ГЕОДЕЗІЯ

GEODESY

L. YANKIV-VITKOVSKA[1], S. SAVCHUK[1], V. PAUCHOK[2]

[1] Department of Higher geodesy and astronomy, Lviv Polytechnic National University, S. Bandera str., 12, Lviv, Ukraine, 79013, e-mail: luba_y@ukr.net
[2]Ternopil National Economic University, Ukraine

THE DETERMINATION AND PROCEDURE TRANSFORMATION OF THE IONOSPHERE PARAMETERS WITH GNSS-OBSERVATIONS

Purpose. Solutions to the problems of coordinate-time provision based on continuous GNSS-observations is based on the processing of large data sets of code and phase measurements. One of the possible additional options for conducting this study is computation of the numerical characteristics of the ionospheric impact on the signals distribution from the satellites – the values of the total electron density (*TEC*). These characteristics reflect the dynamics of the atmosphere ionization that is important in terms of monitoring the circumterrestrial space. Arrays of the *STEC* and *VTEC* values are so significant that there is actual problem of preparing ionosphere parameters for their further analysis and use. To solve this problem, we proposed a technique based on a set of programs that convert *VTEC* data measurements to a format suitable for the analysis. **Methods.** TEC indicators can be computed due to the automated processing of files with GNSS-observation results from each satellite for an individual station. Processing algorithm is based on the use of the computed code and phase pseudo-distances in the receiver and calibration coefficients. This algorithm allows you to get the *TEC* values in two ways: a) according to the phase measurements only and having used the results of phase ambiguities in the network as a whole beforehand and b) according to the code measurements only that were smoothed beforehand. In one-station algorithm, *TEC* value is determined for an individual station according to the measurements of all satellites during the period of 24 hours. For converting *STEC* (along the satellite-receiver beam) in vertical *VTEC,* a vertical single-layer model of the ionosphere is used. This model presupposes that all the electrons are concentrated in a thin layer that is located at a certain height above the Earth's surface. **Results.** For determination of the spatial TEC distribution, an algorithm of processing GPS measurements for multiple-stations was implemented using a network of active reference stations in the Western Ukraine. The network consists of 17 stations that work under control of specialized software in real time to provide the RTK services to the wide range of users interested in geodetic areas. **Scientific novelty.** The program for calculation of the *STEC* and *VTEC* values was written. This program uses already known subprograms, that are used for reading RINEX files, detection, estimation, and elimination of cyclical phase jumps, which arise in the process of measurements, subprograms that we developed for smoothing code measurements, receiving differential corrections at the time, calculation of the horizontal coordinates of the satellite on the observational station, direct calculation of *TEC* and subsequent storage of the received data in the new file on the server of Lviv Polytechnic National University. The entire program was compiled for the Linux operating system and automated for use with observational data of permanent IGS station SULP. The research resulted in improvement of an algorithm for determining the parameters of the ionosphere, development and implementation of software for regular computing of the ionospheric parameters – slant (*STEC*) and vertical (*VTEC*) values of total electron content, and proving of its practical use on SULP station. **Practical significance.** Calculation of the parametres of ionosphere at fixed moments of observation for each GNSS- satellite.

Key words: GNSS-measurements; ionosphere, ionospheric parameters; smoothing, spline approximation.

Introduction

Global operational monitoring of the ionosphere and especially the distribution of its electronic density are important and necessary tasks for a variety of applications [Klobuchar, 1996; Komjathy and Langley, 1996; Tsugawa et al., 2004; Stanislawska et al., 2006, 2012].

Solutions to the problems of coordinate-time provision based on continuous GNSS-observations is based on the processing of large data sets of code and phase measurements. One of the possible additional options for conducting this study is computation of the numerical characteristics of the ionospheric impact on the signals distribution from the satellites – the values of the total electron density (TEC). These characteristics reflect the dynamics of the atmosphere ionization that is important in terms of monitoring the circum-terrestrial space.

However, the TEC values have one major disadvantage. They are determined with accuracy to arbitrary constant – calibration coefficients (DCB data) that are related with hardware delays of signals in electronic channels of satellite antennas and ground receiver. This fact makes it impossible to interpret measurement results unambiguously. Development of a method for determining the absolute TEC value using regular GNSS-observations will simplify the data processing by extracting the results of phase ambiguities and improve the reliability of the received result by applying appropriate mathematical smoothing procedures [Matviychuk, 2000].

The accurate calculation of the calibration coefficients is a tedious task but these factors are crucial when determining the TEC value that has physical importance (incorrect calibration usually results either in the negative TEC value or in value that exceeds the physically possible maximum). Calculation of calibration coefficients requires the analysis of the long time series of data (continuous observations for a few days) and appropriate computational procedure. For a network of the IGS stations and airborne transmitters of navigation satellites, calibration coefficients are regularly published on the Internet. Calibration is necessary when using a receiver that is not a part of the IGS network. Improving the accuracy of the calibration algorithm will allow facilitating the data interpretation and reducing the systematic error of the method.

Materials and methods

TEC indicators can be computed due to the automated processing of files with GNSS-observation results from each satellite for an individual station. Processing algorithm is based on the use of the computed code and phase pseudo-distances in the receiver and calibration coefficients (DCB data). This algorithm allows you to get the TEC values in two ways: a) according to the phase measurements only and having used the results of phase ambiguities in the network as a whole beforehand and b) according to the code measurements only that were smoothed beforehand.

We chose the method a) as the main. Taking into consideration the procedure for determining the phase ambiguities using the network software, the actual obtaining of TEC values is possible with some delay. In our case, the delay was 15 seconds. This is the minimum time required for absolute determination of integer component of the phase measurements. With this interval, we obtain series of TEC values for each satellite that is observed at a given time on a separate station.

Method b) was chosen as control one. This method is not associated with the assessment of ambiguity and uses phase measurements only to detect phase changes over time. Code pseudoranges are smoothed by the functions that are selected based on the approximated phase changes over time. Code pseudoranges smoothed in such a way are used in the formation of the TEC values. One of the problematic issues that can significantly affect the accuracy of the ionospheric parameters is GNSS signal delays in the hardware of the receiver (DCB).

For determination of the TEC values, two algorithms are used: one-station algorithm (a separate permanent station) based on the presented variant b); and multiple-station algorithm (network of active reference stations) based on variant a).

In one-station algorithm, TEC value is determined for an individual station according to the measurements of all satellites during the period of 24 hours. For converting *STEC* (along the satellite-receiver beam) in vertical *VTEC,* a vertical single-layer model of the ionosphere is used. This model presupposes that all the electrons are concentrated in a thin layer that is located at a certain height above the Earth's surface. The height of the layer is considered to be fixed and equal to 450 km. Geometric factor is used for recalculation.

Results and discussion

The basic algorithm of the TEC computation using GNSS-observations consists of the following main steps:

1. Obtaining files with observation results for a separate station. As a result, we receive code and phase pseudoranges at two frequencies L1 and L2.
2. Introduction of additional parameters of the station: its coordinates, satellites cutoff angle, value for signal differential delay of the receiver station.

3. Obtaining differential code delays for all available satellites at the time of the calculation from the FTP-server CODE.

4. Analysis of the observational data (code and phase measurements, detection and elimination of cyclic phase slips, smoothing code measurements with the phase ones).

5. Calculation of the slant value of total electron content (*STEC)* at fixed moments of observation for each GNSS- satellite.

6. Determination of the vertical values of total electron content (*VTEC)* on the fixed points of observation in view of *STEC* data from all available GNSS- satellites.

7. Creation of files with the computation results.

The program for calculation of the *STEC* and *VTEC* values was written in the C++ programming language. This program uses:

- already known subprograms (classes) that are used for reading RINEX files, detection, estimation, and elimination of cyclical phase jumps (”cycle slip”), which arise in the process of measurements,
- subprograms that we developed for smoothing code measurements, receiving differential corrections at the time of calculation from the FTP-server CODE, calculation of the horizontal coordinates of the satellite on the observational station, direct calculation of TEC and subsequent storage of the received data in the new file on the server of Lviv Polytechnic National University.

The entire program was compiled for the Linux operating system and automated for use with observational data of permanent IGS station SULP (fig. 1). The station software generates hourly observation files with the recording interval of 1 second. Then, these files are automatically directed and executed by the program that we developed. Every hour we receive text files (with record intervals of 1 second) that contain the results of *STEC* and *VTEC* values [Yankiv-Vitkovska, 2012].

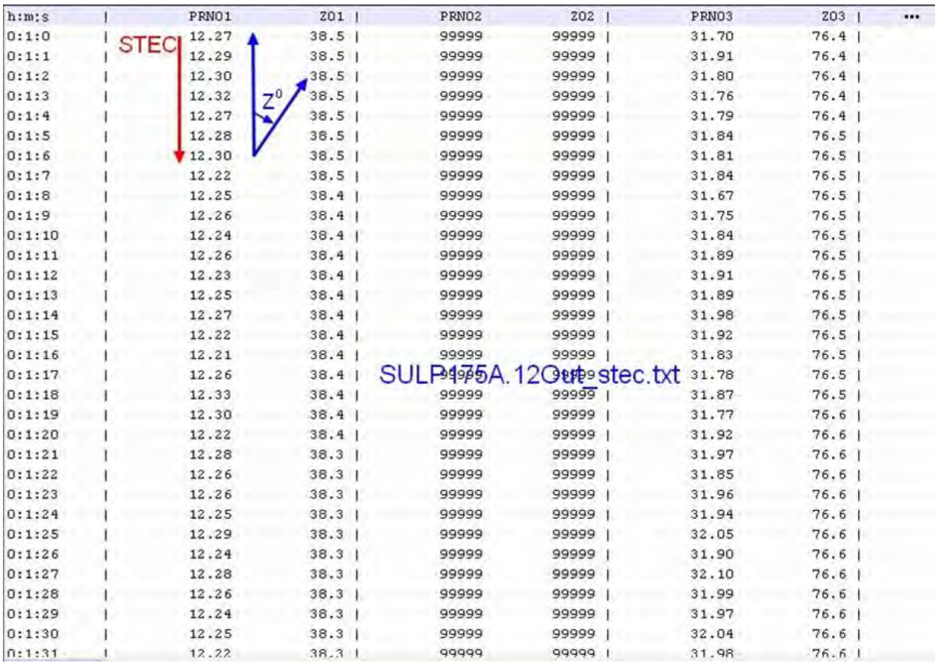
An example of the file with slant TEC values for the SULP station is shown in figure 2 and with vertical TEC values – in figure 3.

For determination of the spatial TEC distribution, an algorithm of processing GPS measurements for multiple-stations was implemented using a network of active reference stations in the Western Ukraine.

The network consists of 17 stations that work under control of specialized software in real time to provide the RTK services to the wide range of users interested in geodetic areas. Figure 4 shows the location scheme of stations in this network (http://zakpos.zakgeo.com.ua/).

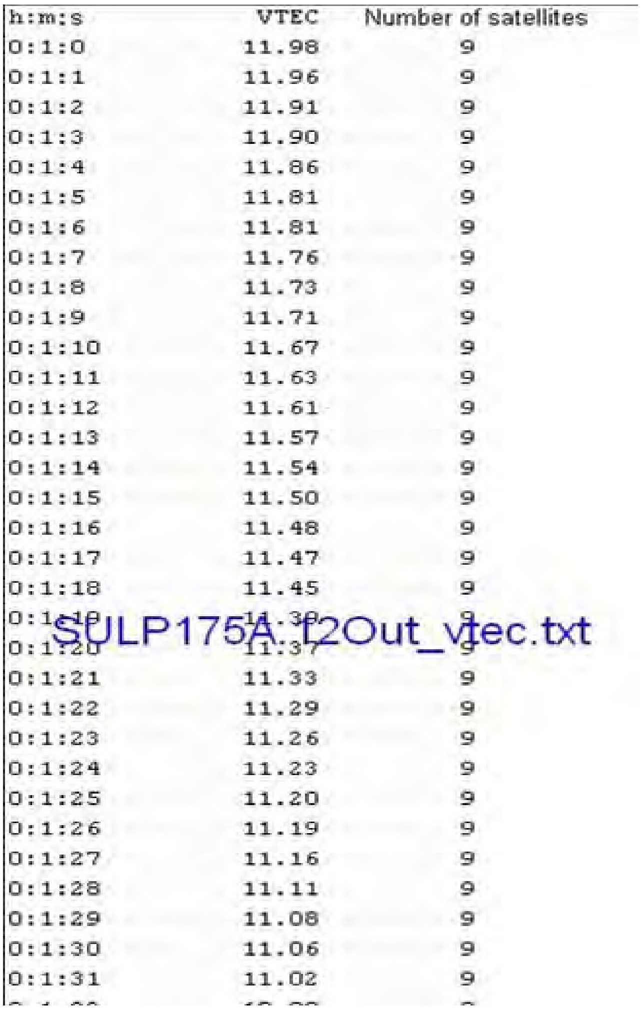
A developed program reads data from the text files and “automatically generates” two programs of the Matlab computing system. On the one hand, this is a simple data format change in a text file. In terms of computing, this is a record of data in the form of explicitly declared large numerical arrays. In the first program, discrete functional dependencies of the *VTEC* change over time (fig. 5) are described using the assignment operator. They are two-dimensional arrays of data, time series, clearly declared in the program text. Then, using these time series, the spline interpolation for all their nodes is constructed (fig. 6).

Fig. 1. GNSS equipment of the SULP station



h:m:s	PRN01	Z01	PRN02	Z02	PRN03	Z03	...
0:1:0	12.27	38.5	99999	99999	31.70	76.4	
0:1:1	12.29	38.5	99999	99999	31.91	76.4	
0:1:2	12.30	38.5	99999	99999	31.80	76.4	
0:1:3	12.32	38.5	99999	99999	31.76	76.4	
0:1:4	12.27	38.5	99999	99999	31.79	76.4	
0:1:5	12.28	38.5	99999	99999	31.84	76.5	
0:1:6	12.30	38.5	99999	99999	31.81	76.5	
0:1:7	12.22	38.5	99999	99999	31.84	76.5	
0:1:8	12.25	38.4	99999	99999	31.67	76.5	
0:1:9	12.26	38.4	99999	99999	31.75	76.5	
0:1:10	12.24	38.4	99999	99999	31.84	76.5	
0:1:11	12.26	38.4	99999	99999	31.89	76.5	
0:1:12	12.23	38.4	99999	99999	31.91	76.5	
0:1:13	12.25	38.4	99999	99999	31.89	76.5	
0:1:14	12.27	38.4	99999	99999	31.98	76.5	
0:1:15	12.22	38.4	99999	99999	31.92	76.5	
0:1:16	12.21	38.4	99999	99999	31.83	76.5	
0:1:17	12.26	38.4	[illegible]	[illegible]	31.78	76.5	
0:1:18	12.33	38.4	99999	99999	31.87	76.5	
0:1:19	12.30	38.4	99999	99999	31.77	76.6	
0:1:20	12.22	38.4	99999	99999	31.92	76.6	
0:1:21	12.28	38.3	99999	99999	31.97	76.6	
0:1:22	12.26	38.3	99999	99999	31.85	76.6	
0:1:23	12.26	38.3	99999	99999	31.96	76.6	
0:1:24	12.25	38.3	99999	99999	31.94	76.6	
0:1:25	12.29	38.3	99999	99999	32.05	76.6	
0:1:26	12.24	38.3	99999	99999	31.90	76.6	
0:1:27	12.28	38.3	99999	99999	32.10	76.6	
0:1:28	12.26	38.3	99999	99999	31.99	76.6	
0:1:29	12.24	38.3	99999	99999	31.97	76.6	
0:1:30	12.25	38.3	99999	99999	32.04	76.6	

Fig. 2. File fragment with slant TEC values



h:m:s	VTEC	Number of satellites
0:1:0	11.98	9
0:1:1	11.96	9
0:1:2	11.91	9
0:1:3	11.90	9
0:1:4	11.86	9
0:1:5	11.81	9
0:1:6	11.81	9
0:1:7	11.76	9
0:1:8	11.73	9
0:1:9	11.71	9
0:1:10	11.67	9
0:1:11	11.63	9
0:1:12	11.61	9
0:1:13	11.57	9
0:1:14	11.54	9
0:1:15	11.50	9
0:1:16	11.48	9
0:1:17	11.47	9
0:1:18	11.45	9
0:1:19	11.39	9
0:1:20	11.37	9
0:1:21	11.33	9
0:1:22	11.29	9
0:1:23	11.26	9
0:1:24	11.23	9
0:1:25	11.20	9
0:1:26	11.19	9
0:1:27	11.16	9
0:1:28	11.11	9
0:1:29	11.08	9
0:1:30	11.06	9
0:1:31	11.02	9

Fig. 3. File fragment with vertical TEC values

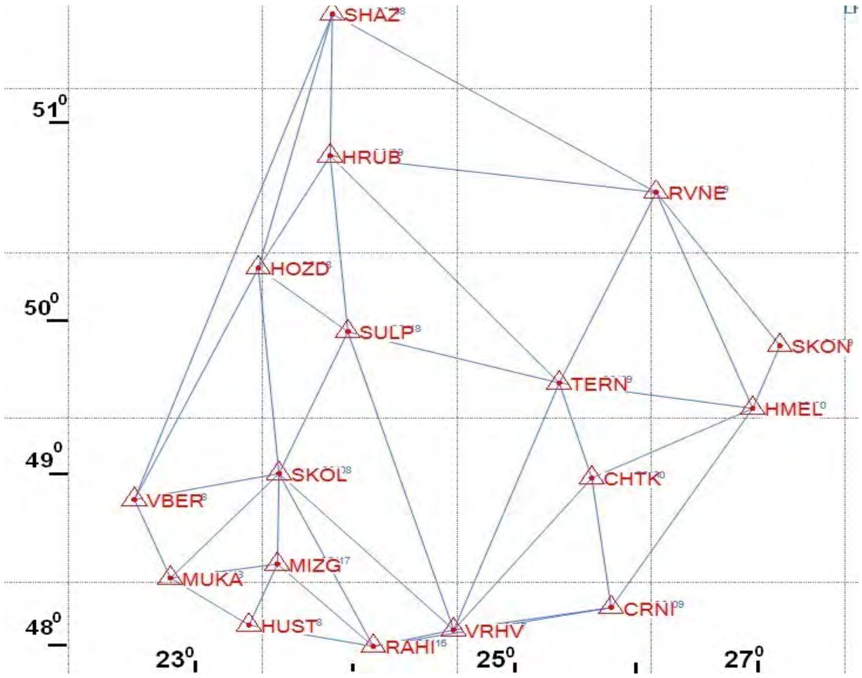


Fig. 4. Location scheme of active reference stations

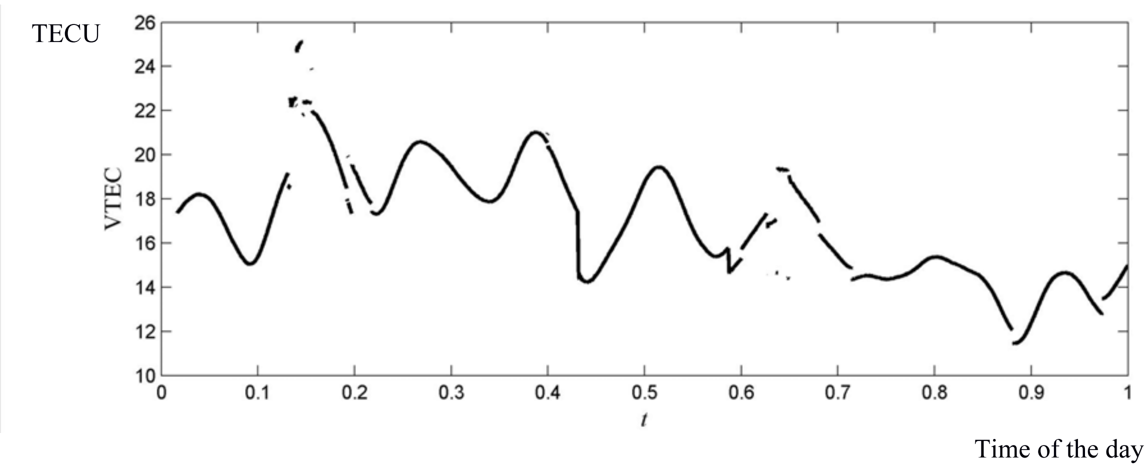


Fig. 5. Functional dependencies of VTEC over time

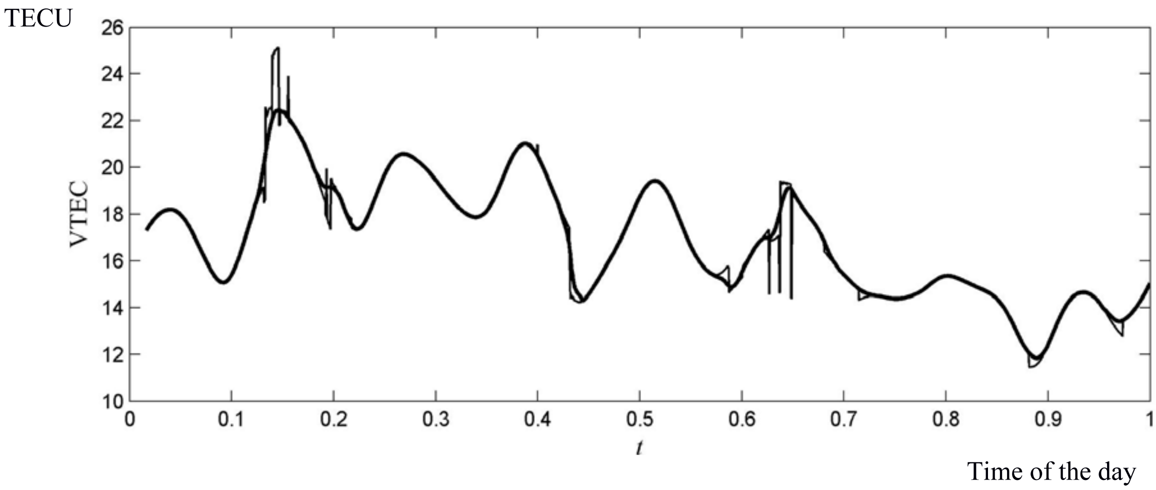


Fig. 6. Spline interpolation of the VTEC time series

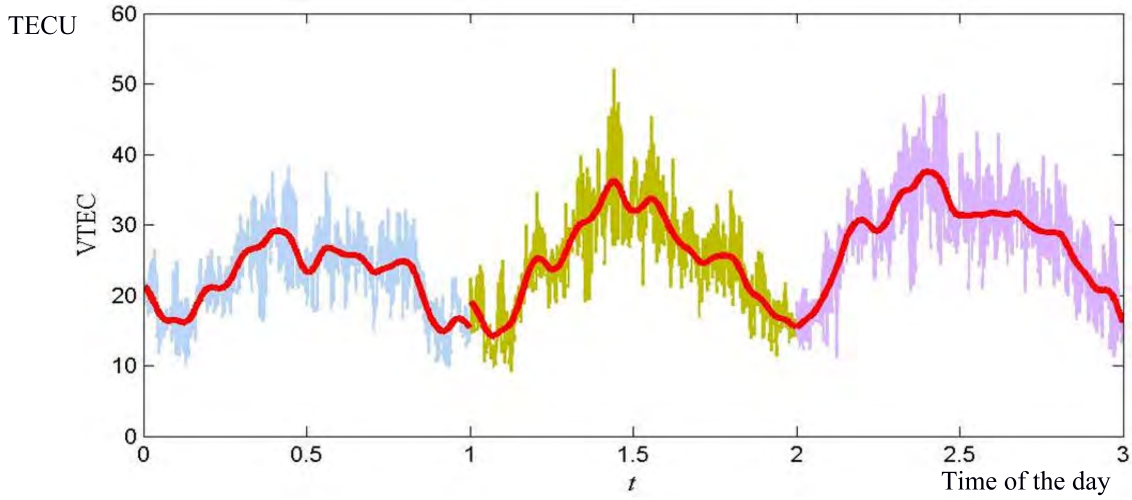


Fig. 7. Smoothing VTEC time series by approximating spline

The second program implements the approximation of the above-described splines with a wider level in determining the functional dependencies. Weak smoothing is used for this approximation as well. This fact made up for specific errors in the measured data that were caused by the peculiarities of the receiver-antenna electronic channel and close environment to the station. Simultaneously, another approximation spline was calculated with significant smoothing of the data (fig. 7). It is necessary to highlight the daily change of the *VTEC* rate.

Because of the consistent usage of these two programs, two spline approximation objects are created. One of these programs accurately approximates the measurement data. Another program includes approximation of the smoothed values for the measurement data. Due to this approach, for further *VTEC* calculations, it is sufficient to read the named objects of approximations from their files and identify *VTEC* at any moment of time using spline-computing functions according to their argument as the defined splines reflect *VTEC* changes as analytically set functions [Yankiv-Vitkovska 2013].

Conclusions

In this research, we used spline approximation to determine the smoothed *VTEC* values. This approximation is constructed using the approximation function *fit* of the software tool for curvilinear approximation "**Curve Fitting Toolbox**" of the computing system Matlab. We chose this method of smoothing based on computational experiments that were aimed at comparing different smoothing methods. In particular, during these experiments, spline approximation methods were used using the function **spaps** from "**Spline Toolbox**" and a smoothing function from "**Curve Fitting Toolbox**".

We would like to mention an important aspect concerning smoothing function *smooth*. Sometimes, in a short time interval, the *STEC* value from individual satellites undergoes significant changes. It may seem like a temporary increase in errors on the graph or "amplification" of original "measurement obstacles". Therefore, there is no reason to assume that the measurement error is less (or greater), if the data is defined using a larger number of satellites. Thus, we cannot know a priori, in which nodes of the *VTEC* time interval the error rate is higher and in which it is less, because smoothing with the smooth function leads to severe impact of short-term deviations on the smoothing results than on any other data. This disadvantage can be avoided with applying smoothing approximation using spline function *fit*. We chose the value of the parameter that describes the intensity of smoothing in experimental way using qualitative analysis of the *VTEC* time-series and their smoothed values.

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Л. ЯНКІВ-ВІТКОВСЬКА[1], С, САВЧУК[1], В. ПАУЧОК[2]

[1] Кафедра вищої геодезії та астрономії, Національний університет "Львівська політехніка", вул. С. Бандери, 12, Львів, Україна, 79013, ел.пошта: luba_y@ukr.net
[2] Тернопільський національний економічний університет

ВИЗНАЧЕННЯ ПАРАМЕТРІВ ІОНОСФЕРИ І МЕТОДИКА ЇХ ПЕРЕТВОРЕННЯ З GNSS-СПОСТЕРЕЖЕНЬ

Мета. Розв'язування задач координатно-часового забезпечення на основі безперервних GNSS-спостережень базується на опрацюванні великих масивів даних кодових та фазових вимірювань. Одним із можливих додаткових варіантів такого опрацювання є обчислення числових характеристик впливу іоносфери на поширення сигналів від супутників – значень загальної концентрації електронів *TEC*. Ці характеристики відображають динаміку іонізації атмосфери, що важливо з погляду моніторингу навколоземного простору. Масиви значень *TEC* (*STEC* і *VTEC*) такі значні, що виникає актуальна задача підготовлення даних параметрів іоносфери для їхнього подальшого аналізу та використання. Для розв'язання цієї задачі ми пропонуємо методику, що ґрунтується на комплексі програм, які перетворюють дані вимірювання *VTEC* до форми, зручної для аналізу. **Методика.** Обчислення TEC відбувається внаслідок автоматизованого опрацювання файлів GNSS-спостережень для окремої станції по кожному супутнику. Алгоритм опрацювання базується на використанні виміряних кодових і фазових псевдовідстаней у приймачі та калібрувальних коефіцієнтів. Він дає змогу отримувати значення *TEC* у двох варіантах: а) лише за фазовими вимірюваннями, попередньо використавши розв'язки фазових неоднозначностей у мережі загалом та б) лише за кодовими вимірюваннями, попередньо згладивши їх. Після чого кодові псевдовідстані згладжуються підібраними на основі апроксимованих змін фази у часі відповідними функціями. В одностанційному варіанті визначаються значення TEC над окремою станцією за вимірюваннями всіх супутників на 24-годинному інтервалі. Для перерахунку STEC у вертикальний VTEC використовується одношарова модель іоносфери. **Результати.** Для отримання просторового розподілу TEC був реалізований алгоритм багатостанційної обробки GPS вимірів з використанням мережі активних референцних станцій Західного регіону України. Мережа складається із

17 станцій, які працюють під управлінням спеціалізованого програмного забезпечення у режимі реального часу для забезпечення послугами RTK широкого кола користувачів геодезичного спрямування. **Наукова новизна:** Розроблено програму для обчислення похилих *STEC* і вертикальних *VTEC* значень *TEC*, що використовуються для читання RINEX файлів, виявлення, оцінки та усунення циклічних фазових стрибків, що виникають під час вимірювань; підпрограми для згладження кодових вимірювань, отримання диференційних поправок на момент обчислення, обчислення горизонтальних координат супутника на станцію спостережень, безпосереднє обчислення *TEC* і подальшого зберігання отриманих даних *VTEC* і *TEC* в нових файлах на сервері Львівської політехніки. Вся програма була скомпільована для операційної системи Linux і доведена до автоматизованого використання з даними спостережень перманентної IGS станції SULP. **Практична значущість.** Обчислення параметрів іоносфери на фіксовані моменти спостереження від всіх доступних GNSS-супутників.

Ключові слова: GNSS-виміри; іоносфера, іоносферні параметри; згладжування, сплайн.

Л. ЯНКИВ-ВИТКОВСКАЯ[1], С. САВЧУК[1], В. ПАУЧОК[2]

[1] Кафедра высшей геодезии и астрономии, Национальный университет “Львовская политехника”, ул. С. Бандеры, 12, Львов, Украина, 79013, эл. почта: luba_y@ukr.net

[2] Тернопольский национальный экономический университет, Украина

ОПРЕДЕЛЕНИЕ ПАРАМЕТРОВ ИОНОСФЕРЫ И МЕТОДИКА ИХ ПРЕОБРАЗОВАНИЯ С GNSS-НАБЛЮДЕНИЙ

Цель. Решение задач координатно-временного обеспечения на основе непрерывных GNSS-наблюдений базируется на обработке больших массивов данных кодовых и фазовых измерений. Одним из возможных дополнительных вариантов такой обработки является вычисление числовых характеристик влияния ионосферы на распространение сигналов от спутников – значений общей концентрации электронов *TEC*. Эти характеристики отражают динамику ионизации атмосферы, что важно с точки зрения мониторинга околоземного пространства. Массивы значений *TEC (STC* и *VTEC)* так значительны, что возникает актуальная задача подготовка данных параметров ионосферы для их дальнейшего анализа и использования. Для решения этой задачи нами предлагается методика, базирующаяся на комплексе программ, которые преобразуют данные измерения *VTEC* к форме, удобной для анализа. **Методика.** Вычисление *TEC* происходит вследствие автоматизированной обработки файлов GNSS-наблюдений для отдельной станции по каждому спутнику. Алгоритм обработки базируется на использовании измеренных кодовых и фазовых псевдорасстояний в приемнике и калибровочных коэффициентов. Он позволяет получать значение *TEC* в двух вариантах: а) только за фазовыми измерениями, предварительно использовав решения фазовых неоднозначностей в сети в целом и б) только по кодовым измерениям, предварительно сгладив их. После чего кодовые псевдорасстояния сглаживаются подобранными на основе аппроксимированных изменений фазы во времени соответствующими функциями. В одностанцийном варианте определяются значения *TEC* над отдельной станцией по измерениям всех спутников на 24-часовом интервале. Для пересчета *STEC* в вертикальный *VTEC* используется однослойная модель ионосферы. **Результаты.** Для получения пространственного распределения *TEC* был реализован алгоритм многостанционные обработки GPS-измерений с использованием сети активных референцных станций Западного региона Украины. Сеть состоит из 17 станций, которые работают под управлением специализированного программного обеспечения в режиме реального времени для обеспечения услугами RTK широкого круга пользователей геодезического направления. **Научная новизна**: Разработана программа для вычисления наклонных *STEC* и вертикальных *VTEC* значений *TEC*, используемых для чтения RINEX-файлов, выявления, оценки и устранения циклических фазовых скачков, возникающих в процессе измерений; подпрограммы для сглаживания кодовых измерений, получения дифференциальных поправок на момент вычисления, вычисления горизонтальных координат спутника на станциюнаблюдений, непосредственное вычисление *TEC* и дальнейшего хранения полученных данных и в новых файлах на сервере Львовской политехники. Вся программа была скомпилирована для операционной системы Linux и доведена до автоматизированного использования с данными наблюдений перманентной IGS станции SULP. **Практическая значимость**. Вычисление параметров ионосферы на фиксированные моменты наблюдения от всех доступных GNSS спутников

Ключевые слова: GNSS-измерения; ионосфера, ионосферные параметры; сглаживание, сплайн.

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