Magnetic Storms at High Latitudes and Slips in GPS Operating

V. I. Zakharov[1,2], **Yu. V. Yasyukevich**[2], **and M. A. Titova**[3]

[1]Lomonosov Moscow State University, Moscow, Russia
[2]Institute of Solar-Terrestrial Physics of Siberian Branch of Russian Academy of Sciences
Irkutsk, Russia
[3]IZMIRAN, Moscow, Russia

Abstract— We analyzed strong magnetic storm and sub-storm influence on the GPS operating in the Arctic region. 5-years dynamic were analyzed based on IGS and CHAIN data ($\sim$ 200 receivers at more than 55°N latitude). The main studied parameters were phase and pseudorange slips as well as sharp physically unrealistic total electron (TEC) values variations (TEC slips). TEC slips were found to increase 100–200 times higher than just instrumental noses under helio-geomagnetic disturbances of different nature. The major cause of phase and pseudorange slips is GPS signal absorption in the ionosphere. The absorption is caused by high-energy particle precipitation during magnetic storms at high latitude.

1. INTRODUCTION

Analysis of the navigation and communication systems shows that currently the reliability of their operation is determined not only and not so much by instrumental failures, but increasingly influencing of different geo- and helio-physical factors, i.e., space weather, which is more pronounced at high Arctic latitudes. Strong geomagnetic disturbances can have a significant impact on the operating of radio systems using ionospheric radio channel. The same is true for the operating stability of the global navigation satellite systems such as GLONASS and GPS. The reason is influence of strong disturbances of electron density. The disturbances lead to sharp fluctuations in the group, phase and amplitude characteristics of the radio signal. Amplitude scintillation of navigation signal due to scattering of the radio signal on small-scale irregularities with size of the first Fresnel zone [1], which is of 100–300 m for GPS/GLONASS. There is a lot of papers deal with operation stability of GPS system under disturbed conditions [2–4]. A number of studies is devoted to high latitudes GPS operation [3, 5, 6].

At the same time, data on the direct measurement of navigation signal parameters failures at high latitudes is not enough and they are very fragmented. It is worth to note that geomagnetic disturbance in the majority of works were associated with sharp changing in the planetary index Dst, while at high latitudes strong substorms take place, which associated with local perturbations of currents in the magnetosphere. In addition, some fragmentary of data at high latitudes connected with lack of dense receivers network in this region. Recently the situation has changed. Development of global and regional GPS/GLONASS networks lead to increasing the statistics of navigation measurement parameters failures and total electron content (TEC) slips, including statistics at high latitudes.

2. EXPERIMENTAL DATA AND TECHNIQUE

As a slip we take two types of phenomena. First, we take "instrumental" failure, i.e., loss of pseudorange measurements or navigation signal phase for both operating frequencies. In the data files it corresponds to lack of measurement of these parameters. These slips are of technical nature and connected with the quality of electronic components of the radio transmission unit (RTU). The second group of slips is so-called TEC slips. TEC slip can be defined as sharp TEC variations, the values of which have no physical meaning (or, possibly due to unknown at this time processes and phenomena). For example, TEC rate higher than (2 ... 5) TECU/min surpass regular variability of the ionosphere, which is usually less than (0.1 ... 1) TECU/min.

The total electron content is determined based of dual-frequency phase measurements of GPS signal [7]:

$$I = \frac{1}{40.308} \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} \left[(L_1\lambda_1 - L_2\lambda_2) + K + nL \right], \tag{1}$$

where, f_1, f_2 — operating frequency of GPS; $L_1\lambda_1$, $L_2\lambda_2$ — additional paths of radio signals caused by the phase delay in the ionosphere, m; L_1, L_2 — the number of phase rotation at operating frequencies; λ_1, λ_2 — wavelengths, m; K — constant, due to the ambiguity of the phase definition, nL — error in determining the phase path.

The probability of slip of the parameter i (phase slip, pseudorange, TEC) for the selected station during the observation time T for a single navigation satellite is:

$$P_{T,i,\mathrm{GPS}} = \frac{N_{i,\mathrm{GPS}}(T)}{S_{i,\mathrm{GPS}}(T)} \times 100\% \tag{2}$$

where $N_i(T)$ is the total number of slips of the parameter I for chosen GPS satellite during the observation time T. $S_i(T)$ is the total number of observations of the parameter i for a observation time.

To complete description of a GPS station, similar to (2) we calculated the overall probability of slips of the parameter i at the station during time T for all visible satellites. As a characteristic of the observation network consisting of M receivers we calculated N and S parameters for all line-of-sites "satellite-receiver".

In this paper we studied the GPS slips dynamics during 2010–2014. For all stations of IGS network [8], located to the north of 55°N (Arctic region), we recorded pseudorange and phase at both operating frequencies. There were 97 stations in the IGS network in 2010 and 188 in 2014. In addition we used data from the network CHAIN (Canada), which included from 8 to 18 stations (http://chain.physics.unb.ca).

We used observational data in the RINEX format. All used data include more than 8.5 million hours of joint observations of P1, P2, L1, L2.

To determine the start of the geomagnetic disturbance and its strength, we used high-latitude AL, AU, AE magnetic indexes, instead of commonly used Dst and SYM-H indexes which describe the equatorial perturbations. AL, AU, AE were obtained with 1-min resolution (http://wdc.kugi.kuoto-u.ac.jp/dstae/index.html), but we used the 1-hour averaged indexes to better comparison with slips. In some cases, for interpretation we used magnetometers and riometers observations.

3. EXPERIMENTAL RESULTS

In the Fig. 1 we show the example of basically data of GPS slips on the subnet during strong magnetic substorm 09 March 2012 (upper panel), overall dynamics of L2 slips (middle left), L1 slips (middle, right) and TEC slips (bottom, left) for all line-of-sights "satellite receiver". You can see slips statistic for the period of 11 days. Elevation cut were 10°. The blue curve shows the dynamics of AE-index. Bold horizontal lines define dispersion of slips over the last month against mean value (green line). One can see that response to magnetic substorm in L2 slips 5–7 times higher than in L1 slips.

It is worth to note that during strong disturbances dynamics of slips agree with AE index dynamics. The correlation during storm is usually more than 0.7 and can reach more than 0.9. Without geomagnetic disturbances slip probability is determined by internal problems of navigation equipment and generally poorly correlated with AE index. Similar situation take place when one use pseudorange measurements P1 and P2.

We also consider the time dynamics of TEC slips (see Fig. 1, left bottom panel). As the level of TEC slips we chose value 2 TECU/min. Dynamics of TEC slips corresponds to L2 slips. However, probability of TEC slips is 50–150 times greater than those of L2 slips.

In the Table 1 we show results of slips studies for 2010–2014. Overall, our studies show that the probability of L2 slips $\sim$ 10 times larger than L1 those during magnetic storms and substorms of G3class. Growing storm strength, this ratio slightly decreases: $P_{\mathrm{L2}}/P_{\mathrm{L1}}$ is up to 5–7. TEC slips are important parameters for research applications option. As we obtained, for TEC slips dynamics during geomagnetic disturbances is even more pronounced. For example, the probability of TEC slips for TEC rate more than 1 TECU/min increases depending on the class of the storm more than 6–15 times. For TEC slips supposed as a TEC rate more than 2 TECU/min, increase in the probability of slips is 4–10 times.

Right bottom panel in the Fig. 1 shows the riometer data at Dawson Station (DWS, 64.0°N, 139.1°W) recorded on March 09, 2012. There is an increase in absorption during the magnetic storm up to 8 dB. We should note that there were events with absorption increasing up to 17 dB.

The observed effects are generally easy to explain. According to the GPS interface control documents [9], they took different power for two operating frequencies. The power at f_2 is 3 dB less than those at f_1. This fact along with significant absorption increasing due to particle precipitation during magnetic storms is a major cause of differences in slips probability.

Table 1: Maximal probabilities of slips for different substorms. Elevation cutoff is 10°.

Substorm level	***AE*, nT**	**Max *P(L1)*, %**	**Max *P(L2)*, %**	**Max *P(TEC1*)*, %**	**Max *P(TEC2*)*, %**
G3	~ 600	$0.1 \ldots 0.2$	$0.9 \ldots 1.5$	$1 \ldots 6$	$0.6 \ldots 4$
G4	$\sim 600 \ldots 1500$	$0.15 \ldots 0.25$	$1.2 \ldots 3.5$	$5 \ldots 15$	$3 \ldots 6$
G5	> 1500	$0.25 \ldots 0.45$	$3.5 \ldots 5.5$	$15 \ldots 35$	$7 \ldots 15$

*TEC1 and TEC2 correspond to the maximum derivative of the TEC more 1 or more 2 TECU/min, respectively.

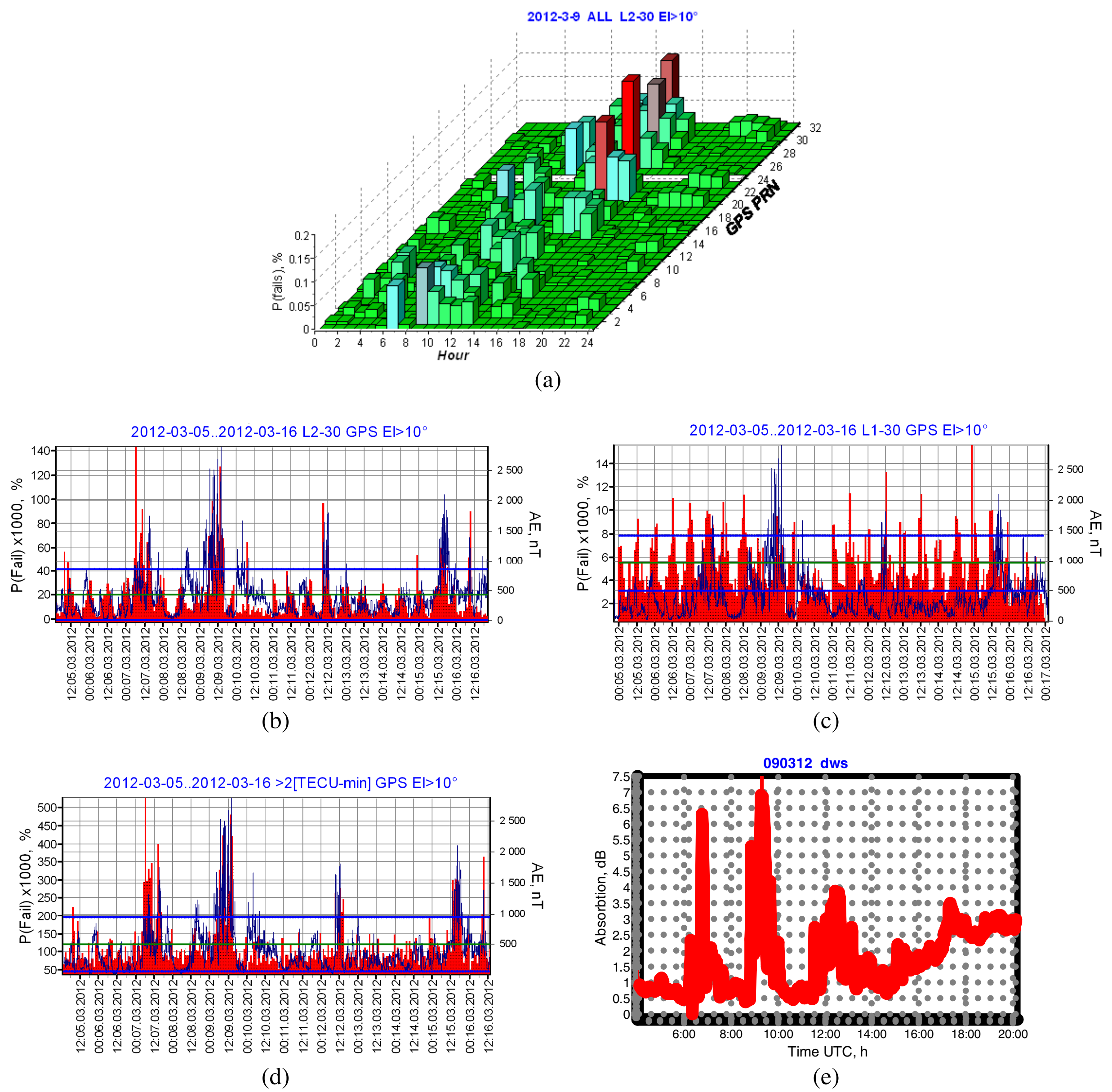

Figure 1: (a) Example of basically data of GPS slips on the subnet during strong magnetic substorm 09 March 2012. (b) The probability of L2 slips, (c) L1 slips, and (d) TEC slips on March 03–16, 2012. Thin blue curve is for AE index. (e) We show the level of radio weaves absorption recorded by DWS station (64.048°N, 139.11°W).

The entire analysis we carried out for the three elevation cuts — 10°, 15° and 20°. The first two angles correspond to cuts which frequently used in the ionosphere and near-Earth space studies. 20° elevation cut is recommended for navigation applications. Analysis showed that slips probability is reduce by 15–20% when you use 20° elevation cut instead of 10°.

4. CONCLUSIONS

Our analysis showed that:

- L1 phase slips even under quiet conditions 3–15 times less than L2 those.
- Similar relation is true for slips of P2 and P1.
- The probability of L2 slips $\sim$ 10 times larger than those of L1 slips during magnetic storms and substorms of G3 class. For G4 and G5 storms this ratio decreases slightly — up to 5–7 times. Similar results were obtained for the probability of P1 and P2 slips.
- TEC slips dynamics during magnetic storms more pronounced as compared with L1 and L2 slips. The probability of TEC slips $\sim$ 100–200 times higher than those of L2 slips. Increasing the class of storm from 3 to 4 or from 4 to 5 TEC slips corresponding jumps of 1TECU/min increase more than 6–15 times. For TEC slips corresponding 2 TECU/min jump this value is 4–10 times.
- The main cause for L1, L2 slips increasing is absorption increasing, which is associated with high-energy particles precipitation at high latitudes during geomagnetic storms.
- Analysis showed that a possible solution to reduce the impact of slips on the navigation system of GPS is increasing the power of the navigation signal as well as increasing the cut-off elevation mask up to 20 °.

ACKNOWLEDGMENT

The authors thank networks IGS [8] and CHAIN (http://chain.physics.unb.ca) for providing GPS data. Development of techniques for analyzing and investigation of slips during 2013–2014 were supported by the grant of the Russian Science Foundation (project No. 14-37-00027). Titova M. A. carried out data processing and riometers data analysis.

REFERENCES

1. Yeh, K. C. and C. H. Liu, "Radio wave scintillations in the ionosphere," *Proc. IEEE*, Vol. 70, No. 4, 24–64, 1982.
2. Skone, S. and M. de Jong, "Limitations in GPS receiver tracking performance under ionospheric scintillation," *Physics and Chemistry of the Earth 2001*, Part A, Vol. 26, No. 6–8, 613–621, 2001.
3. Doherty, P. H., S. H. Delay, C. E. Valladares, and J. A. Klobuchar, "Ionospheric scintillation effects in the equatorial and auroral regions," *Proceedings of International Beacon Satellite Symposium*, 328–333, Boston College, Institute for Scientific Research, Chestnut Hill, MA, USA, Jun. 4–6, 2001.
4. Afraimovich, E. L., E. I. Astafyeva, V. V. Demyanov, I. K. Edemskiy, N. S. Gavrilyuk, A. B. Ishin, E. A. Kosogorov, L. A. Leonovich, O. S. Lesyuta, K. S. Palamartchouk, N. P. Perevalova, A. S. Polyakova, G. Ya. Smolkov, S. V. Voeykov, Yu. V. Yasyukevich, and I. V. Zhivetiev, "A review of GPS/GLONASS studies of the ionospheric response to natural and anthropogenic processes and phenomena," *J. Space Weather Space Clim.*, Vol. 3, A27, 2013.
5. Aarons, J. and B. J. Lin, "Development of high latitude phase fluctuations during the January 10, April 10–11, and May 15, 1997 magnetic storms," *Atm. Sol.-Terr. Phys.*, Vol. 61, 309–327, 1999.
6. Basu, S., S. Basu, E. MacKenzie, and H. E. Whitney, "Morphology of phase and intensity scintillations in the auroral oval and polar cap," *Radio Sci.*, Vol. 20, No. 3, 347–356, 1985.
7. Hoffman-Wellenhoft, B., *GPS Theory and Practice*, 656, Springer-Verlag Vienna, New York, 1998.
8. Dow, J. M., R. E. Neilan, and C. Rizos, "The international GNSS service in a changing landscape of global navigation satellite systems," *Journal of Geodesy*, Vol. 83, No. 3–4, 191–198, 2009, DOI: 10.1007.
9. "Global positioning systems directorate," Systems Engineering & Integration, Interface Specification, IS-GPS-200, Sep. 5, 2012, www.gps.gov/technical/icwg//IS-GPS-200G.pdf.