Powerful Solar Radio Bursts as a Potential Threat to GPS Functioning

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Abstract

We investigate the GPS performance quality of X6.5 and X3.4 solar flares, which produced a solar radio burst with unprecedented radio flux density on 6 and 13 December 2006. We use GPS data from the global network of two-frequency receivers (more then 1500 sites) and from the Nationwide GPS array of Japan GEONET (13 December; 1200 sites). We have found significant experimental evidence that the high precision GPS positioning was partially paralyzed on all sunlit sides of the Earth for more than 10 min. We prove that the high level of phase slips and count omissions are caused by the wideband solar radio noise emission. Our results are serious ground for revision of the role of space weather factors in functioning of modern satellite systems and for more careful account of these factors by engineering development and operation.

1. Introduction

The flare X6.5 on December 6, 2006 is of unusual interest not only to astronomers 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 at least by two orders of magnitude. This led to fatal failures in functioning of broadband satellite radio systems including global positioning system (GPS). The functioning failures and deep damping of a GPS signal were registered at separate standard GPS receivers and specialized monitors of ionospheric scintillations in the L range [1-2]. It has been predicted by Klobuchar et al. [3] 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 (sfu) proposed by Klobuchar et al. [3]. Chen et al. [4] found that a much lower threshold (4,000–12,000 sfu) should be adopted for codeless or semicodeless two-frequency GPS receivers. However, the global scale of the failure of all GPS during this flare was unclear. 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 6 December, 2006, and 13 December, 2006, respectively.

Our database of GPS RINEX files consists of data from over 1500 GPS sites (http://sopac.ucsd.edu/other/services.html). In addition to December 6, 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 December 13, 2006 (ftp://terras.gsi.go.jp/data/GPS_products/). We calculated the relative density **P(t)** of GPS phase slips and count omissions **W(t)** for 30-sec series on two GPS frequencies ***f1*** (1227.60 MHz) and ***f2*** (1575.42 MHz) [5, 6].

2. Results

According to the data from the Owens Valley Solar Array (OVSA), the solar radio noise level on December 6, 2006, in the GPS frequency range exceeds 10^6 sfu [1] (background noise is 10^2 sfu). On Figure 1a dependences **P(t)** on the Earth sunlit side (200°-300° E; -80°+80° N) are given for all satellites with numbers PRN observed for 19:15–19:45 UT. Obviously, maximal values $\mathbf{P_{max}}$ can reach 100 % and 78% (PRN24, **n=465;** and PRN28, **n=410**), while for satellite PRN26 values $\mathbf{P_{max}}$ = 17.7 % is close to $\mathbf{P_{max}}$ **= 18.5 %,** obtained for all satellites. This distinction qualitatively testifies that the effective power of separate GPS satellites transmitters differed over 2-5 times. Unfortunately, the time resolution of the **P(t)** dependence (dT=5 min) appeared to be insufficient to display thin time structures of a radio emission flux (Figure 1e), obtained with the resolution not worse than 1 s. Nevertheless, it is possible to note the concurrence in the form of envelopes of the phase slip distribution and solar radio flux.

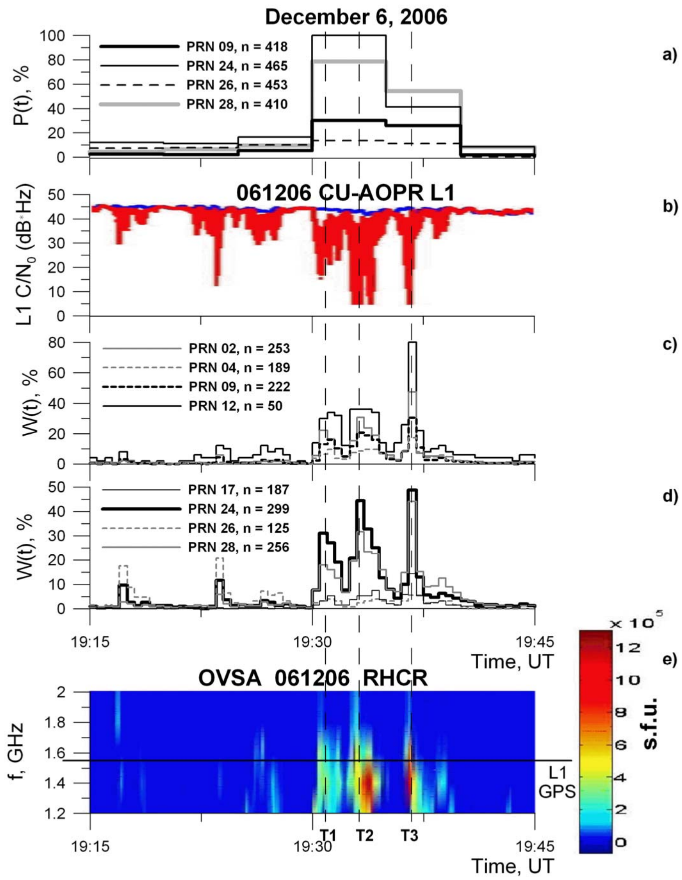

Figure 1. GPS phase slips and count omissions during the December 6, 2006, solar flare, at the sunlit hemisphere.

On Figure 1c and 1d, the relative number of GPS sites **W(t),** where count omissions of 30-sec counts have been observed, are given for all satellites with numbers PRN observed for 19:15-19:45 UT. It is evident that maximal values $\mathbf{W_{max}}$ can run to 80% and 49% (PRN12, **n=50** GPS sites**;** and PRN24, **n=299** GPS sites). The sharp increase of slips and count omissions are demonstrated to be of full agreement with the moments of the most powerful solar radio bursts (moments **T1, T2, T3).**

According to the data from the RSTN / Learmonth solar radio spectrographs, the RHCP solar radio noise level on 13 December, 2006, at 1415 MHz exceeded 10^5 sfu (Figures 2e, 3e). The saturation of dependence of the solar radio flux at the first interval from 02:20 to 02:28 UT (marked be symbol ***A***) and at the second interval from 03:30 to 03:38 UT (marked be symbol ***B***) can be noted. The horizontal line marks the spectrograph amplitude saturation level (~ 110,000 sfu).

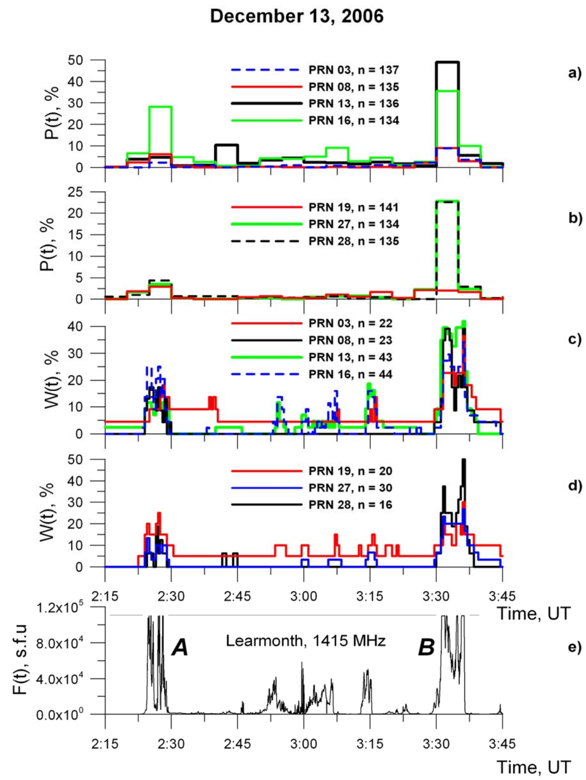

Figure 2. GPS phase slips and count omissions during the solar flare on December 13, 2006, at the sunlit hemisphere.

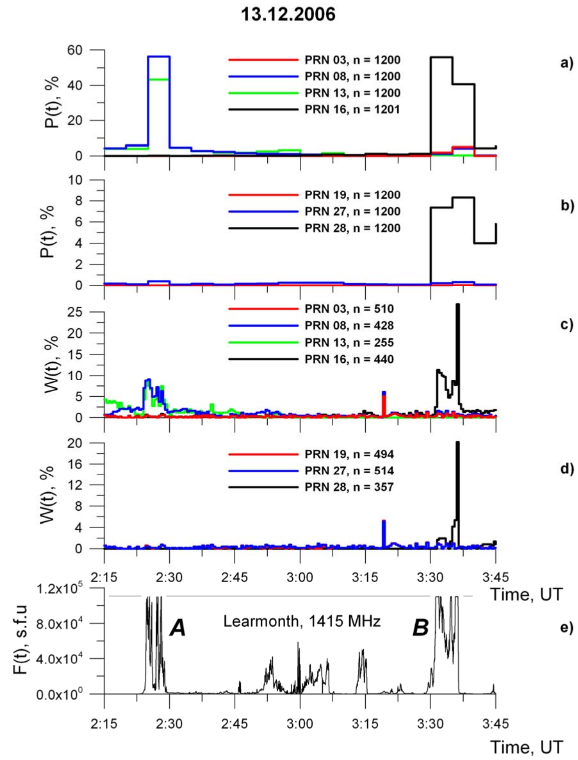

Figure 3. GPS phase slips and count omissions during the solar flare on December 13, 2006 – GEONET, Japan.

On Figure 2a and 2b, **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 $\mathbf{P_{max}}$ can reach 49 % and 36% (PRN13, **n=136;** and PRN16, **n=134**), while for satellite PRN08 values $\mathbf{P_{max}}$ (9%) is close to $\mathbf{P_{max}}$ (**14%),** obtained for all satellites. On Figure 2c and 2d, the relative number of GPS sites **W(t),** where the count omissions of 30-sec counts were observed, are given for all satellites with numbers PRN observed from 02:15 to 03:45 UT. Obviously, maximal values $\mathbf{W_{max}}$ can run to 50% and 42% (PRN28, **n=16** GPS sites**;** and PRN13, **n=43** GPS sites). The sharp increase of slips and count omissions are shown to coincide totally with the impulse SRB during the periods ***A*** and ***B*,** including thin time SRB structure.

There are too few GPS sites for whole sunlit side on December 13, 2006. 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 3a and 3b, 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 $\mathbf{P_{max}}$ can reach 56 % (PRN08 and PRN 16, **n=1200 sites)**, while for satellites PRN03, 19, 27, 28 values $\mathbf{P_{max}}$ (~ 9%) is close to $\mathbf{P_{max}}$ **(6%),** obtained for all satellites. On Figure 3c and 3d, the relative number of GPS sites **W(t),** where the count omissions were observed, are given for all satellites with numbers PRN observed from 02:15 to 03:45 UT. Maximal values $\mathbf{W_{max}}$ can reach 27% and 20% (PRN16, **n=440** GPS sites**;** and PRN28, **n=357** GPS sites). The sharp increase of slips and count omissions are shown to coincide totally with the impulse SRB during the time intervals ***A*** and ***B***.

3. Discussion and Conclusion

Our results agree with the calibrated data on amplitude measurements using several GPS receivers intended for determining characteristics of GPS signal scintillations [1], caused by scattering by ionospheric irregularities. Borrowed from [1] data obtained for one of all sites, located in the sunlit zone, are presented on Figure 1**b** (grey 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 relation **L1 S/N** on the basic GPS frequency L1 (down to the fatal value - 30 dB) with a high accuracy are synchronous with impulses of a powerful radio emission (Figure 1**e**, a vertical dotted lines according to the time moments T1, T2, T3). In Figure 1b (black 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. It means that during the 2006 December 6 flare the wideband solar radio emission exceeded in intensity the background noises, which were taken into account when constructing GPS systems, by 2–3 orders of magnitude.

The lower signal/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-200). Phase slips at L_2 can also be caused by the lower signal/noise ratio when using commercial noncoded receivers for L_2 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 L_2 is at best 13 dB lower than the mode of fully coded reception.

So, significant experimental evidence was found that the highly precise GPS positioning on entire sunlit sides of the Earth was partially disrupted for more than 10-15 min on December 6 and 13, 2006. The high level of phase slips and count omissions resulted from the wideband solar radio noise emission. Our results are serious grounds for revising the role of space weather factors in functioning of modern satellite systems and for accounting these factors in developing and operating more carefully. Another important conclusion of our investigation is that the continuous calibrated monitoring of a level of the solar radio emission flux, carried out using a large number of solar radio spectrographs, allows us to estimate a level of radio noise of solar origin in the range of frequencies GPS-GLONASS-GALILEO.

4. Acknowledgments

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5. References

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