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Methods and software for calculating total electronic content based on GNSS data

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Keywords
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Abstract

Methods for determining the total electron content in the ionosphere by global navigation system signals are investigated. Methods for correction phase ambiguity due to «cycle slip» and determining differential code delays are proposed and implemented. Software for finding the full electronic content and constructing maps of vertical full electronic content over the territory of the Republic of Belarus was developed.

Introduction

Relevance of the study of processes occurring in the ionosphere is due to the fact that the spatial and temporal inhomogeneities of the electromagnetic field in the upper atmosphere of the Earth play an important role in the functioning of modern technological systems [1-3]. For example, maintenance of serviceability of equipment installed onboard satellites, accuracy of objects location with global navigation satellite systems, characteristics of radio-wave propagation, ground-based electrical generating, electrical and pipe-line systems operation depend on knowledge of upper atmosphere state at ionospheric heights.

One of the most effective ways to study ionosphere is radio sounding using high orbital navigation satellites [1-3]. Currently, there is a network of 96 continuously operating points of the precise positioning satellite system on the territory of the Republic of Belarus, which can be used for measurements. Data from these stations allow us to calculate the total electron content (TEC), which describes the number of electrons on the line connecting the satellite with the ground receiving station. Based on the TEC, the vertical total electron content (VTEC), which characterizes the integral concentration of electrons in a vertical column above a given point on the Earth's surface, is found.

Material and Method

The passage of electromagnetic signals through the ionosphere depends on the concentration of free electrons in it. In addition, the effect of the ionosphere on radio signals depends on the frequency of the signal, i.e. ionosphere is a dispersing medium. This effect changes the speed of propagation of signals with respect to the speed of light due to the presence of a refractive index other than 1. Depending on whether the group or phase of the signal is considered, these refractive indices will be different. They are related by the following expression [4]:

$$n_{gr} = n_{ph} + f\frac{dn_{ph}}{df}$$

where n_{gr} and n_{ph} are refractive indices for group and phase signals, f - signal frequency.

The total electron content is defined as the integral of the electron density along the path between the satellite and the receiving station: $TEC = \int_S n_e(s)ds$. It is expressed in TEC Units (TECU), where 1TECU is defined as 10^{16} electrons contained in a cylinder with a cross section of 1 m^2, aligned with the beam path. TECU can be calculated both by the difference between pseudoranges P_1 and P_2 , and by the difference between phases L_1 and L_2 by the following formulas [4]:

$$TEC_{gr} = \frac{1}{40,28}\left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right)\left[P_2 - P_1 + c\left(D_r + D_s\right)\right],\; TEC_{ph} = \frac{1}{40,28}\left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right)\left[\lambda_1 L_1 - \lambda_2 L_2 - N + c\left(D_r + D_s\right)\right],$$

where λ_1 and λ_2 are wavelengths corresponding to frequencies f_1 and f_2 , c is the velocity of light in the vacuum, N is phase ambiguity due to the integer number of wavelengths at the measurement distance, D_s и D_r are the differential code delays in the satellite and receiver apertures.

TEC calculations were performed with the so-called non-geometric linear combination of two frequencies L_1 and L_2, which contains only ionospheric information. The TEC obtained from phase measurements is smoother than that obtained from code measurements for phase measurements, it is additionally necessary to correct the initial phase ambiguity associated with cycle slip. For this purpose, the method described in [5] was used.

For a number of problems, the TEC value is not very convenient, because, firstly, it strongly depends on the angle of elevation of the satellite, and, secondly, it cannot be referred to any specific point of space. More convenient is a quantity called the vertical total electron content, which is defined as the integral concentration of electrons in a vertical column above the Earth's surface. For this purpose, some height h is chosen, at which the center of gravity of the electron concentration is located. The point at this chosen height is called the Ionospheric Pierce Point (IPP) and is defined as a point on the beam connecting the satellite to the receiver at the chosen height above the Earth's surface. In the following calculations, this altitude was set to h = 504 km. The WTPP is calculated from the IPP values using the formula: $VTEC = TEC \cdot \cos\chi$, where χ is the elevation angle of the satellite.

In this work, we used a method based on [6] to estimate the differential code delays D_s and D_r . The satellite and receiver delays D_s and D_r are considered unknown parameters, which are calculated using the method of least squares using the values of the vertical total electron content.

Results and discussion

Software for processing radio-tomographic data of high-orbit ionosphere control provide implementation of methods and algorithms for obtaining, processing and storing data on ionosphere conditions over the territory of the Republic of Belarus and neighboring countries, received on the basis of radio signals from high-orbit navigation satellite systems, fixed by the satellite system of precise positioning of the Republic of Belarus (SSTP RB). The software will be a part of space system of radiometric control of near-Earth space based on ICA and specialized ground facilities, which will make it possible to increase the safety level of operation of complex infrastructure objects on the territory of the Republic of Belarus.

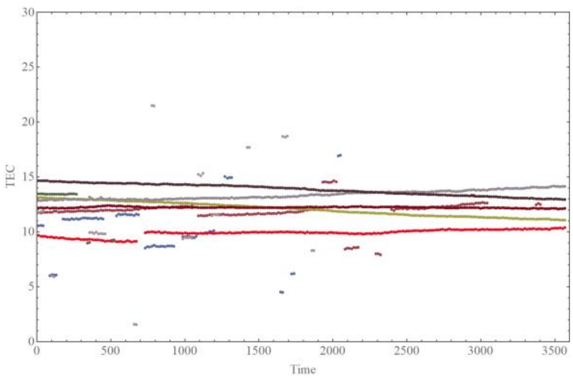

Figure 1. Values of electronic contents before cycle slip correction

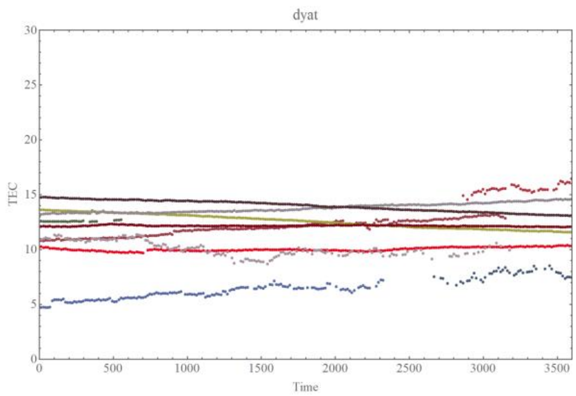

Figure 2. Values of electronic contents after cycle slip correction

The software is written in the Python programming language version 3.10, using third-party cross-platform free libraries Matplotlib, NumPy, Plotly, SciPy, georinex, Pandas, pymap3d, Xarray, PyKrige, GeoPandas.

Figure 1 shows the values of total electron content before the cycle slip correction, obtained from the phase pseudorange of GPS satellite signals for May 5, 2022, between 00:00:00 and 01:00:00 UTC. Figure 2 shows the same values after the cycle slip correction. It can be seen that the outliers associated with slippage are effectively corrected by the used algorithm.

As an example of the operation of the algorithm for determining the differential code delays, we present the results of calculation of the total electronic content using data from May 5, 2022 from the observation station "Borisov", located in the city of Borisov. Figure 3 shows the values of total electron content before the correction of differential code delays for all 32 GPS satellites. Figure 4 shows the same values after the differential code delay correction.

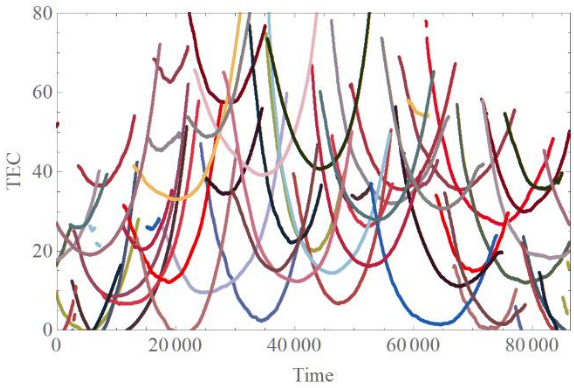

Figure 3. TEC values before differential code delay correction

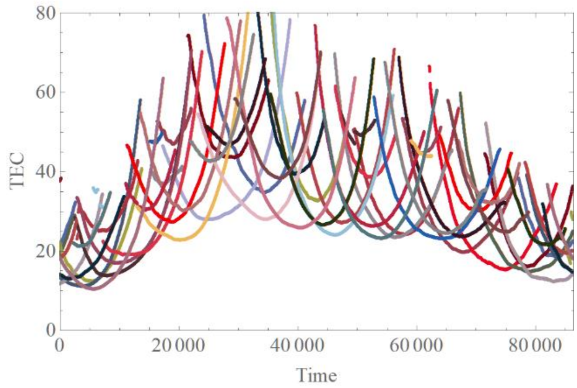

Figure 4. TEC values after correction of differential code delays

An example of calculation of the vertical total electron content at different points in time on May 05, 2022 according to data from 15 observation stations and GPS satellites is shown in Figure 5.

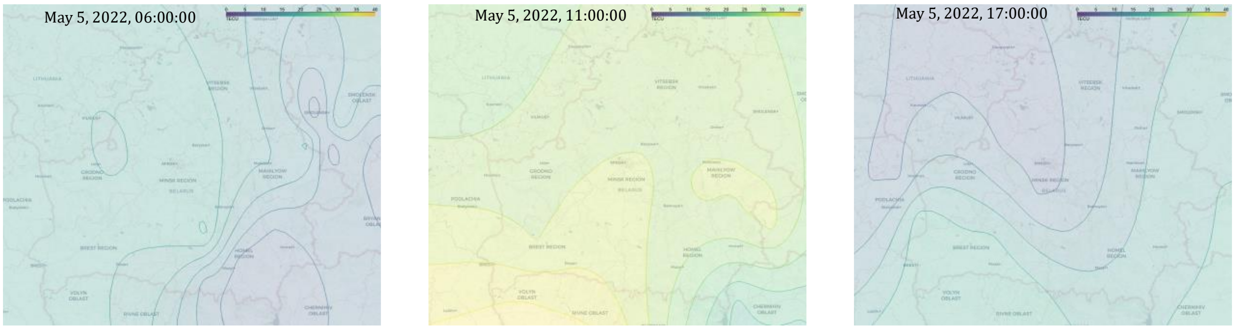

Figure 5. Example of Calculation of Vertical Total Electronic Content over the Territory of the Republic of Belarus

Conclusion

Methods and software tools for calculating total electronic content from data of global navigation satellite systems are presented. Further direction of work - three-dimensional reconstruction of the electron content in the ionosphere on the basis of the obtained data.

References

1. Artemiev, V. M., Naumov, A. O., Stepanov, V. L., & Murashko, N. I. (2008). Method and Results of Real Time Modeling of Ionosphere Radiotomography on the Basis of the Kalman Filter Theory. Journal of Automation and Information Sciences, 40(2), 52–62.
2. Belokonov, I. V., Krot, A. M., Kozlov, S. V., Kaplarchuk, E. A., Savinykh, I. E., & Shapkin, A. S. (2023). A method for estimating the total electron content in the ionosphere based on the retransmission of signals from the global navigation satellite system GPS (In Russ.). Informatika [Informatics], 20(2), 7–27.
3. Milanowska, B.; Wielgosz, P.; Krypiak-Gregorczyk, A.; Jarmołowski, W. (2021) Accuracy of Global Ionosphere Maps in Relation to Their Time Interval. Remote Sensing, 13(18), 3552.
4. Hofmann-Wellenhof, B. (2008). GNSS – Global Navigation Satellite Systems. GPS, GLONASS, Galileo, and more. Springer, Berlin, Germany, 546.
5. Hieu, La Van, Ferreira, V. G., He, X., Tang, X. (2014). Study on cycle-slip detection and repair methods for a single dual-frequency global positioning system (GPS) receiver. Boletim de Ciências Geodésica, 20 (4), 984-1004.
6. Wang, Y., Zhao, L., & Gao, Y. (2021). Estimation and analysis of GNSS differential code biases (DCBs) using a multi-spacing software receiver. Sensors (Basel), 21(2), 443.