Requirements for nanosatellite-mounted GNSS-based instrument measuring ionospheric total electron content

P N Nikolaev, I A Kudryavtsev and S V Shafran

Inter-University Department of Space Research, Samara University, 34 Moskovskoye shosse, Samara 443086, Russia

E-mail: nikolaev.pn@ssau.ru

Abstract. A navigation receiver mounted on board of a micro/nanosatellite can be used as part of a scientific instrument for ionospheric study, for instance, identification of patterns in solar-terrestrial links and obtaining a set of statistical data to find the correlation between local fluctuations of the ionosphere and climatic changes. Such a device should produce an array of navigation measurements of carrier phases and pseudoranges, and also calculate on their basis the values of the absolute total electron content (TEC), which are used to study the ionosphere.

To calculate the absolute TEC, we use a known technique that combines carrier phase and pseudorange measurements. Taking into account the peculiarities of this technique and the geometry of the measurements, we put forward a number of requirements for a scientific instrument to study the ionosphere.

1. Introduction

Currently existing Continuously Operating Reference Stations (CORS) network, used to eliminate ionospheric errors of navigation measurements, does not allow investigating wave processes in the ionosphere and constructing global space-time models due to their relatively small number. The use of a navigation receiver for receiving signals from global navigation satellite systems (GNSS) as part of a scientific instrument on micro/nanosatellites can help in solving these fundamental problems, thereby providing global coverage. Computed tomography methods can be applied to data measured by this scientific GNSS-based instrument [1-12].

The characteristics of the ionosphere, for instance the electron density, are investigated using data of the carrier phase delay of two-frequency radio signals from GNSS satellites. The phase incursion due to the propagation of a radio signal along the transmitter-receiver ray is determined [13]:

$$\phi_{1,2} = \frac{2\pi f_1 f_2}{c} \left( S - \frac{\chi}{f_1 f_2} \int_{r}^{T} N_e(s) ds \right) + \phi_0,$$

(1)

where $f_1$ and $f_2$ are carrier frequencies of GNSS; $c \approx 3 \cdot 10^8$ m·s$^{-1}$ is speed of light; $S$ is geometric path traversed by the ray; $\chi = 40.4$ m$^2$·s$^{-2}$ is aspect ratio; $\int N_e(s) ds$ is total electron content (TEC), which is the linear integral of the electron density along the propagation path of the electromagnetic wave and is expressed in TECU units (Total Electron Content Unit, 1 TECU = $10^{16}$ el·m$^{-2}$) [13]; $N_e(s)$ is electronic density on the path $s$; $T$ and $R$ are the positions of the transmitter and receiver, respectively; $\phi_0$ is unknown initial phase.

Based on two-frequency carrier phase measurements, the TEC is calculated as follows [13]:
where $\Phi_1 = L_1 \lambda_1$ and $\Phi_2 = L_2 \lambda_2$ are carrier phase delays for frequencies $f_1$ and $f_2$, respectively; $L_1$ and $L_2$ are carrier phase measurements; $\text{const}_{1,2}$ is phase measurement ambiguity caused by an unknown initial phase; $\sigma_L$ is phase measurement error.

In the case of using GNSS signals, the error in the TEC calculations from the measured carrier phase does not exceed 0.01 TECU. However, the TEC is determined up to an additive constant caused by the ambiguity in the determination of the initial phase, for the elimination of which it is necessary to involve additional a priori information.

To resolve the ambiguity of phase measurements, phase-difference methods of radio tomography are used, where the Doppler frequency with a small measurement error is used as the initial data [14]. Phase-difference methods make it possible to reconstruct small irregularities in the ionosphere, but, unlike phase methods, they are not able to investigate the background values of the electron density with high accuracy.

Besides phase and phase-difference measurements, the TEC can be obtained from pseudoranges delays acquired at two GNSS transmitted frequencies. According to the authors of [13], the TEC calculated as:

$$\text{TEC}_P = \frac{1}{\chi} \frac{f_1^2 \cdot f_2^2}{f_1^2 - f_2^2} \left[ (P_2 - P_1) + \sigma_P \right],$$

where $P_1$ and $P_2$ are pseudorange delays for frequencies $f_1$ and $f_2$, respectively; $\sigma_P$ is pseudorange measurement error.

With the help of two-frequency measurements of pseudorange delays, it is possible to obtain the absolute TEC, but such measurements are highly noisy. The noise level in this case is several TECU [14]. Therefore, when studying disturbances in the ionosphere, it is preferable to use carrier phase measurements or their combination with pseudorange delay measurements.

Figure 1 shows a perspective scheme for sounding the ionosphere (gray stripe) by signals transmitted by GNSS satellites and received by the nanosatellite (ns). According to this scheme, ns has to be able to receive signals crossing the F layer of the ionosphere from two navigation satellites spaced apart in orbit. With such a sounding geometry, the angle $\alpha$ between the rays can reach about 150-160 deg, respectively. For simultaneous reception of these signals, it is necessary to point the navigation patch antenna to the Earth's center.

Figure 1. Scheme of possible ionospheric sounding by GNSS satellites (nanosatellite receives signals from two GNSS satellites).

2. TEC calculation technique
For precise determination of the absolute TEC we use a combination of two-frequency pseudorange and carrier phase measurements [15,16]. For this purpose, for each ray we determine time intervals at which the navigation measurement data do not have phase disruptions (continuous data series) and calculate the leveling bias $B_{rs}$:

$$B_{rs} = \sum_{i=1}^{N} \frac{1}{\sigma_i^2} \left[ \left( P_{i1}'' - P_{i2}'' \right) - \left( \Phi_{i1}'' - \Phi_{i2}'' \right) \right],$$

(4)

where $r$ is the number of the GNSS receiver; $s$ is the number of the GNSS satellite; $\sigma_i$ is standard deviation (SD) of pseudorange noise. The value of $\sigma_i$ depends on a number of factors (receiver type, elevation angle etc.). The SD of the phase measurements noise is not taken into account in the calculations due to its smallness.

The addition of the $B_{rs}$ coefficients to the TEC values calculated from the two-frequency phase measurements, which makes it possible to eliminate the ambiguity of the phase measurements:

$$\text{TEC}_{rs} = \frac{1}{\chi} \frac{f_1^2 \cdot f_2^2}{f_1^2 - f_2^2} \left[ \left( \Phi_1 - \Phi_2 \right) + B_{rs} \right].$$

(5)

3. Experiment of TEC calculations

We applied this technique to an array of GPS navigation measurements obtained using a set of Delta-3 receiver and GrAnt antenna.

3.1. Instrumentation

3.1.1. GPS constellation. The established GPS orbital constellation consists of 32 main spacecrafts located on six circular orbits, designated by Latin letters from A to F. The inclination of the orbital planes is 55°, the longitudes of the ascending nodes differ by 60°. An orbital altitude of 20200 km corresponds to an orbital period of 11h 58min. Each spacecraft emits navigation signals at several carrier frequencies [17].

3.1.2. Delta-3 receiver with GrAnt antenna. The set of Delta-3 receiver and GrAnt antenna is located in Samara (Russia) in Samara National Research University (53.21° N, 50.18° E). GrAnt antenna tracks GPS, GLONASS and Galileo signals. Delta-3 receiver operates as a receiver for post-processing, as a base station and as a scientific station collecting information for ionosphere monitoring.

3.2. Observation

We conducted navigation measurements on October 07, 2020 from 06:00 to 09:00 UTC. We considered GPS signals at frequencies $f_1$ (1.5754 GHz) and $f_2$ (1.1765 GHz) for a GPS satellite with $SV = 23$. Figure 2 shows the elevation angle of this satellite for time interval of measurements.

Figure 3 shows the experimental dependence of the moving SD with a 5 minute window on the elevation angle, which was used to calculate the absolute TEC by formula 5.

Figure 4 shows the TEC estimates obtained both for pseudorange measurements (gray line) using formula 3, and for a combination of phase and pseudorange measurements (black line) using formula 5. SD for phase measurements is less than 0.01 TECU, the relative error in the determination TEC is less than 0.1% respectively.
Figure 2. Elevation angle for GPS satellite (SV = 23).

Figure 3. The moving SD (5 minutes window) of pseudorange measurements depending on elevation angle.
Figure 4. (grey) TEC observations calculated from pseudorange delays $P_{1i}$ and $P_{2i}$; (black) TEC observations calculated from phase ranges $\Phi_{1i}$ and $\Phi_{2i}$ with considering $B_{rs}$.

4. Discussion and Conclusion
The development of a scientific instrument for micro/nanosatellites, allowing to measure TEC, will create preconditions for the deployment of a space monitoring system using scientific micro/nanosatellites [18-21]. There is a hypothesis that fluctuations of the ionosphere are precursors of earthquakes. The instrument will allow collecting measurements to confirm this hypothesis and will serve as an important stage in the creation of technology to predict earthquakes [22].

For computer tomography of ionosphere, it is necessary that the nanosatellite be able to simultaneously receive signals from several GNSS satellites positioned in the same orbital plane. When the patch antenna is pointed to the Earth's center (the radiation pattern of antenna lies in the lower half-plane passing through the local horizon line and perpendicular to the orbital plane – figure 1), this condition is met and the antenna receives signals from two GNSS satellites spaced apart in the orbit (for example, from two GLONASS satellites spaced 180 degrees apart). To receive signals from other GNSS satellites located in the upper half-plane, it is necessary to mount a second antenna, thereby increasing the total field of view to 360 degrees.

The characteristic presented in figure 3 was obtained for the case of the ground-based antenna with orientation along the zenith, and when the satellite moves in orbit, this characteristic will undergo changes. Accordingly, it must be evaluated by the computational means of a scientific instrument in flight. In addition, in order to use formula (4) and find bias as accurately as possible, it is necessary to obtain a complete arc of measurements (from low to high elevation) for each GNSS satellite, i.e. carry out continuous measurements and store data for at least one orbit turn.

As can be seen from formula (2), the error in the TEC estimate is linearly related to the error in the phase delay; accordingly, for an error in determining the TEC of 0.01 TECU, it is necessary that the error in determining the phase delay does not exceed 4.5 arcmin.

The requirements mentioned above are necessary for the design of a scientific instrument for studying the ionosphere from TEC measurements by computed tomography methods.
Acknowledgments
The reported study was funded by RFBR and BRFBR, project number 20-58-00016.

References
[1] Aleshin I M, Alpatov V V, Vasîl’ev A E, Burguchev S S, Kholodkov K I, Budnikov P A, Molodtsov D A, Koryagin V N and Perederin F V 2014 Online service for monitoring the ionosphere based on data from the global navigation satellite system J. Geomagnetism and Aeronomy 54 pp 456–462
[2] Alpatov V V, Kunitsyn V E, Lapshin V B, Romanov A A and Tasenko S V 2012 Experience creating Roshydromet network radio tomography for the study and monitoring of the ionosphere J. Heliogeophysical Research 54 (4) pp 496–502
[3] Andreeva E, Galinov A, Kunitsyn V, Mel’nikchenko Y, Tereshchenko E, Filimonov M and Chernyakov S 1990 Radiotomographic reconstruction of ionization dip in the plasma near the Earth J. JETP Letters 52(3) pp 145–148
[4] Bust G S and Mitchell C N 2008 History current state and future directions of ionospheric imaging J. Reviews of Geophysics 46(1) p 23
[5] Garcia R and Crespion F 2008 Radio tomography of the ionosphere: Analysis of an underdetermined ill-posed inverse problem regional application J. Radio Sci. 43(2)
[6] Kunitake M, Ohtaka K, Maruyama T, Tokumaru M, Morioka A and Watanabe S 1995 Tomographic imaging of the ionosphere over Japan by the modified truncated SVD method J. Ann. Geophysicae Copernicus 13 (12) pp 1303–1310
[7] Kunitsyn V E, Kozharin M A, Nesterov I A and Kozlova M O 2004 Manifestations of heliogeophysical disturbances in october 2003 in the ionosphere over western Europe from GNSS tomography and ionosonde measurements J. Moscow Univ. Phys. Bull. 59(6) pp 68–71
[8] Kunitsyn V E, Andreeva E S, Kozharin M A and Nesterov I A 2005 Ionosphere radio tomography using high-orbit navigation systems J. Moscow Univ. Phys. Bull. 60(1) pp 94–108
[9] Ma X F, Maruyama T, Ma G and Takeda T 2005 Three-dimensional ionospheric tomography using observation data of GPS ground receivers and ionosonde by neutral network J. Geophys. Res. 110 A05308
[10] Markkanen M, Lehtinen M, Nygrén T, Pirritina J, Helenius P, Vilinenius E, Tereshchenko E D and Khudukon B Z 1995 Bayesian approach to satellite radiotomography with applications in the Scandinavian sector J. Ann. Geophys. 13 pp 1277–1287
[11] Mengist C K, Ssessanga N, Jeong S H, Kim J H, Kim Y H and Kwak Y S 2019 Assimilation of multiple data types to a regional ionosphere model with a 3D-Var algorithm (IDA4D) J. Space Weather 17(7) pp 1018–1039
[12] Wen D B, Wang Y and Norman R 2012 A new two-step algorithm for ionospheric tomography solution J. GPS Solut. 16 pp 89–94
[13] Davies K 1965 Ionospheric Radio Propagation (U. S. Department of Commerce, National Bureau of Standards) p 470
[14] Kunitsyn V E and Tereshenko E D 2003 Ionospheric tomography (Springer) p 272
[15] Lanyu G E and Roth T 1988 A comparison of mapped and measured total ionospheric electron content using global positioning system and beacon satellite observations J. Radio Sci. 23(4) pp 483–492
[16] Mannucci A J, Ho C M and Lindqwister U J 1988 A global mapping technique for GPS-driven ionospheric TEC measurements J. Radio Sci. 33(8) pp 565–582
[17] Official U.S. government information about the Global Positioning System (GPS) and related topics [Online] 2020 [cited 2020 Sep 21] Available from: https://www.gps.gov/
[18] Romanov A A, Trusov S V, Adzhalova A V, Romanov A A and Urlichich Ju M 2012 Method of monitoring vertical distribution of ionospheric electron concentration
Patent RU 2445652 C1

[19] Romanov A A, Trusov S V, Novikov A V, Adzhalova A V, Romanov A A and Selin V A 2009 Vosstanovlenie dvumernogo raspredeleniya elektronnoj koncentracii ionosfery v ploskosti orbit nizkoorbital'nyh ISZ na osnove analiza harakteristik kogerentnogo izlucheniya J. Electromechanical matters. Vniien studies 111(4) pp 37–42. Russian

[20] Solodovnikov G, Sinelnikov V and Krokhmalnikov E 1988 Remote Sounding of the Earth Ionosphere by Satellite Beacons (Nauka, Moscow) p 191. Russian

[21] Romanov A A, Romanov A A, Trusov S V and Urlichich U M 2013 Sputnikovaja radiotomografija ionosfery (Fizmatlit, Moscow) p 296. Russian

[22] Pulinets S A, Uzunov D P, Davidenko D V, Dudkin S A and Cadikovskij E I 2014 Prognoz zemletrjasenij vozmozhen?! (Trovant) p 144. Russian