from the Trieste Solar Radio Spectrograph, Italy, the RHCP solar radio noise level exceeded 3×10^3 sfu at 1420 MHz on 28 October 2003 (Fig. 4e). Insignificant saturation can be noticed in the dependence of the solar radio flux from 11:05 to 11:08 UT (time interval *A*) and a strongly pronounced saturation from 11:40 to 12:00 UT (time interval *B*).

Fig. 4d (heavy black line) presents the $P(t)$ dependences for the 28 October 2003 flare on the Earth sunlit side (330–120°E; −80 to +80°N) derived for $n = 2452$ LOS, for all observable PRN at the elevation angle threshold $\Theta > 10^\circ$ from 11:00 to 12:00 UT. $P(t)$ was observed to significantly exceed the background level P_{max}~0.2–0.3% typical of the weakly disturbed ionosphere (Afraimovich et al., 2002a, b) from 11:02 to 11:10 UT. This corresponds to an abrupt increase in the solar radio emission flux (time interval *A*). The maximum value of the maximal relative density of slips $P_{max} = 1.7\%$ exceeds the background one by a factor of ~10. At the same time, the average density of slips on the night side of the Earth for $\Theta > 10^\circ$ ($n = 12{,}070$ LOS) does not exceed the background one (Fig. 4d, thick gray line).

More substantial evidence of GPS-operation quality deterioration can be found by estimating the average relative density of slips for individual GPS satellites. Fig. 4a–c, presents the $P(t)$ dependences for all satellites with PRN observed from 10:00 to 12:00 UT. The maximum values of P_{max} can reach 11% and 10.2% (PRN05 and PRN18, $n = 100$), whereas the values of P_{max} (2.3%) for satellite PRN29 are close to P_{max} (1.7%) determined for all the satellites.

The sharp increase in slips and count omissions coincides with the most powerful solar radio bursts for time intervals *A* and *B*.

It should be noted that although the power of the solar radio burst on 28 October 2003 is 2–3 orders of magnitude less than that on 6 and 13 December 2006, the maximum values of phase slips are only 5–10 times as small.

Our results agree with data obtained by Chen et al. (2005). Their study found severe signal corruptions at dayside GPS receiver stations during large solar radio bursts accompanying the 28 October 2003 super flare. Almost none of the GPS L_2 signals was tracked during the solar flux peak for areas near the subsolar point. The rate of loss of lock on the GPS L_2 frequency was compared with the solar radio flux density in different bands. A correlation index equal to 0.75 was revealed in the 1415 MHz solar radiation band.

4. A comparison between GPS signal parameter measurement failures for different types of GPS receivers during the powerful solar flare on 13 December 2006

A comparison of different types of GPS receivers' response to wideband solar radio noise emission is of great interest. The dense network of GEONET GPS receivers, equipped with 1200 TRIMBLE-5700 and 25 TRS-LEGACY receivers, is best suited for this purpose. Since the entire network covers a rather small area, all the receivers were under a similar influence of the solar radio noise emission during the powerful solar flare on 13 December 2006.

For all LOS, we determine the relative density $Q(t)$, % of measurement slips of the main GPS signal parameters: L_1 and L_2 are the phase delay, and P_1 and P_2 are the group delay for GPS frequencies f_1 and f_2. Fig. 5 presents the relative density $Q(t)$ of measurement slips of the L_1, P_1, L_2, and P_2 parameters registered by the TRIMBLE-5700 (thick gray lines, Q_a) and TRS-LEGACY (black lines, Q_b) receivers on 13 December 2006, panels c, d, a, and b, respectively.

Obviously, the significant failures in measuring the main GPS signal parameters by TRIMBLE-5700 receivers are not only registered at auxiliary frequency L_2, but at basic GPS frequency L_1 as well. Nevertheless, the significant measurement slips of the main parameters by TRS-LEGACY receivers are only registered at auxiliary frequency L_2.

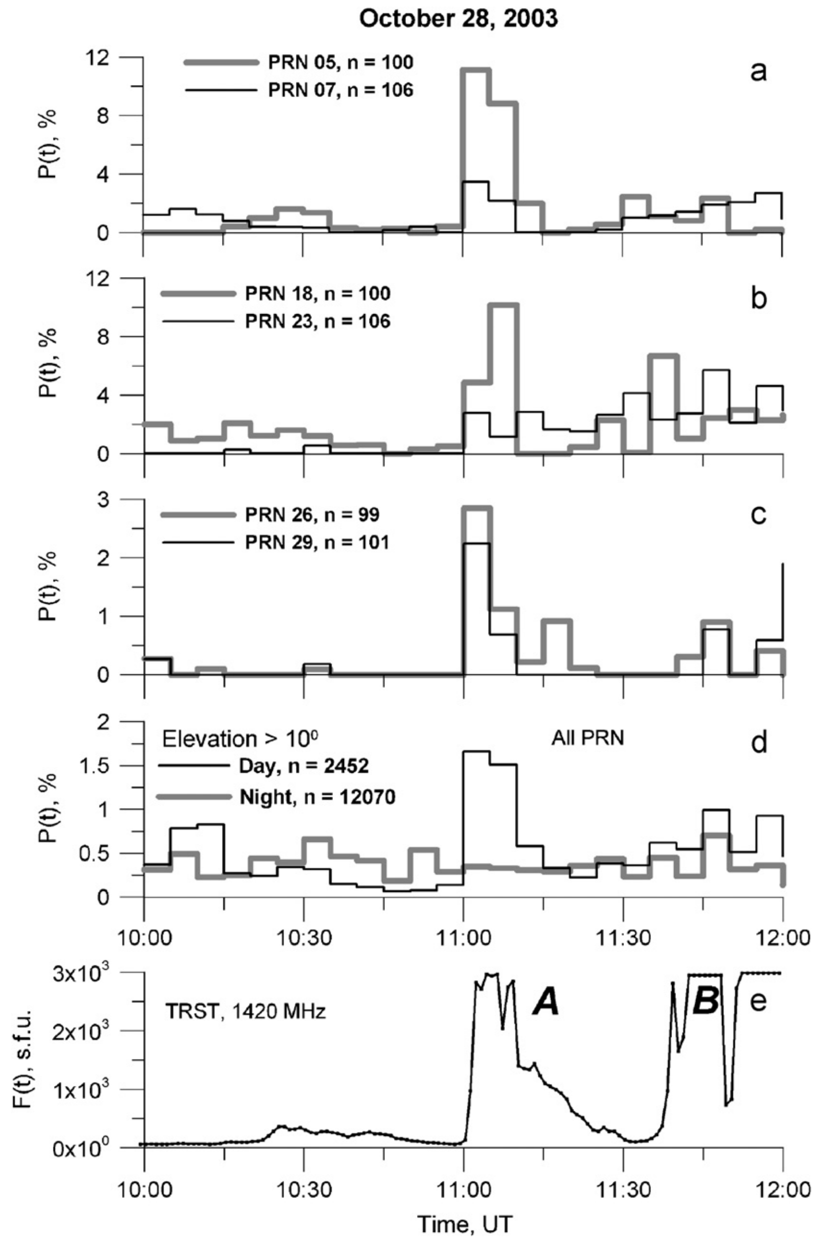

Fig. 4. GPS phase slips during the solar flare on 28 October 2003 in the sunlit hemisphere. The relative density $P(t)$ of L_1–L_2 phase slips for all (d) and individual GPS satellites (a), (b), and (c). The flux $F(t)$ of RHCP radio emission (1420 MHz) registered by the Trieste Solar Radio Spectrograph (e).

Our results agree with the data obtained by Chen et al. (2005). The authors revealed a significant difference between the signal tracking of different types of GPS receivers during the 28 October 2003 super flare.

5. Discussion: the origin of phase slips and count omissions during powerful solar flares

Our results agree well with calibrated data on amplitude measurements by several GPS receivers intended for determining the characteristics of GPS signal scintillations (Cerruti et al., 2006a) caused by scattering by ionospheric irregularities (Yeh and Liu, 1982). The data from Cerruti et al. (2006a) obtained for a site located in the sunlit zone are presented in Fig. 2b (gray line). The high temporal resolution of measurements (50 Hz) enabled us to conclude that a sharp reduction in the signal/noise ratio L_1 S/N at basic GPS frequency L_1 (down to the fatal value of 30 dB) is, with a high accuracy, synchronous with impulses of powerful radio emission (Fig. 2e, a vertical dashed lines corresponding to time moments, T_1, T_2, and T_3). The S/N ratio for the same satellite for the preceding day (5 December) is given for comparison in Fig. 2b (black line). In this case, the S/N ratio for all the observation intervals practically does not differ from

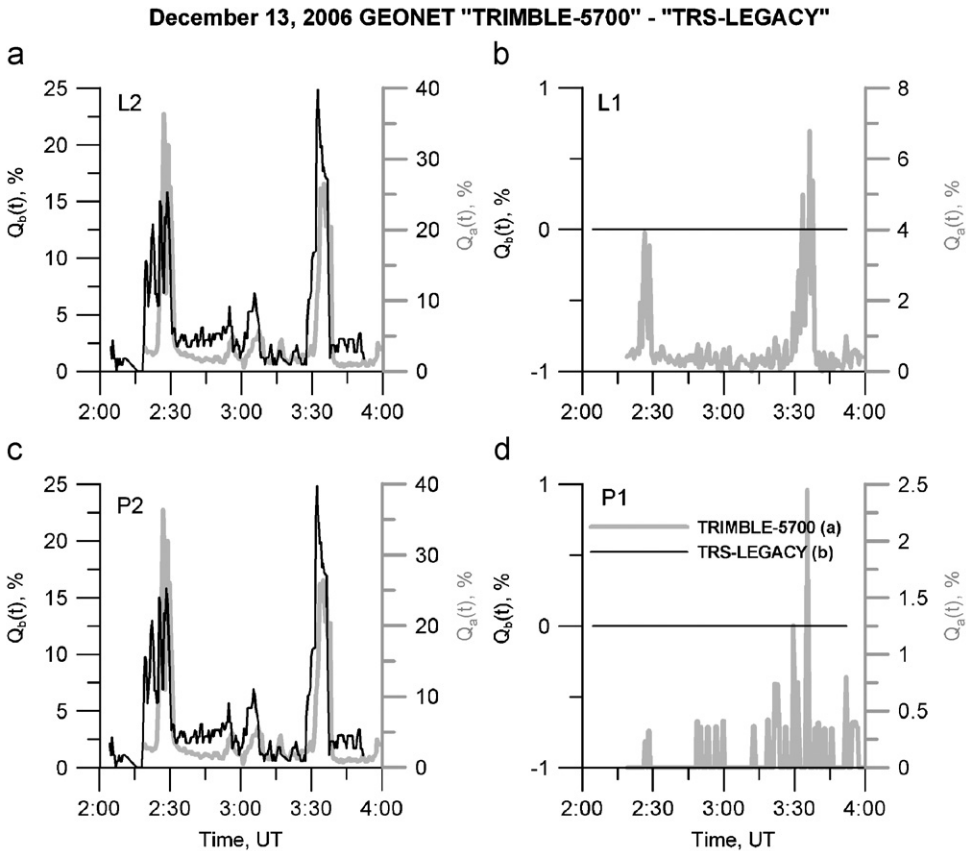

Fig. 5. GPS slips of phase (L) and group (P) delay measurements from GEONET during the solar flare on 13 December 2006. The relative density $Q(t)$ of measurement slips of the L_1, L_2, P_1, and P_2 parameters registered by TRIMBLE-5700 and TRS-LEGACY receivers (thick gray lines Q_a, and black lines Q_b, respectively).

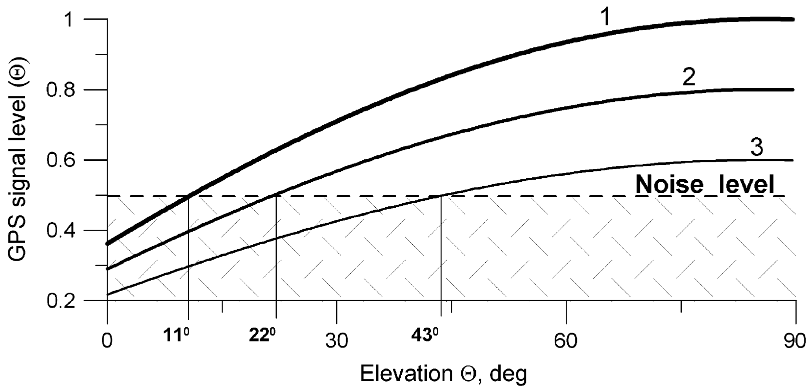

Fig. 6. The GPS signal level versus elevation Θ for different satellite transmitter powers.

40 dB of the GPS standard. It means that during the 6 December 2006 flare the wideband solar radio emission was 2–3 orders of magnitude higher than the background noises allowed for in the development of GPS systems.

Under usual conditions, signal scintillations resulting from ionospheric-inhomogeneity scattering in the auroral and equatorial zones (Yeh and Liu, 1982), do not considerably affect the GPS operation (Afraimovich et al., 2002a, b; Kintner et al., 2001). In the middle latitudes, noticeable GPS signal scintillations occur only during magnetic storms (Karasawa et al., 1985; Afraimovich et al., 2002a, b, 2003; Conker et al., 2003; Doherty et al., 2001; Ledvina et al., 2002; Skone and De Jong, 2000, 2001). But there were very strong amplitude "scintillations" against a background of low geomagnetic activity during the 6 December 2006 flare.

During the powerful solar radio bursts on 6 December 2006, scintillation index S4 (Yeh and Liu, 1982) increased up to very high values of about 1.0 (Cerruti et al., 2006a). However, these data do not completely refer to the effect of GPS signal scintillations, for which S4 is usually within 0.1–0.2 (Yeh and Liu, 1982). In the receiver band, the broadband noise of high-power solar radio emission considerably exceeded the signal level.

Fig. 6 qualitatively illustrates the GPS phase slip mechanism during the flare. The dependences of the GPS signal level on the LOS elevation angle Θ are denoted 1, 2, and 3. A monotonous reduction in the signal level is associated with an increase in the satellite-receiver distance. Under usual conditions, due to correlation processing of a broadband signal in the receiver, the additive noise in ~40 dB is below the level of signals; that is why it cannot be distinguished in Fig. 6. During powerful solar radio bursts, the noise level at low elevations (Fig. 6, a horizontal dashed line) was comparable to the signal level. This caused failures in the phase tracking of the GPS signal. Obviously, for a satellite with the highest effective signal power (curve 1) this condition was fulfilled at quite low angles of elevation (11°), for less powerful signal 2 at 22°. For the weakest signal 3, slips appear at high angles of elevation, 43°. As a result, navigation using this satellite was practically impossible during the flare.

This explanation agrees with our experimental data. Fig. 2a presents the $P(t)$ dependences for the 6 December 2006 flare on the Earth's sunlit side (200–300°E; −80 to +80°N) for $n = 12{,}929$ LOS for all observable PRN at the threshold for elevation angle $\Theta > 40°$ from 19:15 to 19:45 UT (dashed line). In this case the average density

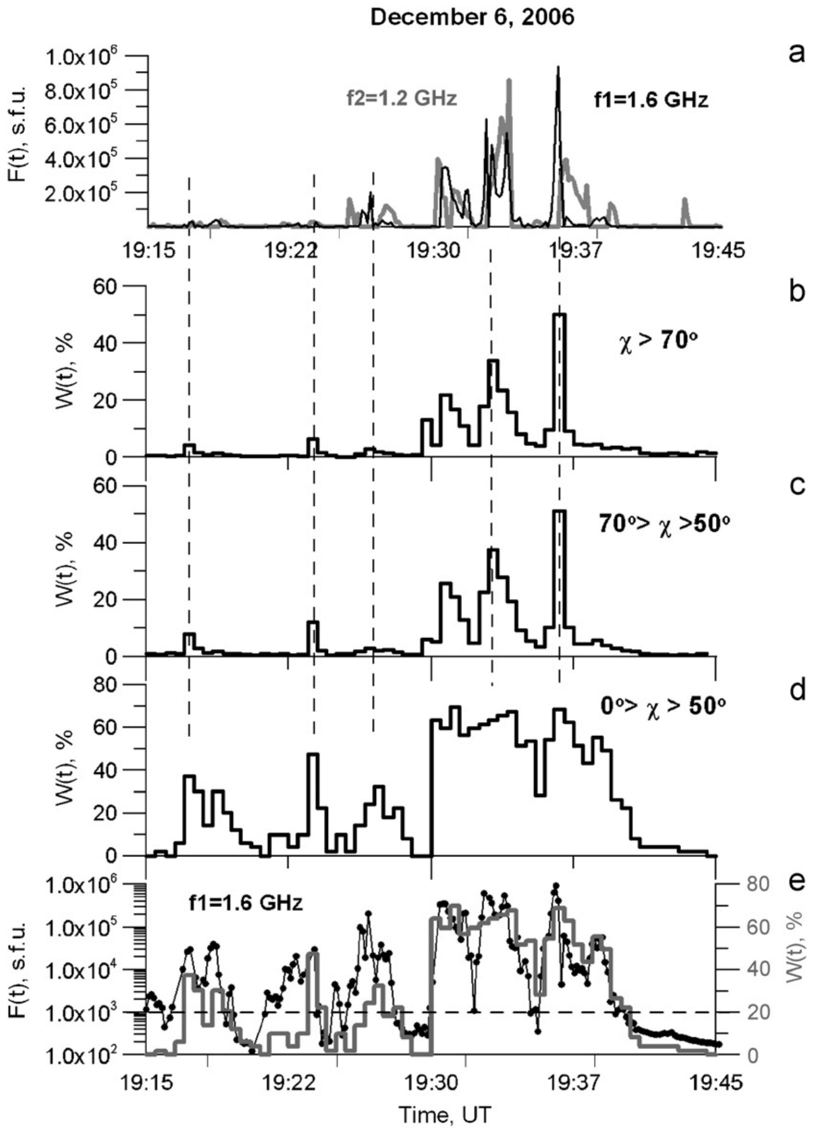

Fig. 7. The count omissions of GPS measurements vs. the Sun zenith angle χ during the 6 December 2006 radio burst: (b) $\chi > 70°$; (c) $70° > \chi > 50°$; and (d) $0° > \chi > 50°$. (a) Intensity of the solar radio flux $F(t)$ at $f_2 = 1.2$ GHz (the thick gray curve) and $f_1 = 1.6$ GHz (the black curve), observed by the OVSA Radio Spectrograph; (e) the same for $f_1 = 1.6$ GHz on the logarithmic scale. For comparison, the relative dependence of count omissions $W(t)$ for small values of the zenith angle $0° >$ and $\chi > 50°$ is shown in (e).

of slips did not exceed the background (Fig. 2a, black line from 19:15 to 19:45 UT). Thus, for high elevation angles of LOS at the satellite, the possibility of slips is one order of magnitude smaller than for low angles.

According to the said mechanism, the dependence of the maximum slip density is not proportional to the maximum radio emission power. It can be determined by the signal-to-noise ratio threshold, which may be different for different satellites. Therefore the spread of values of P_{max} and W_{max} slip indices obtained for the flares under analysis (differing by no more than a factor of 10–20 for the different flares) is essentially smaller than that for the flare radio emission power (10^6–10^3 sfu, i.e. 1000 times).

The lower signal-to-noise ratio at L_2 is primarily due to the fact that the L_2 power at the GPS satellite transmitter output is 6 dB less than the fundamental frequency f_1 with the C/A code (ICD-200c). Similar correlations of the effective radiated power of L_1 (30 W) and L_2 (21 W) signals are also typical of the Russian GLONASS system (Perov and Kharisov, 2005).

Phase slips at L_2 may also be caused by a lower signal-to-noise ratio for L_2 when commercial non-coded receivers are used. These receivers have no access to the military "*Y*" code, and have to use the non-coded or semi-non-coded mode of reception. As a result, the signal-to-noise ratio at L_2 is at best 13 dB lower than the mode of fully coded reception.

Hence the difference in signal powers at L_1 and L_2 for commercial receivers can be over 10 dB. This may result in increasing slip density at L_2, owing to the influence of additive interferences. Different types of GPS receivers differently respond to this power difference; on the whole, however, the pattern of the dependence upon local time, latitude range, and geomagnetic activity remains sufficiently stable.

Our results confirm the conclusion by Chen et al. (2005). Direct interference from solar radio bursts is not usually considered as a potential threat to GPS signal tracking, since the flux densities of most bursts are below a threat threshold for the GPS L_1 frequency (40,000 sfu), proposed by Klobuchar et al. (1999). Analysis by Chen et al. (2005) indicated that a much lower threshold should be adopted for codeless or semi-codeless dual-frequency GPS receivers. A correlation analysis revealed that GPS signal losses of lock are primarily caused by microwave in-band interference, and the threat threshold of solar radio burst effects on the GPS system should be re-evaluated, since the flux density of the burst at 1415 MHz was just 4000–12,000 sfu. This threat threshold is far below what was previously proposed (Klobuchar et al., 1999).

Nevertheless our data suggest that deleterious effects appear at F_{min}, i.e. below the estimate by Chen et al. (2005). Obviously, the interference level depends on the Sun zenith angle χ (Carrano et al., 2007). In Fig. 7, we present the dependence of count omissions of GPS measurements upon the Sun zenith angle χ during the burst on 6 December 2006. The magnitude of the flux $F(t)$ of solar radio emission, as measured by OVSA at $f_2 = 1.2$ GHz and $f_1 = 1.6$ GHz, is shown in both the linear (a) and the logarithmic scales (e). The count omissions $W(t)$ are demonstrated in panels (b) $\chi > 70^\circ$, (c) $70^\circ > \chi > 50^\circ$, and (d) $0^\circ > \chi > 50^\circ$. The vertical dashed lines mark the moments of maximum count omissions.

Comparison of count omissions $W(t)$ for small values of the zenith angle $0^\circ \chi > 50^\circ$ to the $F(t)$ intensity for $f_1 = 1.6$ GHz (close to the basic GPS frequency) shows their close similarity (Fig. 7e). It is also necessary to note that the threshold F_{min}, at which GPS receiver failures occur for small Sun zenith angles, does not exceed 1000 sfu (horizontal dashed line). An increase in count omissions for high zenith angles χ testifies to the solar origin of interference (noise) at these GPS frequencies. A decrease in failures when the zenith angle increases is caused by a decrease of antenna gain and increase of losses in the atmosphere (Carrano et al., 2007). During the solar radio bursts on 6 and 13 December 2006, the Sun zenith angle χ exceeded 50–60° for most GPS sites (see the location of sunlit points in Fig. 1). Therefore the $F(t)$ intensity was essentially reduced, and the GPS performance failure was not so destructive.

7. Conclusion

Significant experimental evidence has been found that, for over 10–15 min, high-precision GPS positioning was partially disrupted on the entire sunlit side of the Earth on 6 and 13 December 2006. The high level of phase slips and count omissions resulted from the wideband solar radio noise emission. The statistics of phase slips obtained in our study for the entire sunlit side of the Earth confirm the suppression of GPS receivers' operation during the 6 December 2006 flare more reliably than the published data (Cerruti et al., 2006a, b; Carrano et al., 2007; Carrano and Bridgwood, 2008; Kintner, 2008) for just a few GPS sites.

Our results provide serious grounds for revising the role of space weather factors in the operation of modern satellite systems and for considering these factors more carefully in practice. Similar failures in the operation of satellite navigation systems (GPS, GLONASS, and European system GALILEO) can be fatal for operating safety systems as a whole and lead to great financial losses.

Another important conclusion of our investigation is that the continuous calibrated monitoring of the solar radio emission flux level by a large number of solar radio spectrographs allows us to estimate the level of radio noise of solar origin at GPS–GLONASS–GALILEO frequencies.

Indeed, powerful solar radio bursts can serve as a global and free tool for testing satellite broadband radio systems, including GPS.

A series of the most powerful flares on 5 and 13 December 2006, i.e. in a deep minimum of the solar cycle, was absolutely unexpected. The research and analysis of these flares and their aftereffects (consequences) in space environment are not completed yet (Gary, 2008). The space weather anomaly caused by the 6 December 2006 X6.5 flare has generated a need for introducing one more parameter of powerful flare consequences—a powerful flux of flare radio emission in a wide range of frequencies, sufficient for a temporary disruption of the normal operation of the radio-electronic equipment in orbital and ground-based navigation systems (GPS, GLONASS, and the future GALILEO receivers). The consequences do not depend on the localization of the flare on the solar disk.

It is of great practical importance to develop methods and means for forecasting the pre-flare activity of the Sun.

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