Analysis of Speed and Acceleration of GPS/GLONASS Phase in the Polar Ionosphere

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Abstract— Currently polar ionosphere is of great interest. This is connected with creation of global model of ionospheric storms and providing stable navigation in polar region. Currently dual- and multi-frequency GNSS phase measurements have been utilized widely and these measurements combination yields us current TEC-values along all SV's line-of-sights in view. One of the main parameters is stability of phase measurements and their noise level.

We carry out the GNSS signal monitoring campaign under the polar ionosphere condition (in Taimyr cape, Russia) in 2013. JAVAD Delta-G3T receiver was used. We observed amount of the rapid and sharp phase acceleration variations. The absolute value of these variations were as much as 30–40% up to 2–2.5 times higher in comparison the background level for both GPS and GLONASS signals. In some cases we found a strong positive correlation between the phase acceleration variations and TEC variations in the variation frequency band of 0.08–1 Hz. It is well known that this frequency band relates to the 1-st Fresnel zone sized ionospheric irregularities. On the other hand we found some cases when there was no an obvious correlation between the 0.08–1 Hz TEC-variations and the phase acceleration variations. In these cases the phase acceleration variations could be inspired by the SV's reference oscillator frequency drift.

In order to separate all the observed phase acceleration variations according to they physical origin we arranged a new measurement campaign of both GPS and GLONASS signals in Norilsk (69°N, 88°E) and Irkutsk (52°N, 104°E). Additionally we used Moscow (55°N, 37°E) data. This report is devoted to discussion of the main results of the campaign data treatment.

1. INTRODUCTION

The main limitation of potentially operation of the GPS/GLONASS equipment is influence of inhomogeneous and non-stationary ionosphere on the navigation parameters measurement accuracy. Phenomena in the ionosphere, especially polar, even without geomagnetic disturbances often lead to significant amplitude scintillations of radio signals, as well fast variations of signal phase. First of all, it is carrier phase tracking loop what is affected by such phenomena. The failure of the tracking loop lead to deterioration of the measurement accuracy of navigation parameters in general.

On the other hand, fixing the current changes phase tracking parameters may allow a highly sensitive monitoring of the fine structure of the Earth's ionosphere. This capability, in turn, can be very useful for the construction of based on ionospheric response early warning systems for natural hazards and man-made phenomena. Such system can use monitoring stations distant from the epicenter of the phenomenon.

It is known that for filtering a carrier phase of signals of GLONASS and GPS, optimal filter of the third order is used [1]. The filter is based on the Markov model of a discrete sequence:

$$\varphi_k = \varphi_{k-1} + T_{\text{COR}} \cdot v_{k-1}; \quad v_k = v_{k-1} + T_{\text{COR}} \cdot a_{k-1}; \quad a_k = a_{k-1} + \xi_{\varphi,k-1}, \tag{1}$$

where T_{COR} is integration time; v_k, a_k are velocity and acceleration of phase change at time k, respectively; $\xi_{\varphi,k}$ — white Gaussian noise (WGN) with dispersion D_ξ.

According to up-to-date concepts, forming WGN — $\xi\varphi$, k consists of thermal noise, variations in the relative frequency instability of the reference generator, and variations caused by the movements of the object. The root-mean square (RMS) of the noise is defined as follows [2]:

$$\sigma_\varphi = \sqrt{\sigma_T^2 + \sigma_F^2} + \frac{\sigma_S}{3}, \tag{2}$$

where σ_T, σ_F and σ_S are a carrier phase noise standard deviation (in degrees) which are caused by thermal noise, Alan variations and mechanical vibrations of the receiver, respectively.

The magnitude of each of these RMS noise components in (2) for third-order filter can be calculated based on the following expression [2]

$$\sigma_F = \frac{360}{2\pi}\sqrt{\cdot\frac{Bm}{c/n_0}\left(1+\frac{1}{2T\cdot c/n_0}\right)}, \tag{3}$$

$$\sigma_F = 160\cdot\frac{\sigma_F(\tau)\cdot F_c}{B_n}, \tag{4}$$

$$\sigma_S = 0.4828\cdot\frac{dR^3/dt^3}{(B_n)^3}, \tag{5}$$

where c/n_0 is the signal-to-noise ratio at the input (here assumed to be in the calculations 30 dBW); $\sigma_F(\tau)$ is relatively short-term frequency instability of the reference generator; F_c is a operating frequency; d^3R/dt^3 — The maximum value of jerk along the satellite line of sight.

The phase noise standard deviation value (2) is directly related to the basic equipment settings T and B_n, as well as the signal-to-noise ratio at the input and the frequency stability. In our opinion, however, this noise doesn't account additive component, which connected with random phase rapid variations caused by the influence of non-uniform and non-stationary radio propagation environment (especially the ionosphere). Figure 1 shows the results of phase acceleration against to phase tracking loop settings and structure of the medium of radio waves propagation.

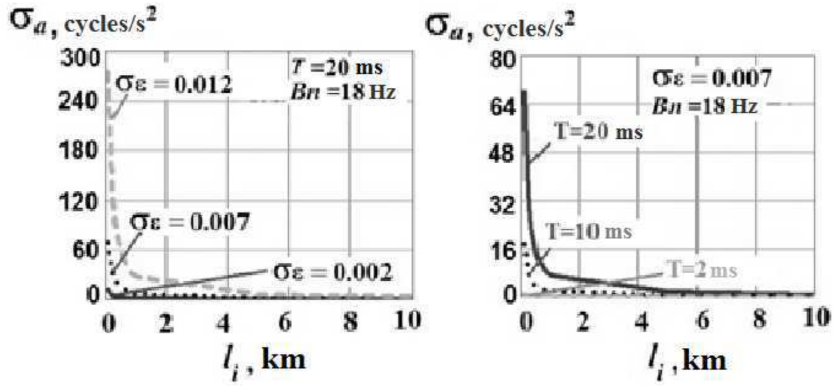

Figure 1: The dependence of the carrier phase acceleration from tracking loop settings and structure of radio wave propagation environment.

We can see predominant influence of small-scale irregularities with size of 0.1–1 km on the formation of ionospheric phase scintillation. The more the irregularities intensity the stronger the effect. Emergence of small-scale ionospheric irregularities is expected to cause a significant increase in the phase. It should reveal in increasing the value of the total nose RMS $\xi_{\varphi,k}$ (1).

We organized an expedition in Hatanga, Krasnoyarsk Region (71,6 N; 102,3 E) from 2 to 5 December, 2013. We used multisystem navigation receiver Javad Delta-G3T with external antenna GrAnt-G3T (http://javad.com/jgnss/products). The receiver recorded carrier phase of GPS and GLONASS satellites at the two (three for some satellite) operating frequencies. Time resolution was 0.02 seconds. To eliminate the influence of troposphere and multipath, data analysis was performed only for the satellites with elevations $\geq 20°$.

Along with phase velocity and acceleration, based on dual-frequency measurements we calculated total electron content (TEC) along the line of sight [3].

Carried out in the polar ionosphere an analysis confirmed above theoretical considerations. First of all, there were many cases abrupt increase in the phase acceleration. It was found for both GPS and GLONASS. Increasing was up to 30–40% and 2–2.5 times against a background level. Such changes in acceleration phase can not be associated with thermal noise or instability of the frequency because these noises have a great time of stationarity. Dynamic phenomena can't be the reason also, since the receiver was mounted on a stationary object.

Note that the December 2, 2013 was not geomagnetic disturbed. On this day in near-Earth space and on the Sun they did not observe any significant geoeffective events [4]. In the absence of disturbing factors background values of the GPS and GLONASS phase acceleration are located approximately in the same range changes from -150 to 150 cycles/sec^2. However, despite the calm conditions one can see increasing of phase acceleration from 30% to 2.5 times in the Figure 4. Observed phenomenon more clearly expressed for GPS data and less — for GLONASS.

More detailed analysis of this phenomenon is shown in Figures 3 and 4. Here we shown 6-minutes series highlighted in Figure 2 by rectangles: gray is for background, black is for perturbations. a) — detrended TEC series; b) — part of the TEC variations spectrum of small-scale irregularities range; c) — signal-to-noise ration (dBW) at f_1; d) — phase acceleration (cycle/sec^2). Left part of each figure corresponds to undisturbed conditions, and right — to disturbed.

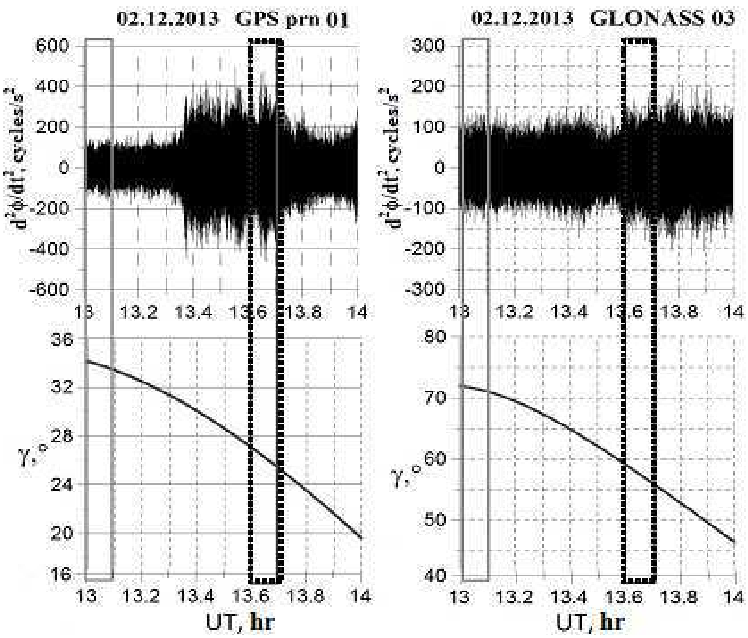

Figure 2: Observations of phase acceleration for GPS PRN01 and GLONASS 03 on December 2, 2013.

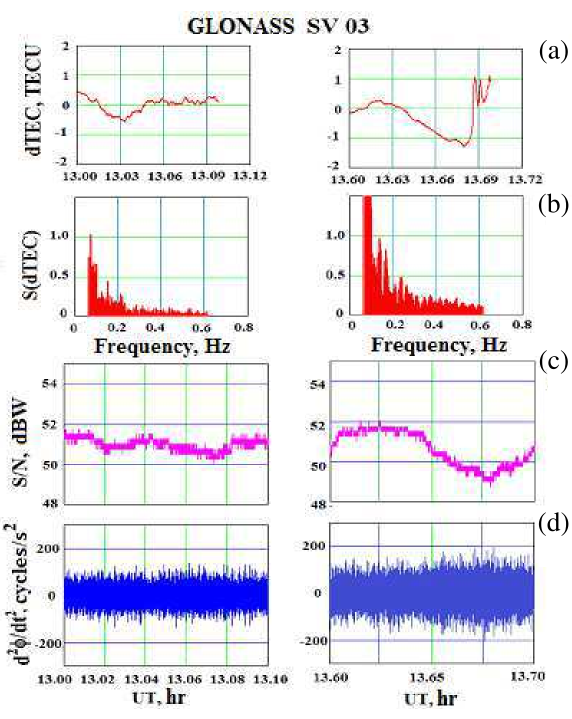

Figure 3: GLONASS phase acceleration and signal-to-noise ratio against small-scale irregularities.

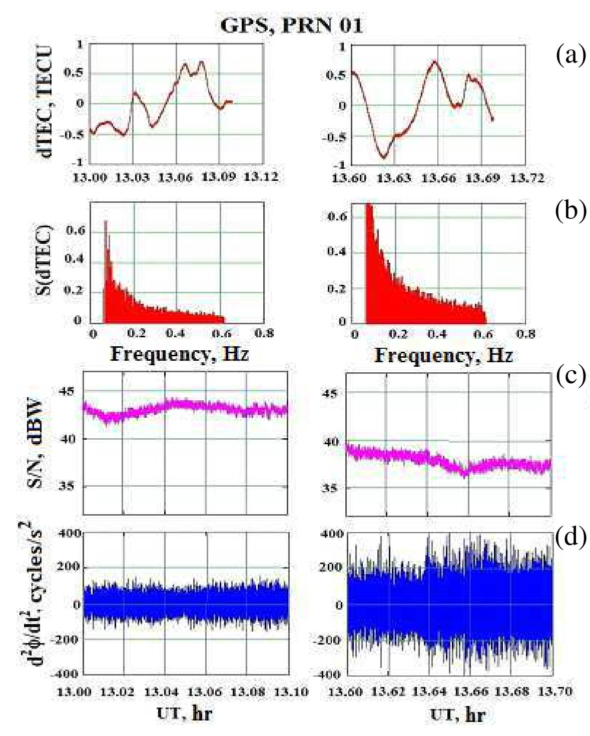

Figure 4: GPS phase acceleration and signal-to-noise ratio against small-scale irregularities.

Detrended TEC series (Figures 3, 4(a)) do not show significant small-scale irregularities. However, the spectral analysis allows us to identify the components of these series of high-frequency TEC variations due to small-scale irregularities. From Figures 3 and 4 (panels (b), (d)) we can see a clear positive correlation between the increase in phase acceleration and the growth of TEC variation spectral components of 0.08–0.6 Hz. This frequency range corresponds to the scope of small-scale ionospheric irregularities with sizes from hundred meters to several kilometers. During these intervals we see decreasing the signal-to-noise ratio (see Figures 3 and 4, panel (c)).

Because small-scale ionospheric irregularities are primarily responsible for the occurrence of rapid variations of amplitude and phase, our results confirm a possible link between non-stationary phase changes and small-scale irregularities in the ionosphere.

On the other hand, authors of [5] insist that these phenomena can be observed without connection with the small-scale irregularities. Similar phase variations may be caused by short-term drift of the reference generator frequency on the satellite.

To prove our experimental data and find out physical nature of phase acceleration occurrence, we carried out complex experiment in two locations: Irkutsk (52°N, 104°E) and Norilsk (69°N, 88°E). We find out that the growth of phase acceleration for the same satellites are not observed simultaneously for Irkutsk and Norilsk. Thus, this phenomenon is not due to short frequency drift of the reference generator. Therefore, we can assume that there is a clear link between non-stationary changes in phase and small-scale irregularities in the ionosphere.

It is important to note that the results obtained here correspond in general to geomagnetically undisturbed conditions. However, even in this case one can observe the change of GPS phase acceleration. This indicates the high sensitivity of phase acceleration to changes in the small-scale structure of the ionosphere. Therefore, the phase acceleration can be recommended as an indicator of weak ionospheric disturbances.

At the same time, further research seems to be need for improving the generally accepted model of phase change. Corrected model should account for the influence of the radio wave propagation medium.

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