

FAILURE OF GPS FUNCTIONING CAUSED BY EXTREME SOLAR RADIO EVENTS

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Abstract. We investigate the performance quality of the Global Positioning System (GPS) during the 2006 December 6 and 2006 December 13 solar flares (soft X-ray class X6.5 and X3.4, respectively), which produced solar radio bursts with unprecedented radio flux density. According to data from the Owens Valley Solar Array (OVSA) and the RSTN spectrograph at Learmonth, the level of solar radio noise during the 6 December and 13 December events in the GPS frequency range exceed 10^6 s.f.u. and 10^5 s.f.u., respectively (compared to $\sim 10^2$ s.f.u. for the quiet Sun). We used GPS data from a global network of dual-frequency receivers (for the 6 December event, more than 1500 sites; <http://sopac.ucsd.edu/other/services.html>) and data of Nationwide GPS array of Japan GEONET (for the 13 December event; 1225 sites; ftp://163.42.5.1/data/GPS_products/). We found significant experimental evidence that during more than 10 minutes the high precision GPS positioning on the entire sunlit side of the Earth has been partially paralyzed. We show that the observed high level of phase slips and count absences are caused by wideband solar radio noise. Our results provide serious grounds for revision of the role of space weather in the functioning of modern satellite systems and suggest the need for a more careful accounting of space weather factors in engineering development and operation. Another important conclusion of our paper is the need for continuous monitoring, by well-calibrated instruments, of the level of integrated flux of solar radio emission. Such monitoring should be carried out by a number of solar radio spectrographs, distributed to cover the entire range of longitudes, to be used for determining the level of radio noise of solar origin in the range of frequencies used by GPS-GLONASS-GALILEO.

1. Introduction

A soft X-ray class X6.5 solar flare occurred on 2006 December 6. This flare is of unusual interest not only to solar physicists and radio astronomers, but to other scientists and engineers as well. In X-ray and Ultra-violet (UV) ranges, this flare was not the most powerful, but the broadband solar radio emission followed the flare exceeded power solar radio bursts (SRB) in all flares known till now by an order of magnitude. This led to fatal failures in functioning of broadband satellite radio systems including the global positioning system (GPS). The functional failures and deep damping of GPS signals were registered at separate standard GPS receivers and specialized monitors of ionospheric scintillations in the L-band range (Cerruti et al., 2006a, 2006b; Carrano et al., 2007).

It has been predicted by Klobuchar et al. (1999) that SRB can affect GPS performance, if a solar flux is sufficiently large in the L band frequency range and with Right Hand Circular Polarization (RHCP) - the polarization to which GPS antennas are receptive. The direct interference from SRB has not been considered as a potential threat to GPS signal tracking, since the flux densities of most bursts are below a threat threshold to the GPS L1 frequency 40,000 solar flux units (s.f.u.) proposed by Klobuchar et al. (1999).

Chen et al. (2005) found that a much lower threshold should be adopted for codeless or semicodeless two-frequency GPS receivers. In that investigation, severe signal corruptions were found by the International GPS Service receiver stations on the dayside during a large solar radio burst that accompanied the super flare of 28 October 2003. Almost none of GPS L2 signals were tracked during the solar flux peak time for areas near the subsolar point. A correlation analysis was performed between the rate of loss of lock on the GPS L2 frequency and the solar radio flux density at different bands. A correlation index equal to 0.75 was revealed in the 1415 MHz solar radiation band that was located between two GPS operating frequencies L2 (1227.60 MHz) and L1 (1575.42 MHz). The correlation analysis indicated that GPS signal losses of lock were primarily caused by the microwave in-band interference, and that the threat threshold of SRB effects on the GPS system should be re-evaluated, since the flux density of the burst at 1415 MHz was just 4,000-12,000 s.f.u., far below the previously proposed threat threshold. The signal-tracking performance of different types of GPS receivers during such a super flare event was also presented.

However, the global scale of the failure of all GPS positioning systems during this flare was unclear. Meanwhile, the problem is of doubtless scientific and practical interest as regards the estimation of the space weather effect on functioning of one of the most reliable and widely used satellite systems, considered practically impregnable. In this study, we investigate GLOBAL failures of GPS performance produced by solar radio bursts with the unprecedented radio flux density during X6.5 and X3.4 solar flares on 2006 December 6, and 13, respectively. Careful study of peak flux distribution of solar radio bursts (observing around the world during 1960-1999) showed that expected average waiting time between bursts with flux density exceeding 1000 s.f.u. was 3.5 days near solar maximum 3.5 days, and 18.5 days at solar minimum (Gelu et al., 2002). Bursts of this flux density double the level of noise, and may create a problem for antennas pointed in the direction of the Sun (Gary et al., 2003).

2. Method of GPS data treatment

We use GLOBDET software developed in the Institute of Solar-Terrestrial Physics, the Siberian Branch of the Russian Academy of Sciences, to treat GPS data from the global network of two-frequency receivers (Afraimovich et al., 2000). Our database of GPS RINEX files consists of data from over 1500 GPS sites (<http://sopac.ucsd.edu/other/services.html>). In addition, for 2006 December 6 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 2006 December 13, (ftp://terras.gsi.go.jp/data/GPS_products/).

We calculate the 30-s series of the phase difference L1–L2 on two GPS frequencies f_1 (1227.60 MHz) and f_2 (1575.42 MHz) along "receiver-satellite" lines-of-sight (LOS) to confirm a slip of measurements of the L1-L2 phase difference (Afraimovich et al., 2002a, 2002b). These data for each GPS satellite are then averaged over a period of $\Delta T = 5$ min at all chosen sites. This allows us to calculate the average observation density $M(t)$ and average slip density $S(t)$ for all n LOS. Further, we calculate the average relative density of slips $P(t) = S(t)/M(t)$, %, and determine the maximal value P_{\max} , %. If the next count in a RINEX file is absent, the number of slips is equated to the number of expected observations; so the density of slips becomes 100 %.

Failures L1–L2 mean impossibility of precision positioning in a two-frequency mode; thus there is a possibility of incorrect position coordinates in single-frequency mode (L1). However positioning in general is impossible if the signal on one of GPS frequencies is not registered at all. For an estimation of probability of such failures for all LOS containing failures L1–L2, we defined the relative number of missed counts $N(t)$ for given 30-s interval of time, in relation to number $M(t)$ of counts expected in the 30-s interval: $W(t) = N(t)/M(t)$, %, and also the corresponding maximal value W_{\max} %. The time resolution of dependence $W(t)$, 30 s, has allowed to carry out a detailed comparison with the time-dependent flux of solar radio emission.

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

3.1. 2006 December 6

This flare was far from the strongest one in the X-ray and UV ranges. However, the broadband solar radio emission (hereafter, BSR), which followed the flare from 19:25 to 19:40 UT, was an order of magnitude stronger than all previously known flares. It is also significant that it was highly right-hand circularly polarized (RHCP), the same sense of polarization used by GPS and other navigation system. This radiation was responsible for malfunctioning of broadband satellite radio systems, including the GPS navigation system. Malfunctioning was noted at some GPS receiving stations, while prolonged signal fades were recorded at the specialized receiving monitors of ionospheric scintillation recorders (Cerruti et al., 2006a). However, the scale of the effects on the entire positioning system during the flare remains unknown. No doubt, this issue is of scientific and practical interest from the point of view of estimating the influence of space weather on the functioning of the widely used satellite system.

According to the data from the Owens Valley Solar Array (OVSA), the solar radio noise level on 2006 December 6, in the GPS frequency range exceeds 10^6 solar flare units (s.f.u.), compared to 10^2 s.f.u. for the background quiet Sun. The RHCP radio emission spectrum in the range of 1.2-2.0 GHz, registered at the solar radio spectrograph OVSA, is shown on Figure 1a.

A planetary index of geomagnetic activity was $Kp \sim 4$ (weakly disturbed ionosphere).

Figure 1b presents $P(t)$ dependences, which took place during the 2006 December 6 flare on the Earth sunlit side (200° - 300° E; -80° + 80° N), received for $n = 12,793$ LOS, for all observable PRN (GPS satellite number) from 18.00 to 20.00 UT (heavy black line) at the threshold for the elevation angle $\Theta > 10^\circ$. A significant excess of the background level $P_{\max} \sim 0.2$ - 0.3 % typical of the weakly disturbed ionosphere (Afraimovich et al., 2002a, 2002b) was observed within the time range 19:30–19:40 UT that corresponded to the abrupt increase of the solar radio emission flux.

The maximal relative density of slips $P_{\max} = 18.5\%$ exceeds the background one by about 50 times. At the same time, the slips' average density on the night side of the Earth for $\Theta > 10^\circ$ ($n = 3521$ LOS) does not exceed the background one (Figure 1b, dotted line).

Even more serious evidence for decrease of the GPS functionality is obtained by estimating the average relative density of slips for separate GPS satellites. On Figure 2a and 2b, dependences $P(t)$ are given for all satellites with numbers PRN observed for 18:00–20:00 UT. Obviously, maximal values P_{\max} can reach 100 % and 78% (PRN24, $n = 465$; and PRN28, $n = 410$), while for satellite PRN26 values $P_{\max} = 17.7$ % is close to the average $P_{\max} = 18.5$ %, obtained for all satellites. This distinction qualitatively suggests that the effective power of separate GPS satellites transmitters differs by a factor of 2-5. Unfortunately, the available time resolution of the $P(t)$ dependence ($\Delta T = 5$ min) appears to be insufficient to display the shorter time variability seen in the radio emission (Figure 2e), shown with 4 s time resolution. Nevertheless, it is possible to note the concurrence of the phase slip distribution and the envelope of solar radio flux.

On Figure 2c and 2d, the relative number of GPS sites $W(t)$, where 30-s missed counts have been observed, are given for all satellites with numbers PRN observed for 18:00-20:00 UT. It is evident that maximal values W_{\max} can

run to 80% and 49% (PRN12, $n = 50$ GPS sites; and PRN24, $n = 299$ GPS sites). The sharp increase of slips and missed counts are demonstrated to be of full agreement with the times of the most powerful solar radio bursts (moments T1, T2, T3).

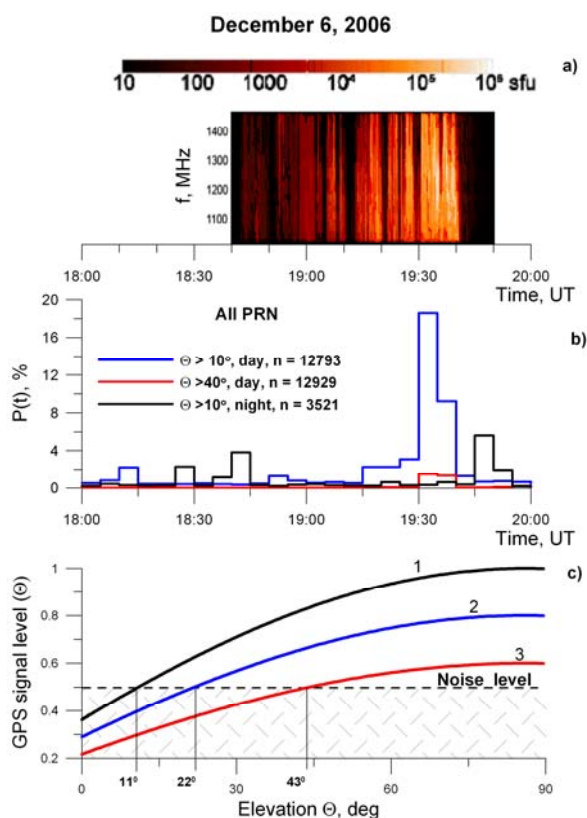


Figure 1. GPS phase slips and missed counts during the 2006 December 6 solar flare. *a)* The spectrum of the RHCP radio emission in the range of 1.2-2.0 GHz, registered with the FST instrument at OVSA. *b)* The relative density of phase slips $P(t)$ for elevations $\Theta > 10^\circ$ and $\Theta > 40^\circ$ on the sunlit side of the Earth (blue and red line, respectively). The dependence of $P(t)$ for the dark side of the Earth ($\Theta > 10^\circ$) is indicated by black line. *c)* The dependencies of a GPS signals level on elevation Θ and different transmitter satellite power.

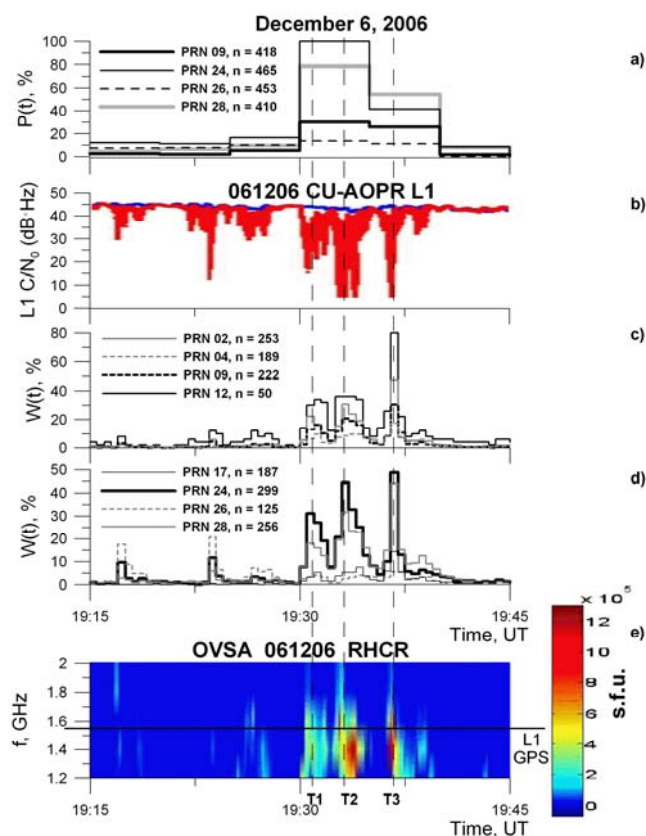


Figure 2. GPS phase slips and missed counts during the 2006 December 6 solar flare. *a)* The relative density $P(t)$ of phase slips of L1-L2 for different GPS satellites. *b)* The signal-to-noise ratio on the L1 basic GPS frequency f_1 registered on December 6 (red line) and December 5 (blue line) by the specialized GPS receiver intended for monitoring scintillations (by Cerruti et al., 2006). *c-d)* The relative number of GPS sites $W(t)$ where the 30-s missed counts were observed for various satellites. *e)* The spectrum of RHCP radio emission in the range of 1.2-2.0 GHz, registered by OVSA.

3.2. 2006 December 13

According to the data from the RSTN / Learmonth solar radio spectrographs (<http://www.ngdc.noaa.gov/stp/SOLAR/ftpsolarradio.html/>), the RHCP solar radio noise level on 2006 December 13 at 1415 MHz exceeded 10^5 s.f.u. (Figure 3e). Note that the RSTN systems saturate near this flux density. The saturation of the solar radio flux at the first interval from 02:20 to 02:28 UT (marked by symbol *A*) and at the second interval from 03:30 to 03:38 UT (marked by symbol *B*) can be noted. The horizontal line marks the spectrograph amplitude saturation level ($\sim 110,000$ s.f.u.). Data from the Nobeyama Radiopolarimeter in Japan indicate that the flux density exceeded 300,000 s.f.u.

On Figure 3a and 3b, $P(t)$ dependences during the 2006 December 13 flare on the Earth sunlit side (40° - 200° E; -80° + 80° N) are given for all satellites with numbers PRN observed for 02:15-03:45 UT. It is clear that maximal values P_{\max} can reach 49% and 36% (PRN13, $n = 136$; and PRN16, $n = 134$), while for satellite PRN08 P_{\max} (9%) is close to the average P_{\max} (14%), obtained for all satellites.

On Figure 3c and 3d, the relative number of GPS sites $W(t)$, where the number of missed 30-sec counts were observed, are given for all satellites with numbers PRN observed from 02:15 to 03:45 UT. Obviously, maximal values W_{\max} can run to 50% and 42% (PRN28, $n = 16$ GPS sites; and PRN13, $n = 43$ GPS sites). The sharp increase of slips and missed counts are shown to coincide with the impulsive SRB peaks during the periods *A* and *B*, including detailed SRB time structure.

There are too few GPS sites for the Earth sunlit side (40-200 E; -80-+80 N) on 2006 December 13 (<http://sopac.ucsd.edu/other/services.html/>). Therefore, we use data from the Japanese GPS network GEONET that consists of 1225 GPS permanent stations. At present, it is the largest regional GPS network in the world.

On Figure 4a and 4b, dependences $P(t)$ during the 2006 December 13 flare over Japan are given for all satellites with numbers PRN observed for 02:15–03:45 UT. Maximal values P_{\max} can reach 56 % (PRN08 and PRN 16, $n = 1200$ sites), while for satellites PRN03, 19, 27, 28 values P_{\max} ($\sim 9\%$) is close to P_{\max} (6%), obtained for all satellites.

On Figure 4c and 4d, the relative number of GPS sites $W(t)$, where the missed 30-sec counts were observed, are given for all satellites with numbers PRN observed from 02:15 to 03:45 UT. Maximal values W_{\max} can reach 27% and 20% (PRN16, $n = 440$ GPS sites; and PRN28, $n = 357$ GPS sites). The sharp increase of slips and missed counts are shown to coincide totally with the impulse SRB during the time intervals A and B.

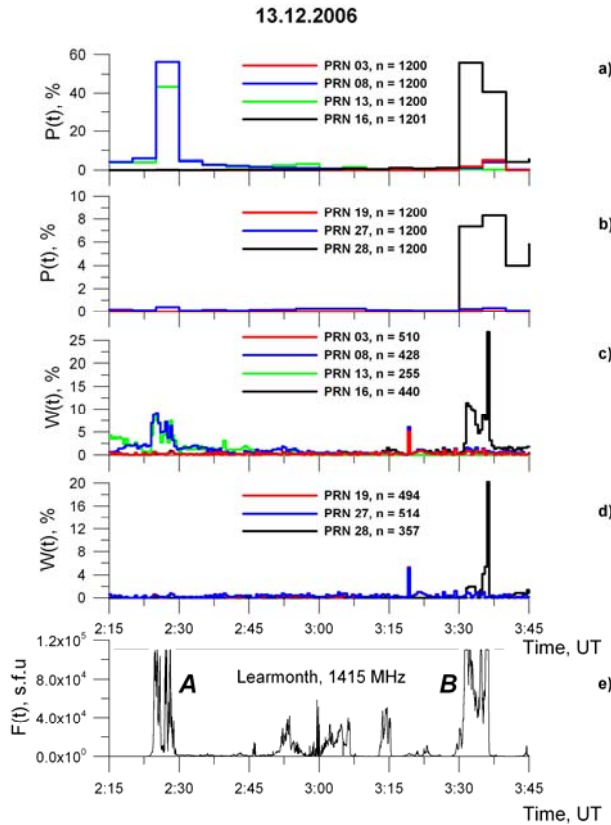


Figure 3. GPS phase slips and missed counts during the solar flare on 2006 December 13 over the sunlit hemisphere. *a-b*) The relative density $P(t)$ of L1–L2 phase slips for different GPS satellites. *c-d*) The relative number of GPS sites $W(t)$ where missed 30-s counts were observed. *e*) The flux of the RHCP radio emission (1415 MHz) registered by the Learmonth solar radio spectrograph. The horizontal line marks the level of spectrograph amplitude saturation ($\sim 110,000$ s.f.u.).

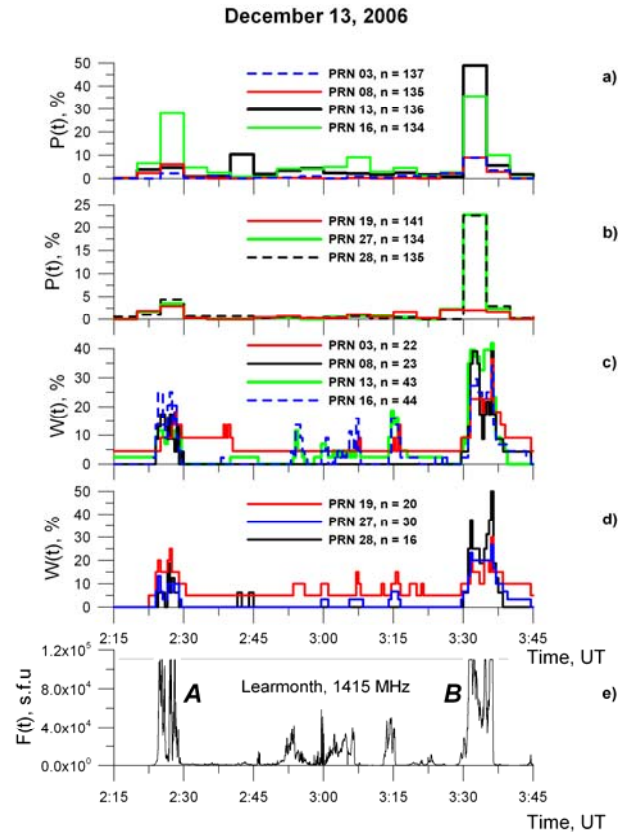


Figure 4. GPS phase slips and missed counts during the solar flare on 2006 December 13 – GEONET; all types of receivers. *a-b*) The relative density $P(t)$ of L1–L2 phase slips for different GPS satellites. *c-d*) The relative number of GPS sites $W(t)$ where the missed 30-s counts were observed. *e*) The flux of the RHCP radio emission (1415 MHz) registered by the Learmonth solar radio spectrograph.

4. Comparison of GPS signal parameter slips for different types of GPS receivers during the powerful solar flare on 2006 December 13

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

For all LOS we determine the relative density $Q(t)$, % of measurement slips of main GPS signal parameters: C1 – the pseudorange, L1, L2 – the phase delay, and P1, P2 – the group delay for GPS frequencies f_1 and f_2 . Figure 5 and Figure 6 present the total number N of 30-sec counts (panel *a*), and the relative density $Q(t)$ of measurement slips

of L1, P1, C1, L2, P2 parameters registered by TRIMBLE-5700 (Figure 5) and TRS-LEGACY receivers (Figure 6) on 2006 December 13, panels *d, e, f, b, c*, respectively.

It is obvious that significant measurement slips of main GPS signal parameters made by TRIMBLE-5700 receivers are registered not only at the auxiliary frequency L2, but also at the basic GPS frequency L1 (but at a much lower rate). In contrast, significant measurement slips of the main parameters performed by TRS-LEGACY receivers are registered only at the auxiliary frequency L2. Our results agree with the data obtained by Chen et al. (2005)

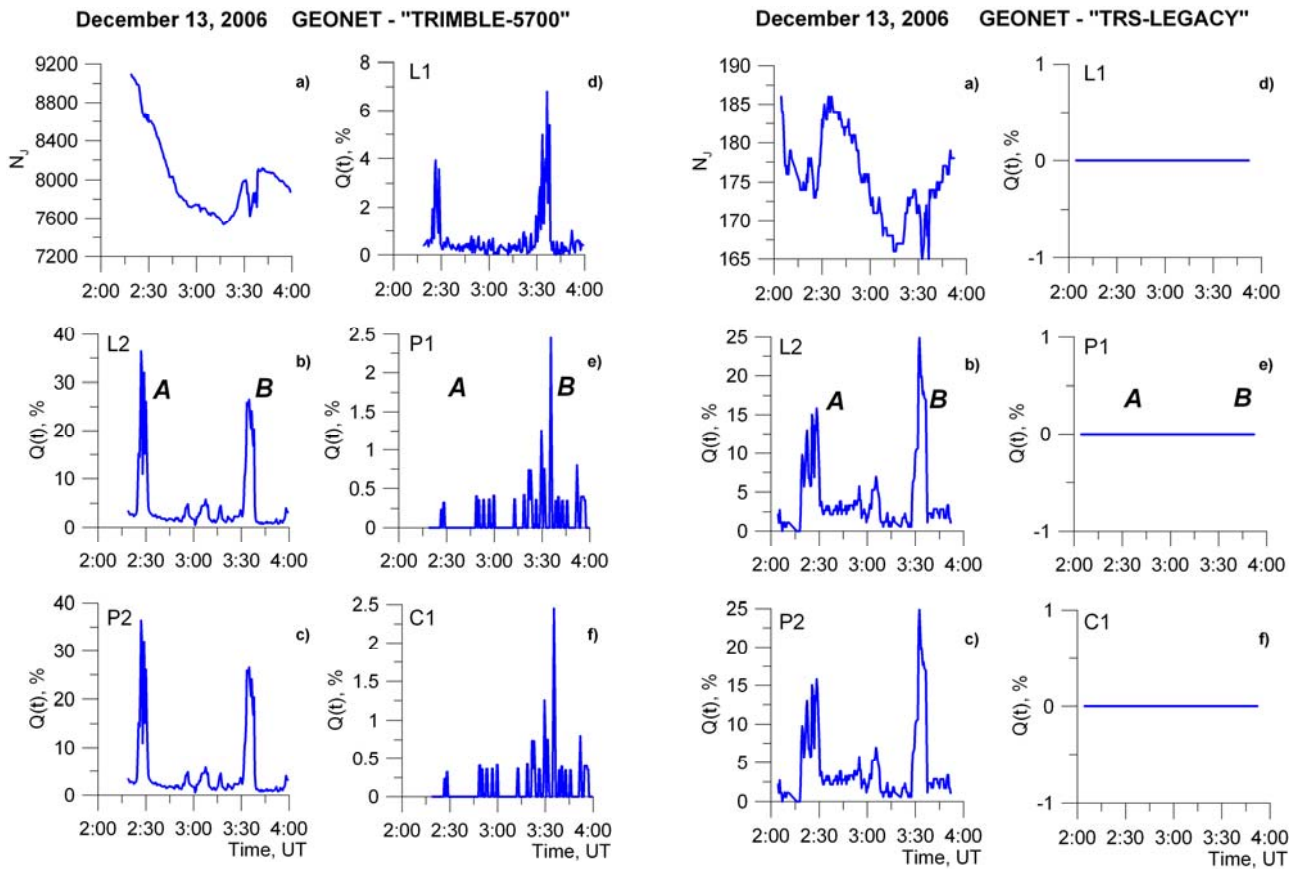


Figure 5. GPS slips of phase (L) and group (P) delay measurements during the solar flare on December 13, 2006, GEONET. The total number N of 30-s counts, and the relative density $Q(t)$ of slips of measurements of L1, C1, L2, P1, P2 parameters registered by TRIMBLE-5700 receivers.

Figure 6. GPS slips of phase (L) and group (P) delay measurements during the solar flare on 2006 December 13, GEONET. The total number N of 30-s counts, and the relative density $Q(t)$ of slips of measurements of L1, C1, L2, P1, P2 parameters registered by TRS-LEGACY receivers.

5. Discussion. The origin of phase slips and missed counts during powerful solar flares

Our results agree with the calibrated data on amplitude measurements using several GPS receivers intended for determining characteristics of GPS signal scintillations (Cerruti et al., 2006a), caused by scattering by ionospheric irregularities (Yeh and Liu, 1982). Data borrowed from Cerruti et al., 2006a obtained for one of the sites located in the sunlit zone, are presented on Figure 2b (red line). The high time resolution of measurements (frequency of 50 Hz) makes it possible to establish that the moments of sharp reduction of the signal/noise on the basic GPS frequency L1 (down to the fatal value -30 dB) with are synchronous to high accuracy with variations in radio flux density (Figure 2e, vertical dotted lines showing the peak times T1, T2, T3). In Figure 2b (blue line), the S/N dependence for the same satellite for the preceding day (December 5) is given for comparison. In this case, the S/N ratio for all observation intervals does not practically differ from a level of 40 dB, corresponding to the GPS standard. This means that during the 2006 December 6 flare the wideband solar radio emission exceeded in intensity the normal background noise for which the GPS systems were designed, by 2–3 orders of magnitude.

Under usual conditions, shallow scintillations due to scattering by ionospheric irregularities in auroral and equatorial zones (Yeh and Liu, 1982) do not considerably influence the GPS functionality (Afraimovich et al., 2002a, 2002b; 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, 2002b, 2003; Conker et al., 2003; Doherty et al., 2001; Ledvina et al., 2002; Scone and De Jong, 2000, 2001). It turned out that during the 2006 December 6 flare against a background of the low geomagnetic activity, very strong amplitude “scintillations” were registered in the middle latitudes.

At the moment of the powerful SRB on 2006 December 6, the increase of scintillation index S4 (Yeh and Liu, 1982) up to very high values of the order 1.0 was reached (Cerruti et al., 2006a). However, this high value is not due solely to the effect of GPS signal scintillations, for which value S4 does not usually exceed 0.1-0.2 (Yeh and Liu, 1982). Rather, in the receiver the broadband noise due to the high-flux density of the solar radio burst considerably exceeded the expected noise level.

Figure 1c qualitatively illustrates the GPS phase slip mechanism during the flare. The dependences of the GPS signal level on the LOS elevation angle Θ at the satellite with transmitters of various effective powers are denoted 1, 2, 3. A monotonic reduction in signal level is associated with the increase in distance between a satellite and a receiver. Under usual conditions, as a result of correlation processing of the broadband signal in the receiver, the additive noise of ~ 40 dB is below that of signals at all elevations.

During the powerful solar radio burst, the noise level at the low elevation (Figure 1c, a horizontal dotted line) reaches a level that causes the failure of phase tracking of the GPS signal. Clearly for a satellite with the highest effective power of a signal (a curve 1), this condition occurs only at quite low angles of elevation (11°), while for a less powerful signal 2 it occurs at 22° . For the weakest signal 3, however, slips begin for elevation angles as high as 43° . As a result, the navigation on this satellite during the flare is practically impossible.

This explanation agrees with our experimental data. Figure 1b presents the $P(t)$ dependences during the 2006 December 6 flare on the Earth sunlit side (200° - 300° E; -80° - $+80^\circ$ N), obtained for $n = 12,929$ LOS, for all observable PRN from 18.00 to 20.00 UT (grey line) at the threshold for the elevation angle $\Theta > 40^\circ$. Thus, for high angles of elevation of LOS to the satellite, the probability of slips is an order of magnitude less than that for low angles.

According to the mechanism described above, the dependence of the maximal slip density is not simply proportional to the maximal radio emission power. It is likely to be determined by the signal-to-noise ratio threshold, which may be different for different types of GPS receivers as well as for effective power of different satellites. Therefore, the relation of P_{\max} and W_{\max} slip indexes obtained for the flares under analysis (not more than 10–20 times) is essentially less than that of the flares' radio emission power (from 10^6 to 10^3 s.f.u., i.e. 1000 times).

The lower signal/noise ratio at L2 is primarily due to the fact that the L2 power at the GPS satellite transmitter output is 6 dB less than that at the fundamental frequency L1 with the C/A code (ICD-200; Hofmann-Wellenhof et al., 1992).

Phase slips at L2 can also be caused by the lower signal/noise ratio when using commercial noncoded receivers for L2 installed at the global GPS network stations. These receivers have no access to the military "Y" code, and have to use the noncoded or semi-noncoded mode of reception. As a consequence, the signal/noise ratio at L2 is at best 13 dB lower than the mode of fully coded reception.

Thus, the difference in signal powers at L1 and L2 for commercial receivers can become larger than 10 dB that can lead to increase of slip density at L2, owing to the influence of additive interference. Different types of GPS receivers respond differently to this; on the whole, however, the picture of the dependence on the local time, latitude range, and level of geomagnetic activity remains sufficiently stable.

Our results confirm the conclusion obtained by Chen et al. (2005). The direct interference from solar radio bursts are not usually considered as a potential threat to GPS signal tracking, since the flux densities of most bursts are below a threat threshold to GPS L1 frequency equal to 40,000 s.f.u. proposed by Klobuchar et al. (1999). The analysis carried out by Chen et al. (2005) indicated that a much lower threshold should be adopted for codeless or semi-codeless dual-frequency GPS receivers. The correlation analysis revealed that GPS signal losses of lock were primarily caused by the microwave in-band interference and that the threat threshold of SRB effects on the GPS system should be re-evaluated, since the flux density of the burst at 1415 MHz was just 4,000–12,000 s.f.u., which is far below the previously proposed threat threshold (Klobuchar et al., 1999).

Nevertheless our data suggest that deleterious effects begin at a value F_{\min} below the estimation given by Chen et al. (2005). In Figure 7, we show an analysis of dependence of missed counts of GPS measurements versus zenith angle of the Sun (Figure 7). The magnitude of flux $F(t)$ of solar radio emission measured by OVSA at frequencies $f_1 = 1.2$ GHz and $f_2 = 1.6$ GHz is shown in both linear (a), and logarithmic scale (e). Missed counts of GPS measurements depending on a zenith angle of the Sun χ during flare 2006 December 6, are shown on panels b) $\chi > 70^\circ$; c) $70^\circ > \chi > 50^\circ$ and d) $0^\circ > \chi > 50^\circ$. Vertical dashed lines mark the moments of time with a maximum quantity of missed counts.

Comparison of missed counts $W(t)$ for small values of zenith angle $0^\circ > \chi > 50^\circ$ with intensity of radio emission $F(t)$ for $f_2 = 1.6$ GHz, close to auxiliary frequency GPS, shows their close similarity (Figure 7e). It is necessary to note also, that the threshold F_{\min} at which GPS receiver failures occur at small values of zenith angle of the Sun, does not exceed 10^3 s.f.u. (as noted by a blue horizontal dotted line). The increase of missed counts at high zenith angles of the Sun testifies to a solar origin of interference (noise) at these GPS frequencies. The drop in number of failures at increasing zenith angle is caused by decrease in antenna gain and an increase in losses in the atmosphere (Carrano et al., 2007).

6. Conclusion

Significant experimental evidence has been found that for over 10-15 min the highly precise GPS positioning was partially disrupted on all sunlit sides of the Earth on 2006 December 6 and 13. The high level of phase slips and missed counts result from the wideband solar radio noise emission. The statistics of phase slips obtained in our

study for the sunlit side of Earth confirms the effect of suppression of GPS receiver operation during the 2006 December 6 flare more reliably than the data (Cerruti et al., 2006a), received at a few specific GPS sites.

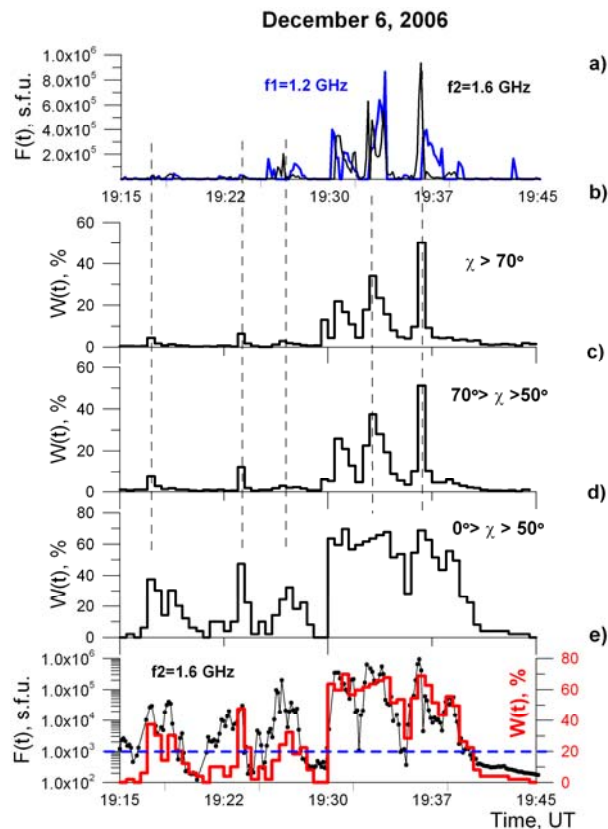


Figure 7. The missed counts of GPS measurements vs. zenith angle of the Sun during the 2006 December 6 radio burst : *b*) $\chi > 70^\circ$; *c*) $70^\circ > \chi > 50^\circ$; *d*) $0^\circ > \chi > 50^\circ$. *a*) Intensity of solar radio flux $F(t)$ in a range of GPS frequencies $f_1 = 1.2$ GHz (blue curves) and $f_2 = 1.6$ GHz (black curves), observed by OVSA; *e*) the same data on a logarithmic scale. For comparison, the relative dependence of missed counts $W(t)$ for small values of zenith angle $0^\circ > \chi > 50^\circ$ is shown in panel *e*.

Our results are serious grounds for revising the role of space weather factors in functioning of modern satellite systems and for accounting more carefully these factors in developing and operating. Similar failures of functioning of satellite navigating systems (GPS, GLONASS, European system GALILEO) can be fatal for the operating safety of systems as a whole and can lead to greater financial losses.

Another important conclusion of our investigation is that the continuous calibrated monitoring of the solar radio emission flux level carried out using a large number of solar radio spectrographs is needed to provide a continuous estimate of radio noise of solar origin in the range of frequencies used by GPS-GLONASS-GALILEO. Indeed, powerful solar radio bursts provide a global and freely available tool for testing satellite broadband radio systems including GPS.

The series of powerful flares on 2006 December 6 and 13 (and also on December 14), i.e. deep in the minimum of the solar cycle, was absolutely unexpected. The study and analysis of their consequences for the space environment is still underway. The space weather anomaly caused by the flare X6.5 of 2006 December 6 underscores the necessity for introducing one more parameter of solar activity – an index of L-band solar radio burst emission, indicating the threat of temporary discontinuance of normal operation of the radio-electronic equipment for orbital and ground navigation (receivers of GPS, GLONASS, in future GALILEO). Consequences do not depend on localization of the flare on the solar disk. Ultimately, development of methods and means to forecast such activity from the Sun is of a great practical importance.

7. Acknowledgments

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