ISSN 1561-8358 (Print)
ISSN 2524-244X (Online)

РАДИОЭЛЕКТРОНИКА, ПРИБОРОСТРОЕНИЕ

RADIOELECTRONICS, INSTRUMENT-MAKING

https://doi.org/10.29235/1561-8358-2024-69-1-53-64
UDC 528.88:550.388.2

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Original article

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DETERMINATION OF TOTAL ELECTRON CONTENT IN THE IONOSPHERE OVER THE TERRITORY OF THE REPUBLIC OF BELARUS BASED ON GLOBAL NAVIGATION SATELLITE SYSTEMS DATA

Abstract. We present the results of experimental studies of electron content in the ionosphere over the territory of the Republic of Belarus based on data from global navigation satellite systems. The results of measurements of the precise positioning system of the Republic of Belarus and navigation data of GPS satellites in RINEX format were used as input data. Expressions for calculation of the total electron content using the two-frequency method and a combination of measurements by phase and code delays are given. Algorithms for eliminating cycle slip and determining differential code biases are used. Examples of calculating the vertical electron content over the Republic of Belarus at different moments of time are demonstrated. The obtained results are reasonable to use in monitoring of the ionosphere in order to provide reliable operation of radio systems, detection of ionospheric anomalies of natural and artificial origin, as well as forecasting of natural phenomena on their basis.

Key words: ionosphere, radio tomography, total electron content, vertical electron content, global navigation satellite system, navigation signal.

Conflict of interest: the authors declare that there is no conflict of interest

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For citation: Naumov A. O., Khmarskiy P. A., Byshnev N. I., Piatrouski M. A. Determination of total electron content in the ionosphere over the territory of the Republic of Belarus based on global navigation satellite systems data. *Vestsi Natsyyanal'nai akademii navuk Belarusi. Seryya fizika-tekhnichnykh navuk = Proceedings of the National Academy of Sciences of Belarus. Physical-technical series*, 2024, vol. 69, no. 1, pp. 53–64. https://doi.org/10.29235/1561-8358-2024-69-1-53-64

Received: 05.07.2023
Approved for publication: 07.09.2023
Signed to the press: 15.03.2024

* Corresponding author / Автор, ответственный за переписку.

Оригинальная статья

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ОПРЕДЕЛЕНИЕ КОНЦЕНТРАЦИИ ЭЛЕКТРОНОВ В ИОНОСФЕРЕ НАД ТЕРРИТОРИЕЙ РЕСПУБЛИКИ БЕЛАРУСЬ ПО ДАННЫМ ГЛОБАЛЬНЫХ НАВИГАЦИОННЫХ СПУТНИКОВЫХ СИСТЕМ

Аннотация. Приводятся результаты экспериментальных исследований концентрации электронов в ионосфере над территорией Республики Беларусь по данным глобальной навигационной спутниковой системы. В качестве входных данных использовались результаты измерений спутниковой системы точного позиционирования Республики Беларусь и навигационные данные высокоорбитальных навигационных спутников в формате RINEX. Приведены выражения для расчета полного электронного содержания при помощи двухчастотного метода и комбинации измерений по фазовым и кодовым задержкам. Решены задачи коррекции проскальзывания цикла навигационного сигнала и определения дифференциальных кодовых задержек. Продемонстрированы примеры вычисления вертикального электронного содержания над Республикой Беларусь в разные моменты времени. Полученные результаты целесообразно использовать при мониторинге ионосферы с целью обеспечения надежной работы радиосистем, обнаружения ионосферных аномалий естественного и искусственного происхождения, а также прогнозирования природных явлений на их основе.

Ключевые слова: ионосфера, радиотомография, полное электронное содержание, вертикальное электронное содержание, глобальная спутниковая навигационная система, навигационный сигнал

Конфликт интересов: авторы заявляют об отсутствии конфликта интересов.

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Вклад авторов: *Наумов Александр Олегович* – обоснование концепции исследования, формулирование идеи, исследовательских целей и задач, разработка методологии и модели исследования; *Хмарский Петр Александрович* – сбор и систематизация данных, проведение сравнительного анализа, написание текста рукописи; *Бышнев Никита Игоревич* – обобщение и интерпретация результатов исследования, работа с графическими материалами; *Петровский Никита Андреевич* – компьютерное и математическое моделирование.

Для цитирования: Определение концентрации электронов в ионосфере над территорией Республики Беларусь по данным глобальных навигационных спутниковых систем / А. О. Наумов [и др.] // Вес. Нац. акад. навук Беларусі. Сер. фіз.-тэхн. навук. – 2024. – Т. 69, № 1. – С. 53–64. https://doi.org/10.29235/1561-8358-2024-69-1-53-64

Поступила в редакцию: 05.07.2023
Утверждена к публикации: 07.09.2023
Подписана в печать: 15.03.2024

Introduction. An important parameter, which is used in various fields of practical activities, is the concentration of electrons in the ionosphere. As is known, the ionosphere contains ions and free electrons, which scatter radio waves and can affect the transmission of radio signals. The propagation of radio waves through the ionosphere is difficult depending on the concentration of electrons and leads to distortions of the radio signal passing through it [1, 2]. Consideration of this information is extremely important for satellite radio navigation, radio communications (especially for long distances), radar systems, etc. Thus, the assessment of electron concentration in the ionosphere allows prediction and understanding the state of the ionosphere and improvement of the performance of communication, location and navigation systems. In addition, estimation of distribution of electron concentration in the ionosphere is important for studies of radio wave propagation in the atmosphere, climate, natural hazards, etc. [1, 3–5]. All these areas are related to forecasting and modeling of ionosphere state and its disturbances, and therefore require reliable data on distribution of electron concentration.

One of the most effective means of studying the ionosphere in recent times is radio-tomography. It allows with the help of satellite transmitting and ground receiving station probing the ionosphere in a wide spatial and temporal range and applying tomographic methods to reconstruct the distribution of electron concentration. Such a radio tomographic system includes a group of satellites moving on circular or elliptical orbits, and a system of ground receiving stations (Figure 1). The important advantage of the method of radio-tomography is that it allows obtaining information about changes in the distribution of electron concentration in the ionosphere in real time, which in turn makes it possible to ensure the stability of technology and communication systems that depend on the ionosphere.

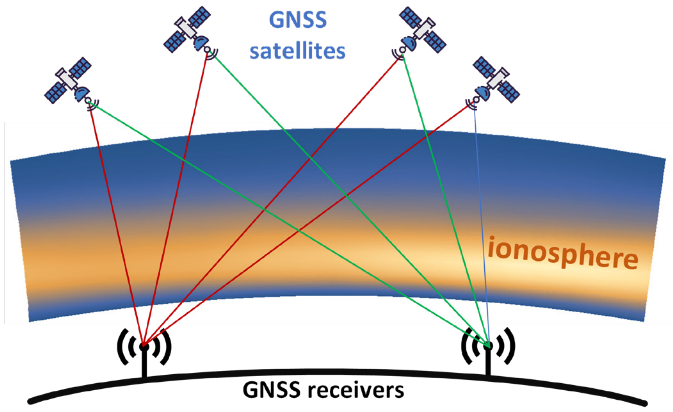


Figure 1. Principle of ionospheric tomography based on data from global navigation satellite systems

Design and development of global satellite navigation systems (GNSS) has opened new opportunities for research of ionosphere. Among the centers involved in these studies should be distinguished [6–15]: National Center for Atmospheric Research (Boulder, USA); Space Radio-Diagnostic Research Center, University of Warmia and Mazury (Olstyn, Poland); Institute for Space-Earth Environmental Research (Japan); Max Planck Institute for Solar System Research; Institute of Space Science (Malaysia); Ionosphere Research Unit, Belgian Institute for Space Aeronomy (Belgium); Department of Physics of the Earth, Astronomy and Astrophysics I (Geophysics and Meteorology), Complutense University of Madrid (Spain); Abdus Salam International Center for Theoretical Physics (Italy) and others.

This work is the first in a planned series of articles devoted to the development and research of algorithms and software for radiometric three-dimensional monitoring of distribution of electron concentration in the ionosphere over the territory of the Republic of Belarus. The purpose of this paper is to develop a method for determining the total electron content (TEC) in the ionosphere over the territory of the Republic of Belarus from data of global navigation satellite systems.

Generalized structural scheme of calculating the electron content in the ionosphere. The process for determining the electron content in the ionosphere based on GNSS is complicated by interference and distortions associated with the reception, transmission and features of the environment of satellite signals [3]. The key problems include [1, 2]: satellite signal cycle slip, phase ambiguity and the presence of differential code biases. All of these factors lead to noise, distortion, and bias of the estimates relative to the true value of the electron content. Thus, correction methods are needed to improve the quality of GNSS-based estimates of electron content in the ionosphere. Based on the analysis of the literature in this area, as well as research and practical experience of the authors in ionospheric radio tomography and related areas, a structural scheme was developed to solve the problem (Figure 2).

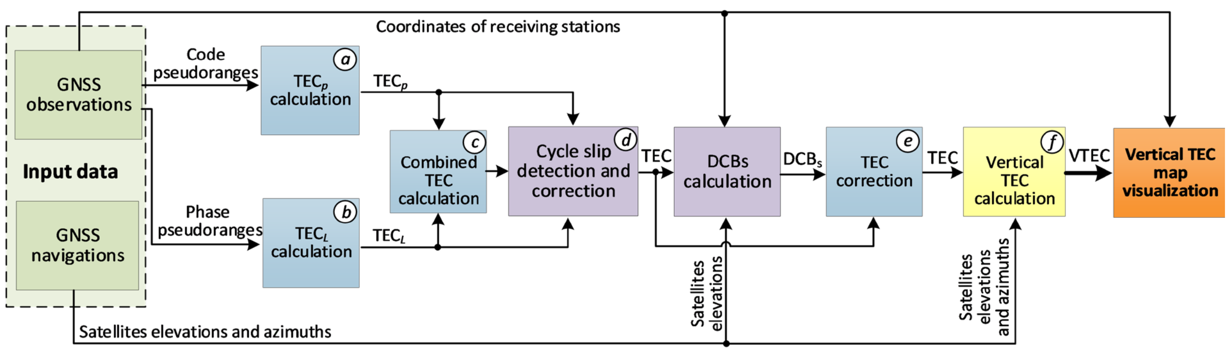


Figure 2. Generalized structural scheme for calculating the total electron content in the ionosphere

The input data for such system are the results of observations of the satellite system of precise positioning of the Republic of Belarus and navigation data of GPS satellite systems [16]. All data are provided in the RINEX format [17], example of which structure is shown in Figure 3.

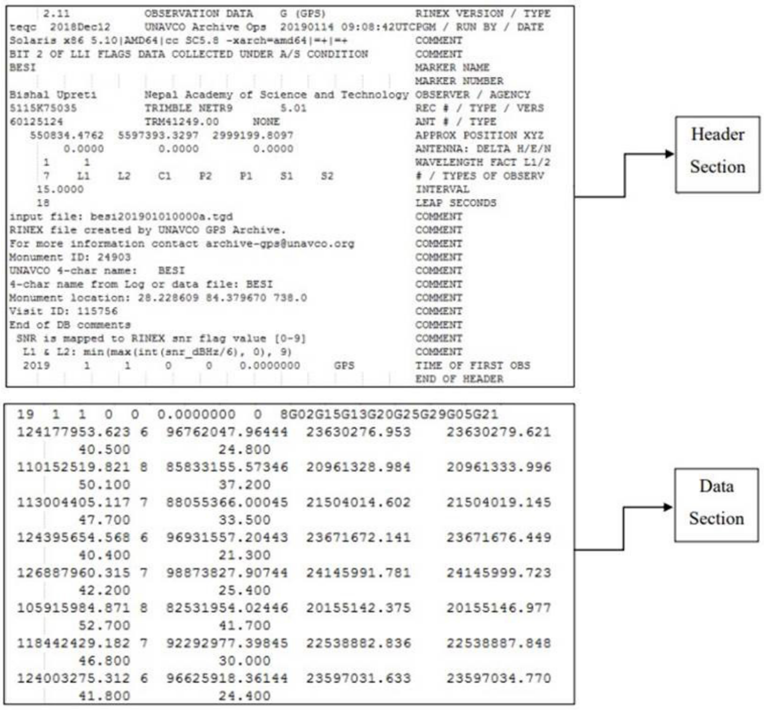


Figure 3. Structure of a file in RINEX format

After processing and transformation of input navigation data from RINEX-files we obtain estimates of phase and code pseudoranges, as well as angular coordinates of satellites. For a given time moment calculation of the total electron content in the ionosphere is reduced to the following stages (examples are shown in Figure 4 and described below in the article in the relevant sections):

calculation of the total electron content on the paths connecting the navigation satellites and ground receiving stations, based on phase (stage *a*) and code pseudoranges (stage *b*);

calculation of the total electron content based on a combination of measurements obtained from phase and coded pseudoranges (stage *c*);

detection of satellite radio signal cycle slip and correction of total electron content (stage *d*);

estimation of satellites and receivers differential code biases and correction of total electron content on their basis (stage *e*);

calculation of the vertical total electron content (stage *f*) and its visualization on the geographical map.

Calculation of total electron content. The principle of radio tomography ionosphere is based on measurements of time delays of radio signals in the atmosphere (troposphere and ionosphere), which depend on several factors [1, 15, 18]: seasonal and daily variations of electron concentration in ionosphere and gas composition in the troposphere; angle of location and azimuth of satellite relative to ground receiving station; latitude and longitude of location. The ionosphere is a dispersing medium in which the degree of delay of radio signals depends on frequency. Gas temperature, concentration of free electrons and plasma density of ionosphere non-linearly depend on height (Figure 5). The principle of ionospheric radio tomography is based on this property. It is important to note that the troposphere is not a dispersing medium, so measurement of delays in it by radio tomography systems is impossible.

Reconstruction of ionosphere is based on the use of projections of the electron concentration, observed by ground-based GNSS receiving stations from different directions during the movement of satellites [19–21]. In this calculation, the input signals are the values of radio signal delays at the locations of GNSS ground receiving stations, while the output signals are the measured projection values equal to

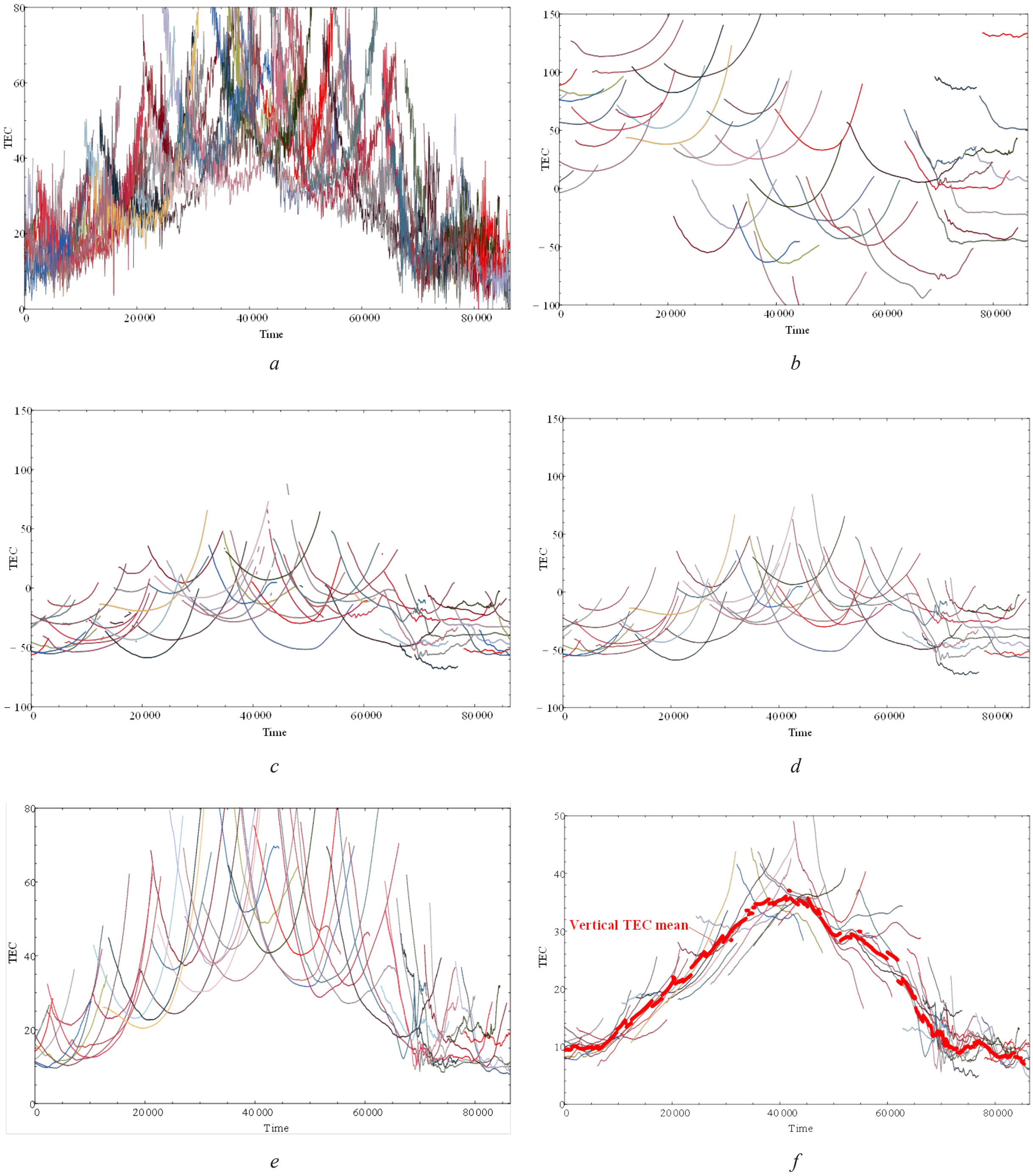
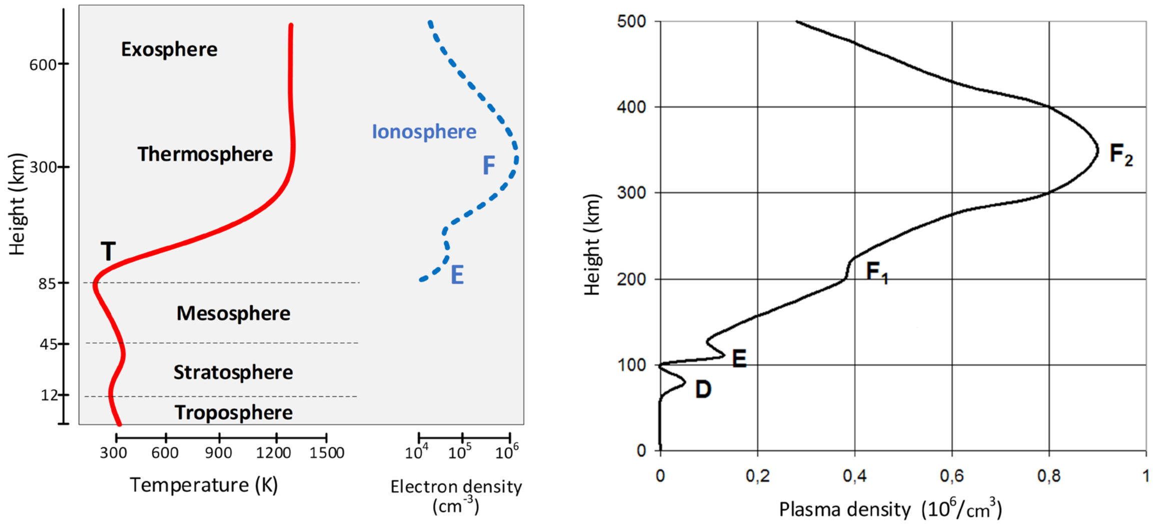


Figure 4. Results of calculations of total electron content by code data of GPS satellites (*a*), phase data of GPS satellites (*b*), after combination code and phase data (*c*); after cycle slip correction (*d*), after correction of differential code biases (*e*) and vertical total electron content (*f*). Observation results are given for one ground station (in the city of Lepel). Different colors mean 32 different GPS satellites



a *b*

Figure 5. Dependence of ionosphere parameters on height: gas temperature and free electron concentration (*a*); plasma density (*b*) on height

the total electron content along the satellite-receiver path. As the satellite moves, there is a sequence of projections at different angles relative to the observation area. The total electron content is defined as the number of electrons in a cylinder with a base area of 1 m^2, which connects the satellite with the ground receiving station. It is expressed in TEC Units (TECU), where 1 TECU is defined as 10^{16} electrons. The total electron content is the linear integral of the electron density along the radio wave propagation path. The lag of the radio signal is related to the integral electron concentration by the formula [1, 15, 18]:

$$d_{\text{ion}} = \frac{A}{f^2}\int_S n_{\text{e}}(S)dS = \frac{A}{f^2}\text{TEC},$$

where d_{ion} – ionospheric delay, m; A = 40.28 – constant characterizing refraction of the ionosphere, m^3/s^2; f – the frequency of the radio signal, Hz; $n_{\text{e}}(S)$ – concentration of electrons along the path S; $\text{TEC} = \int_S n_{\text{e}}(S)dS$.

Since radio tomography ionosphere is based on measurements of time delay of radio signal, here are the basic relations for these measurements. In the absence of obstacles to radio-wave propagation, the range between the satellite and the ground receiving station is determined by the formula

$$P = (T_{\text{r}} - T_{\text{s}})c, \qquad (1)$$

where T_{r} is the time of signal reception, s; T_{s} is the time of signal transmission, s; $c = 3\cdot10^8$ – the speed of light in vacuum, m/s.

In satellite radio navigation the range calculated by expression (1) is a pseudorange, as it is calculated without correction for the difference between the satellite clock and the receiver clock [1, 2]. Provided that the radio signal passing through the ionosphere undergoes a delay and at the same time is radiated with wavelengths λ_1 and λ_2, then the pseudoranges for each of them will be equal [1, 2]:

$$P_1 = P + d_{\text{ion1}} + d_{\text{trop}} + c(\varepsilon_{\text{r1}} + \varepsilon_{\text{s1}});\; P_2 = P + d_{\text{ion2}} + d_{\text{trop}} + c(\varepsilon_{\text{r2}} + \varepsilon_{\text{s2}}), \qquad (2)$$

where P_1, P_2 – pseudoranges at two wavelengths λ_1 and λ_2, m; d_{ion1}, d_{ion2} – ionospheric delay at corresponding wavelengths λ_1 and λ_2, m; d_{trop} – tropospheric delay, m; ε_{r} and ε_{s} – signal delays in the receiver and satellite equipment, s.

At the same time, it is possible to measure the phase delays of signals and obtain pseudorange values on its basis [1, 2]:

$$\lambda_1\varphi_1 = P + \lambda_1\varphi_{\text{ion1}} + \lambda_1\varphi_{\text{trop1}} - c(\varepsilon_{\text{r1}} + \varepsilon_{\text{s1}}) + \lambda_1 N_1;\ \ \lambda_2\varphi_2 = P + \lambda_2\varphi_{\text{ion2}} + \lambda_2\varphi_{\text{trop2}} - c(\varepsilon_{\text{r2}} + \varepsilon_{\text{s2}}) + \lambda_2 N_2, \quad (3)$$

where φ_1 and φ_2 – measured phase values at wavelengths λ_1 and λ_2; φ_{ion} – phase shifts due to the ionosphere; φ_{trop} – phase shifts due to the troposphere; N_1 and N_2 are phase ambiguities at two wavelengths λ_1 and λ_2 due to the integer number of wavelengths at the measurement distance.

Using the approximation given by [22]:

$$\varphi_{\text{ion1}} = -d_{\text{ion1}}/\lambda_1,\ \varphi_{\text{ion2}} = -d_{\text{ion2}}/\lambda_2;\ \varphi_{\text{trop2}} = -d_{\text{trop}}/\lambda_1,\ \varphi_{\text{trop2}} = -d_{\text{trop}}/\lambda_2. \quad (4)$$

Finally using (1)–(4), we can obtain the pseudoranges:

$$P_4 = P_2 - P_1 = d_{\text{ion2}} - d_{\text{ion1}} + c(\varepsilon_{\text{r2}} - \varepsilon_{\text{r1}}) - c(\varepsilon_{\text{s2}} - \varepsilon_{\text{s1}}),$$

$$L_4 = \lambda_1\varphi_1 - \lambda_2\varphi_2 = d_{\text{ion2}} - d_{\text{ion1}} + c(\varepsilon_{\text{r2}} - \varepsilon_{\text{r1}}) - c(\varepsilon_{\text{s2}} - \varepsilon_{\text{s1}}) + N,$$

where P_4 – pseudoranges difference, obtained from the delay times at the two wavelengths λ_1 and λ_2; L_4 – pseudoranges obtained from phase delays at two wavelengths λ_1 and λ_2; $N = \lambda_1 N_1 - \lambda_2 N_2$ – phase ambiguities due to the whole number of wavelengths at the measurement distance.

Delay differences at different frequencies (called differential code biases) are denoted as follows:

$$D_{\text{s}} = \varepsilon_{\text{s2}} - \varepsilon_{\text{s1}};\ \ D_{\text{r}} = \varepsilon_{\text{r2}} - \varepsilon_{\text{r1}}. \quad (5)$$

Thus, we obtain estimates of the TEC value:

$$\text{TEC}_P = \frac{1}{A}\left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right)\left[P_4 + c\left(D_{\text{r}} + D_{\text{s}}\right)\right],\ \ \text{TEC}_L = \frac{1}{A}\left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right)\left[L_4 - N + c\left(D_{\text{r}} + D_{\text{s}}\right)\right], \quad (6)$$

where TEC_P – estimation of the total electron content obtained from the difference in arrival times of the radio signal at the two frequencies f_1, f_2; TEC_L – estimate of the total electron content obtained from the phase difference of the radio signals at the two frequencies.

Elimination of phase ambiguity and calculation of combined TEC. The P_4 and L_4 values are measured in the presence of noise. In this case the measurements L_4 are much less noisy compared to P_4, but there remains the problem of phase ambiguity in determining the value of N. Thus, TEC estimates obtained from code data are usually characterized by a large fluctuation error (see Figure 4, *a*), while TEC estimates based on phase data are characterized by systematic errors (see Figure 4, *b*) associated with ambiguity. Under such conditions, the need for a method that eliminates the problem of phase ambiguity becomes obvious, in order to ensure high accuracy of the measured parameters. This is done by using the phase alignment procedure TEC_L to TEC_P obtained from the pseudoranges. In this phase alignment procedure, first the alignment constant B is determined by averaging over small time-difference intervals P_4–L_4 [23, 24]:

$$B = \frac{1}{K}\sum_{k=1}^{K}\left[P_4(k) - L_4(k)\right] \approx -N, \quad (7)$$

where K – number of measurements; k – time index.

In order to minimize the effects of multipath and noise at low elevation angle in the estimation of the alignment constant B, it is recommended to limit the range of measurements considered, to data obtained within 10° of the peak elevation angle of each arc. As a result, a combined TEC estimate can be obtained:

$$\mathrm{TEC} = \frac{1}{40.28}\left(\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right)\left[\left(B + L_4\right) + c\left(D_\mathrm{r} + D_\mathrm{s}\right)\right]. \quad (8)$$

Thus, the proposed approach will combine the advantages of the two methods for determining the total electron content in the ionosphere – by the difference of time and phase delays. Such a method has less noise emissions, and therefore allows a higher accuracy in estimating the total electron content in the ionosphere (see Figure 4, *c*).

Detection and correction of satellite navigation signal cycle slip. One of the problems in the post-processing of navigation signal data is the problem of cycle slip, which is a discontinuity in the phase synchronization of the satellite signal receiver (Figure 6). The causes of cycle slip are [2]: power loss, very low signal to noise ratio, receiver software failure, satellite oscillator failure, ionospheric distortion, obstacles in the signal path (buildings, trees etc.). Under such circumstances, when the satellite reappears, tracking resumes.

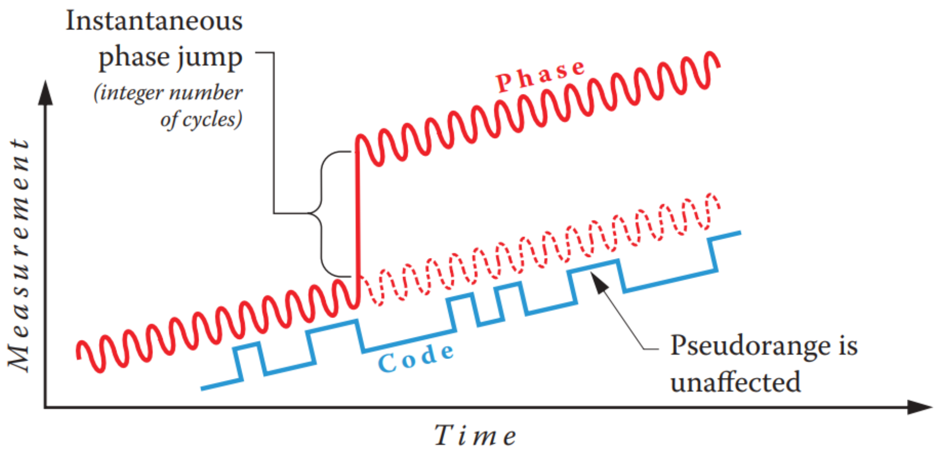


Figure 6. An example of a double difference cycle slip [2]

Cycle slip has the greatest effect on phase pseudoranges. If slippage occurs, its correction is necessary. Cycle slip detection algorithms are used together with correction, among which methods [25] stand out: Turbo Edit (TE), Melbourne–Wübbena wide-lane ambiguity (MWWL), forward and backward moving window averaging (FBMWA), etc. The best efficiency is characterized by modifications of the FBMWA algorithms, but they are not applicable for real-time processing [25]. The essence of this algorithm is reduced to the calculation of the mean value of the phase and its standard deviation in each of the epochs of observation. An epoch is defined as a time of continuous observation of a signal, when the data are not interrupted for more than a set value (for example, 60 s). When the current phase estimate differs from the average value in the previous epoch by more than the threshold value (6 standard deviations are most commonly used), cycle slip is considered detected and an appropriate correction is introduced to eliminate the slip. An example of the operation of such an algorithm is shown in Figure 4, *d*.

Determination of differential code biases and subsequent TEC correction. Another problem arising in the estimation of the total electron content of the ionosphere are differential code biases (DCBs) – these are systematic errors or biases between two observations of the GNSS code at the same or different frequencies [26]. DCBs are necessary for both navigational (code positioning of GNSS receivers) and non-navigational tasks [2]. Correct determination of DCBs is of key importance for ionospheric analysis, as they directly affect the accuracy of total ionospheric electron content measurements. An important problem in DCB estimation is that for all new and upgraded satellite navigation systems is required specification of DCB values (with several GNSS) and the selection of algorithms for their calculation [25]. To estimate the delays D_s and D_r, a method based on signal decomposition by singular numbers using dual-frequency GNSS data was used [24, 28]. In this method, the satellite and receiver delays are considered unknown parameters, which are calculated with the help the least-squares method using the values of the vertical total electron content. Further, the calculated differential code biases were used in correcting the TEC values, an example of which calculations is shown in figure 4, *e*. It can be seen from the figures that the TECs after DCBs correction are characterized by a much smaller scatter of the relative mean value and do not have negative values.

Calculation of the vertical electron content. The value of the slant TEC is calculated by integrating the electron content along the path from the GNSS satellite to the GNSS receiver (Figure 7). This value is not very convenient, since it strongly depends on the satellite elevation angle α. It is more appropriate to use the value of the vertical total electron content (VTEC), which is defined as the integral concentration of electrons in a vertical column above the Earth's surface.

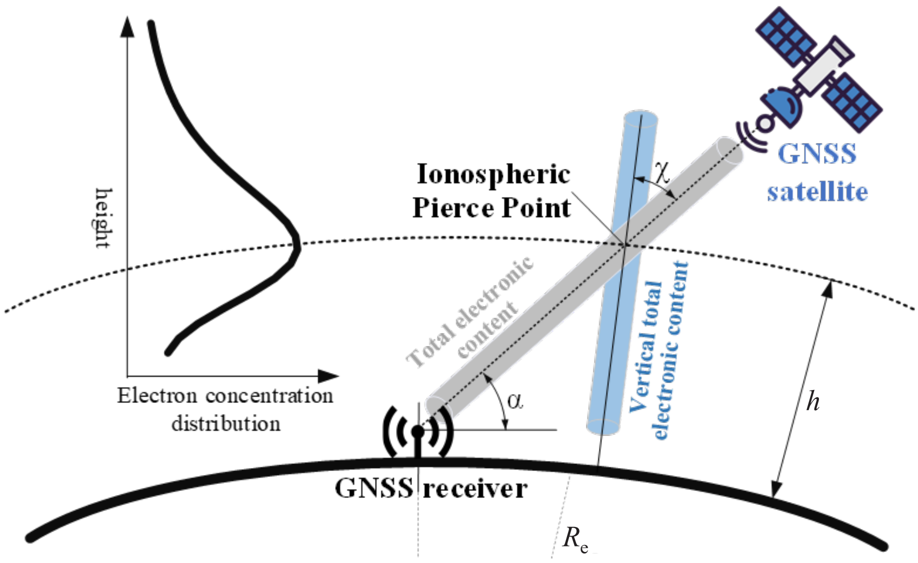


Figure 7. Value of vertical total electron content obtained from slant TEC

For this purpose, some height *h* is chosen at which the electron concentration distribution is maximal. The point at this height is called the Ionospheric Pierce Point and is set on the path connecting the satellite to the receiver [29]. The vertical total electron content (VTEC) is calculated from the slant TEC values (see Figure 7):

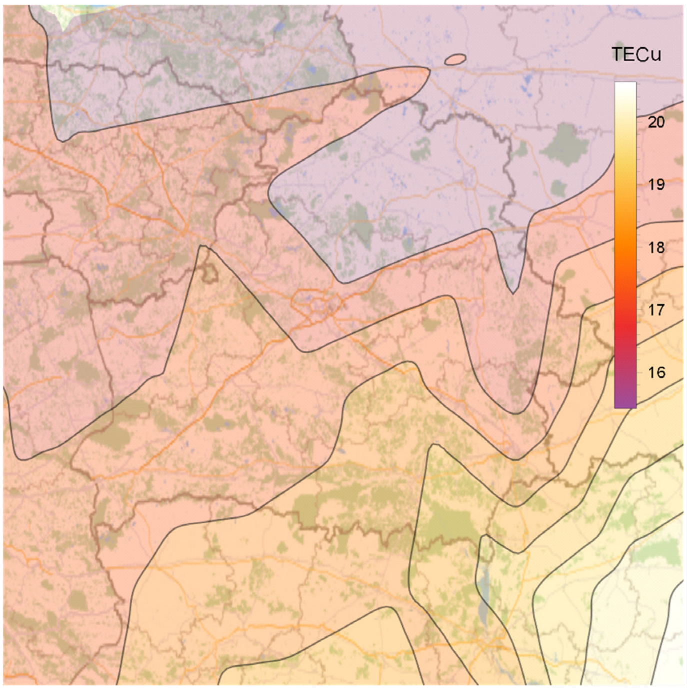
$$\text{VTEC} = \text{TEC} \cdot \cos\chi, \tag{9}$$

where $\chi = \arcsin\dfrac{R_e \cos\alpha}{R_e + h}$ – satellite's zenith angle; α – satellite elevation; R_e – equivalent radius of the Earth (equal to 6378.137 km); *h* – Ionospheric Pierce Point height (in this paper it was considered equal to 506.7 km).

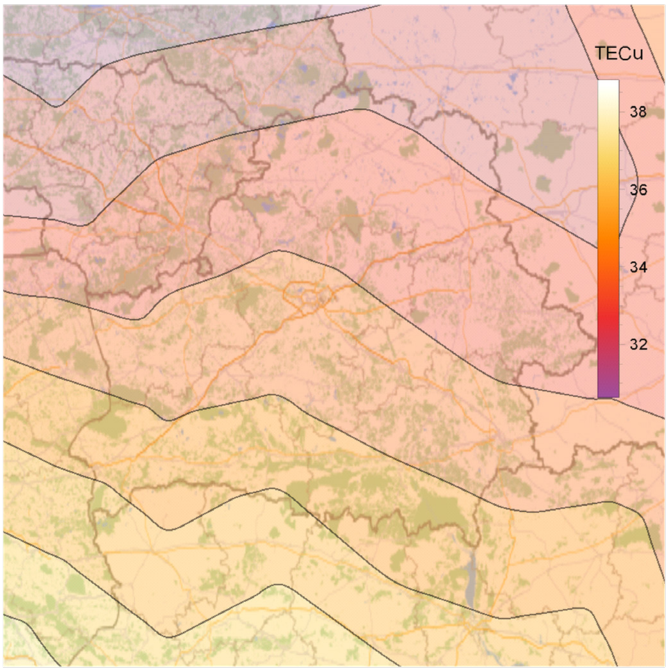
An example of the VTEC calculation and its averaging results is shown in Figure 4, *f*.

Calculation of the vertical total electron content over the territory of the Republic of Belarus. Software tools for processing of radio-tomographic data of high-orbit ionosphere control are written in Python 3.10 programming language, using third-party cross-platform libraries Matplotlib, NumPy, Plotly, SciPy, GeoRinex, pymap3d, Xarray, Pandas. The final results of these software tools are the calculation, interpolation and visualization of the vertical total electron content for a given area.

Figure 8 shows examples of VTEC calculations over the territory of the Republic of Belarus based on data from 96 ground receiving stations at different time moments. It can be seen that, in general, the VTEC over the territory of the Republic of Belarus is distributed uniformly without sharp jumps and large heterogeneities. The concentration of electrons is higher in the daytime (see Figure 8, *a*) than in the early morning (see Figure 8, *b*).



a



b

Figure 8. Example of calculation of the vertical total electron content at different time moments on April 23, 2023 according to 96 observation stations and GPS satellites over the territory of the Republic of Belarus and neighboring states: April 23, 2023, 05:00:00 (*a*); April 23, 2023, 15:00:00 (*b*)

Conclusion. The results of experimental studies of the total electron content in the ionosphere over the territory of the Republic of Belarus from data of global navigation satellite systems and ground receiving stations of the precise positioning system of the Republic of Belarus are presented. The structure of the ionosphere is analyzed and the expressions for calculating the total electron content using a dual-frequency measurement method with a combination of measurements by phase and code delays of radio signals are given on the basis of known dependencies. The results of algorithms for elimination of cycle slip and estimation of differential code biases before and after correction are demonstrated. The set of developed algorithms was implemented in the Python 3.10 programming language using third-party cross-platform free libraries, resulting in calculation and visualization of vertical total electron content over the Republic of Belarus at different time moments. The direction of further research is the development and study of methods for three-dimensional reconstruction of electron distribution in the ionosphere based on the calculated data.

The obtained results are reasonable to use in monitoring of the ionosphere in order to provide reliable operation of radio systems, detection of ionospheric anomalies of natural and artificial origin, as well as forecasting of natural phenomena on their basis. In particular, monitoring of the spatial state of the ionosphere in the selected volume of near-Earth space in real time can be used by the State Enterprise "Belarusian NPP" and other interested organizations of the Republic of Belarus.

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