Geomagnetic Effects on GNSS Measurements

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Abstract— In this paper, the analysis of geomagnetic effects on measurements, made by Global Navigation Satellite Systems (GNSS), relies on both the contribution of the geomagnetic field to the refractive index of ionospheric plasma and the presence of field-aligned random irregularities. The paper reports results of exploration of the possibility for simultaneous removal of first- and second-order errors by modifying the ionosphere-free combination of dual-frequency measurements. The geomagnetic field affects not only the refractive index but also the structure of ionospheric irregularities. Afraimovich et al. (Advances in Space Research, 2011, Vol. 47, 1674–1680) based on the dependence of the GNSS phase slips on the angle between the satellite-receiver line of sight (LOS) and the magnetic field line, have revealed an anisotropy effect of ionospheric irregularities. To analyze the role of this effect on GNSS measurements, we used numerical simulation for studying anisotropy effects of ionospheric irregularities on the probability of occurrence of slips in phase measurements. The simulation results allow us to study and account for the factors which mask effects of this anisotropy. In the future, we are going to exploit this method for estimating the degree of elongation of irregularities to monitor parameters of ionospheric irregularities in the Arctic region.

1. INTRODUCTION

The geomagnetic field significantly affects both the positioning accuracy and the quality of received GNSS signals. When analyzing geomagnetic effects on the positioning accuracy, the consideration of ionospheric plasma anisotropy introduces the third term into the ionospheric component of GNSS signal phase path [1]:

$$\varphi_i = D - 40.3 I_1/f_i^2 - 40.3 I_2/f_i^3 + \dots \tag{1}$$

Here $D = z_t - z_0$ is the satellite-receiver distance; I_1 is the total electron content: $I_1 = \int_{z_0}^{z_t} N(z')dz'$. $I_2 = \int_{z_0}^{z_t} N(z') f_g \mathrm{Cos}\theta dz'$, where $f_g = gB_0$ is the gyrofrequency ($g = e/(2\pi m)$), θ is the angle between $\mathbf{B}_0$ and propagation direction. Neglect of the third term in (1) considering geomagnetic effects on the refractive index of ionospheric plasma allows us to take into account ionospheric plasma effects in the first (isotropic) approximation in dual-frequency measurements. The error of such measurements (second-order error) varies from 1 to 4 cm, depending on geo- and heliophysical conditions. Improvement of GNSS measurement accuracy involves considering this error.

As is seen from (1), ionospheric irregularities cause signal phase fluctuations (phase scintillations). At exceeded phase path fluctuation of a whole number of cycles, there occurs phase tracking slip [2]. Geomagnetic effects produce anisotropy of ionospheric irregularities — their sizes along magnetic field lines exceed transverse sizes. This, in turn, leads to scattering anisotropy effect, i.e., to the dependence of slips in GNSS measurements on satellite-observer LOS orientation relative to magnetic field line. Thus, observation of this dependence can provide valuable information about anisotropy of ionospheric irregularities. In [3], the GEONET network was exploited to study a large-scale "bubble" of ionization observed over Japan on February 12, 2000. The analysis of slips registered at the GPS L2 frequency has revealed that their density reaches its peak in field-aligned LOSs at ionospheric heights. This allowed the authors to conclude that the small-scale structure of the "bubble" extends along the magnetic field. However, the paper did not show how regular such situation can be observed, whether this is associated with the "bubble", and what angular characteristics of slip density will be without such irregularities.

Our paper addresses both the geomagnetic effects on GNSS measurements. First, we, through simulation and using larger body of data, more thoroughly examine the effects of magneto-orientation of irregularities, and then report simulation results of our previously proposed method for eliminating the second-order error.

2. EXPERIMENTAL DATA ON ANISOTROPY OF PHASE SLIPS

To provide sizable observation statistics, we have processed data on 38 days from the Japanese dense network GEONET (Fig. 1(a)). We analyzed slips occurring at the L2 frequency GPS.

Using this dense network of GPS stations, we scanned a large region of the ionosphere: about 40° in latitude and longitude (Fig. 1(b)). We have separately examined four azimuthal sectors of 45° (Fig. 2) with the central direction in azimuths: 0, 90, 180, 270. For these sectors, we derived dependences of density of phase tracking slips at the L2 frequency on the satellite's elevation angle (Fig. 2).

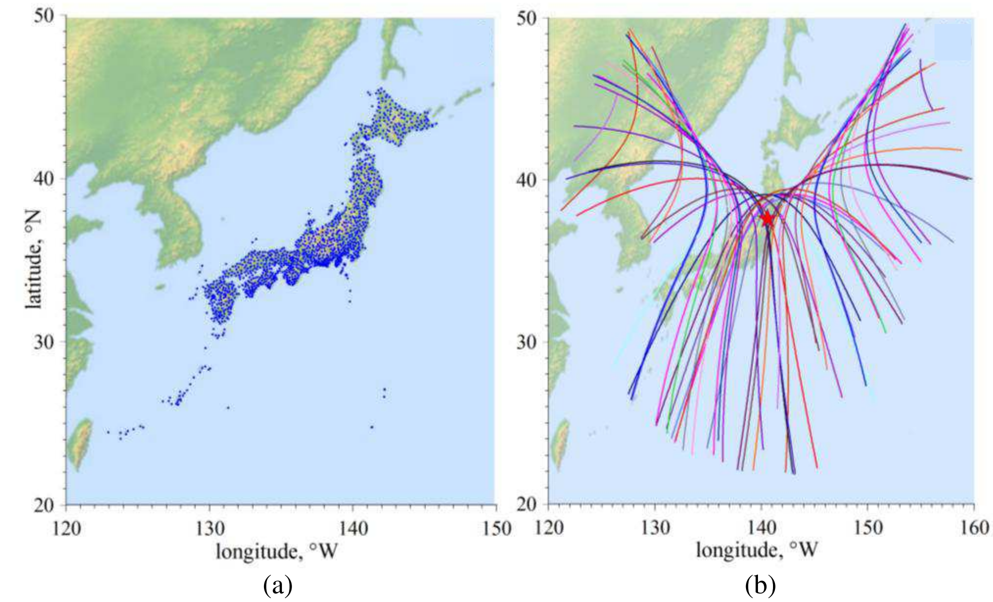


Figure 1: GEONET stations in Japan (blue points a), ionospheric points for 24 hours for one station (coordinates of the station: 37.6 N, 140.6 W).

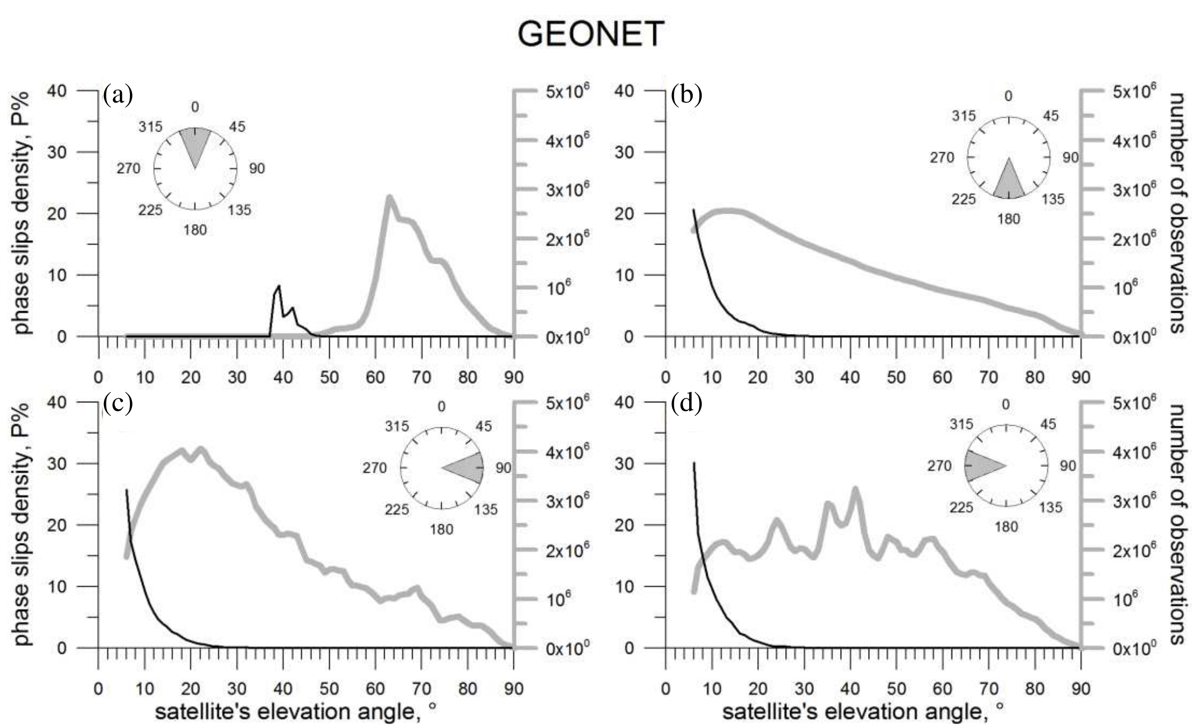


Figure 2: The dependences of the density of phase tracking slips in the GPS (black thin lines) and of the number of observations (gray lines) on the satellite's elevation angle.

We have used data with satellites' elevation angles of over 5 degrees. In the northern sector (Fig. 2(a)) at low elevation angles there are no satellites. This is also evident from the location of ionospheric points (Fig. 1(b)). Other sectors (Figs. 2(b)–(d) exhibit increasing density of phase slips at L2 with decreasing elevation angle (for 6°, a relative number of slips may be as much as 20–30%). However, in the southern sector (Fig. 2(b)) we did not observe an increase in the density of slips in the satellite-observer LOS closely to the direction of the magnetic field.

To identify effects caused by magneto-oriented ionospheric irregularities, we plotted similar dependences separately for February 12, 2000 (Fig. 3). As expected, the effect of magnetic orientation of irregularities did appear for the southern sector (Fig. 3(b)) exhibiting a corresponding 25% increase in density for the 27–29° elevation angles. For other sectors, there is no analogous increase in the slip density (Figs. 3(c), (d)) because the condition of parallelism between the satellite-observer LOS and the magnetic field in the ionosphere is not fulfilled there.

At low elevation angles of satellites, phase slips in the GPS system increases due to the increasing length of propagation path in an inhomogeneous layer of the ionosphere. For the same reason, the amplitude of the observable TEC variations increases with decreasing elevation angle.

This has been confirmed by results of our studies of the dependence of density of occurrence of

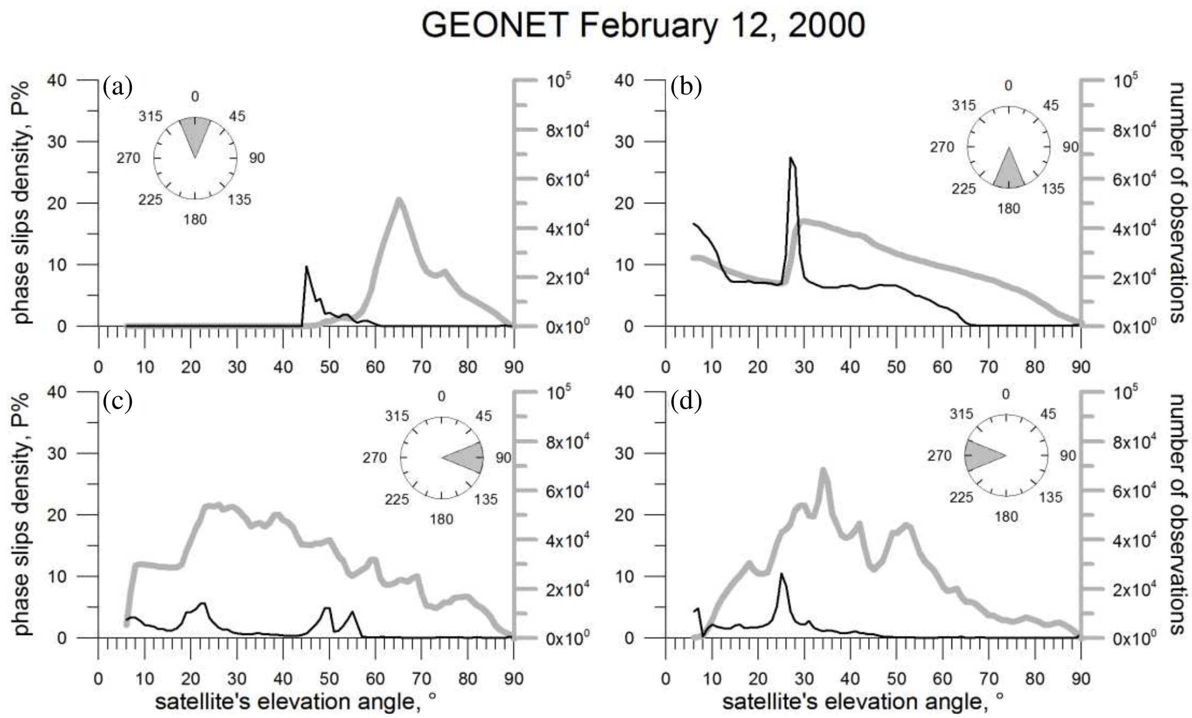


Figure 3: The dependences of the density of phase tracking slips in the GPS (black thin lines) and of the number of observations (gray lines) on the satellite's elevation angle. The data on February 12, 2000.

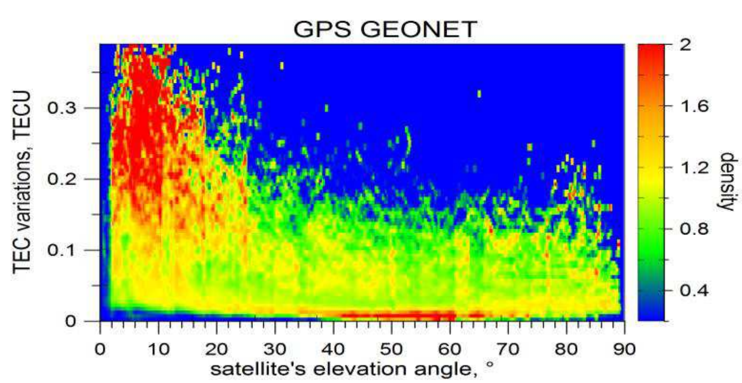


Figure 4: The dependences of the density of occurrence of TEC variations with the corresponding amplitude on GPS satellites' elevation angles. The data were calculated for the GPS station IRKJ for 2008.

oblique TEC variations with varying amplitude on the satellite's elevation angle (Fig. 4). As initial data here, we used data on 100 days from Irkutsk station IRKJ.

3. RESULTS OF SIMULATION OF SLIPS

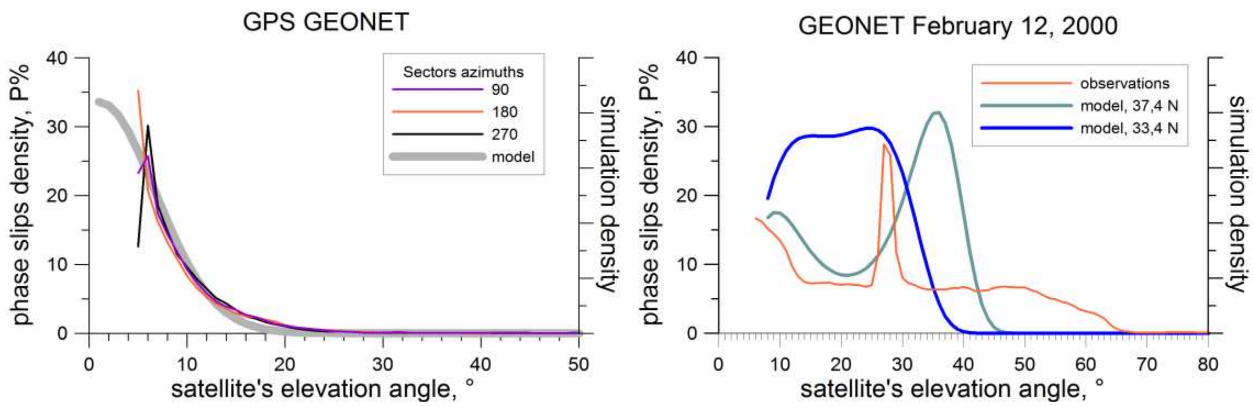
To explain the observed effects, we simulated the probability of slips in the inhomogeneous ionosphere with the power law spectrum of irregularities. We derived the dependence of the probability of the occurrence of phase tracking slips in the GPS system on the satellite's elevation angle (Fig. 5).

In the general case, the extension of the path of signal propagation in the inhomogeneous ionosphere at decreasing elevation angle of satellite raises the probability of phase tracking slips in the GPS receiver (Fig. 5(a)). The simulation results agree with our experimental results obtained from GEONET data. If, in contrast, we take into account the extension of ionospheric irregularities along the magnetic field, the simulation of slip probability may produce a second maximum (Fig. 5(b)). The satellite's elevation angle at which the second maximum is observed will depend on the station latitude as well as on the selected azimuth. So, if the station is shifted from 37.4° to 33.4°N, this elevation angle changes from 37° to 25° (Fig. 5, right panel) at the 180° azimuth.

4. ELIMINATING GEOMAGNETIC EFFECTS FROM DUAL-FREQUENCY MEASUREMENTS

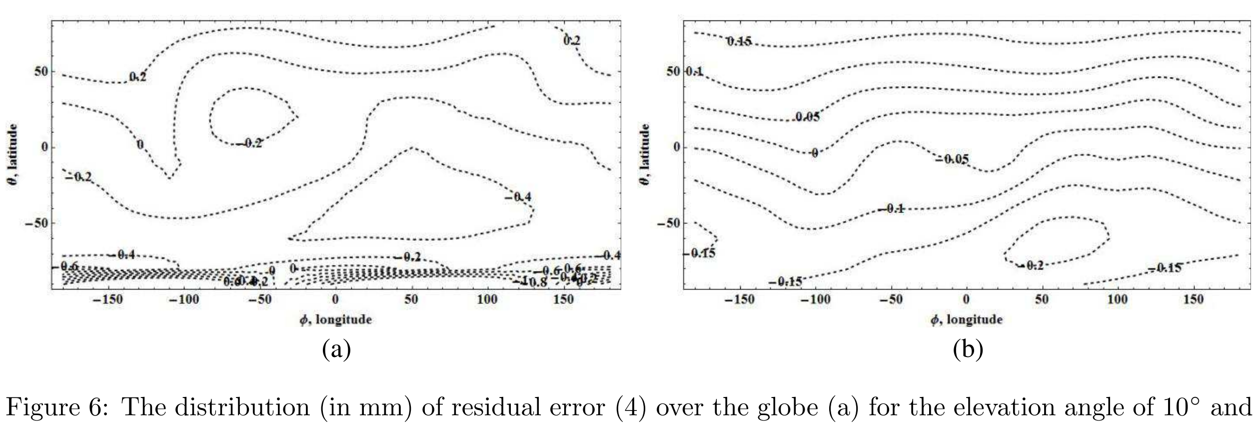
In standard dual-frequency phase measurements, second-order effects are ignored. This assumption allows us to completely remove the second term in (1) and determine the satellite-observer distance:

$$D = \left(\varphi_1 f_1^2 - \varphi_2 f_2^2\right) / \left(f_1^2 - f_2^2\right). \tag{2}$$



(a) (b)

Figure 5: (a) The dependences of the density of phase tracking slips in the GPS in the regular ionosphere (simulation without considering magneto-orientation of irregularities and data on 38 days); (b) analogous dependences for the case of the ionospheric "bubble" (simulation with consideration for magneto-orientation of irregularities). The simulated probabilities are given in arbitrary units (right axes on both the panels), experimental data are in per cent (left axes on both the panels).



(a) (b)

Figure 6: The distribution (in mm) of residual error (4) over the globe (a) for the elevation angle of 10° and the azimuth of −10°; (b) for the elevation angle of 60° and the azimuth of 10°.

To take into account the second-order effects in dual-frequency measurements, we use the relationship between integral I_2 and total electron content I_1 proposed in [4]. The relationship takes into account the slow change of the geomagnetic field within the ionospheric layer:

$$I_2 \approx I_1 f_g \mathrm{Cos}\theta \left|_{z=z_m}\right. , \quad (3)$$

where z_m is usually represented by the height of the main maximum of the ionospheric layer. Approximation (3) yields a distance expression which is similar to (2) but accounts for geomagnetic effects [1]:

$$D_{\mathrm{corr}} = \left(\varphi_1 f_{ef1}^2 - \varphi_2 f_{ef2}^2\right) / \left(f_{ef1}^2 - f_{ef2}^2\right), \quad (4)$$

where $f_{efi} = f_i - (f_g \mathrm{Cos}\theta|_{z=z_m})/2$ is the effective frequency. Yet the residual error is less than 0.5 mm (depending on the position of the receiver) (Fig. 6).

5. CONCLUSION

Observation of slips in GNSS phase measurements may serve as a method for monitoring some parameters of ionospheric irregularities, and a relatively dense network of stations may become a tool for such monitoring. The comparison between observation and simulation results has revealed that in some cases the orientation of ionospheric irregularities manifests itself as anisotropy of observed slips. Such a situation took place on February 12, 2000. However, such an effect is not a regular phenomenon. This event might have been caused by the ionization bubble which emerged from low latitudes and was filled with smaller-scale turbulent irregularities. The slip anisotropy is associated with the anisotropy of small-scale filling and possibly with the orientation and shape of the bubble. A closer correspondence between simulation and observations can be ensured through the use of the model of anisotropic bubble of ionization against slightly anisotropic turbulent ionospheric plasma. The numerical simulation of the modification of the ionosphere-free linear combination of measurements has demonstrated the possibility of eliminating not only the first-order error, but also the second order error, associated with geomagnetic effects on the refractive index of ionospheric plasma, from dual-frequency measurements.

ACKNOWLEDGMENT

We are very grateful to O. A. Kulish for her assistance in preparing the English version of the manuscript. This study was supported by the Grant of the Russian Scientific Foundation (Project No. 14-37-00027).

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