ГЕОДЕЗІЯ

GEODESY

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COMPARISON OF THE MEASURED VALUES OF TOTAL ELECTRON CONTENT (TEC) WITH THE CORRESPONDING TEC VALUES, OBTAINED ACCORDING TO GLOBAL IONOPHERIC MAPS (GIM) DATA

The purpose of this work lies in comparing and defining the differences between the measured values of the total electron content (TEC) and the corresponding TEC values, obtained according to global ionospheric map (GIM) data in different periods of solar activity. **Methodology.** The TEC and the data of global ionospheric maps (GIM) for the SULP station were used in the work, as well as the data from the Ionolab website for better clarity, where the nodal values of the TEC are essentially used, from the same global ionospheric maps (GIM). The essence of the research was to compare the values of TEC, obtained by the two above-mentioned methods in different periods of solar activity (a high solar activity – data for 2013, a low solar activity – for 2018). **Results.** It was determined that the differences of TEC at a low solar activity are mostly negative and reach ≈8 TECU, and at the peak of solar activity both were measured and the model TEC values were basically the same and varied in range from 0.3 to 6.8 TECU. **Scientific novelty.** The variations of the values of total electron content TEC for the SULP station in different periods of the manifestation of solar activity were obtained and given and it was established that at a low solar activity the measured TEC values prevail over the model values by more than 20 % and do not exceed ≈6 TECU, and at a high solar activity both the model and the measured values are practically the same and range approximately from 4 to 31 TECU. **Practical significance.** The results obtained can be used for constructing regional maps and the velocities and direction of ionospheric stain movements, as well as in solving some issues for a certain region.

Key words: total electron content (TEC); global ionospheric maps (GIM); the Earth's ionosphere; GNSS-measurement.

Introduction

The dynamics of the ionosphere is influenced by a number of factors, particularly, the flow of a solar ionizing radiation, geomagnetic activity, and the influence of other various meteorological phenomena. Total electron content (TEC) of the ionosphere is a generalizing physical characteristic of the ionosphere state. The development of research methods and modeling the dynamics of TEC is predetermined, first, by the scientific interest in the problem of studying the upper part of the Earth's atmosphere, as well as by the necessity of solving a number of applied tasks in the field of providing a stable radio communication, satellite navigation, and radar systems [Maslennikova & Bochkarev, 2014; Afraymovych, 2006; Zhang & Zhao, 2018].

Information about TEC may be obtained from dual-frequency GPS observations and global ionospheric maps (Global Ionospheric Maps – GIM), which are provided by various think tanks [ionospheric maps]. However, it should be noted that the uneven distribution of GNSS stations on the Earth's surface and practically its complete absence in the waters of the oceans and the polar regions significantly reduces the accuracy of TEC maps and, as a result, the effectiveness of its use [Wienia, 2008; Feltens et al., 2010; Feltens et al., 2009; Roma-Dollase et al., 2018]. This, in its turn, points to the GIM non-conformity, when taking into account the ionospheric correction for it. Hence, when solving some tasks for a particular region, there is a need for building local maps and the velocities and direction of ionospheric spot movements.

The TEC variations can serve as an indicator of the state of ionospheric plasma. Total electron content in a single atmospheric column is determined by comparing the delay in the inclined propagation path of a signal at two frequencies (1.545 and 1.226 GHz). The delay is recorded by dual-frequency receivers, which are located all over the globe and are included into the global IGS network [Yankiv-Vitkovska, 2012; Hernández-Pajares et al., 2016; Hernández-Pajares et al., 2017]. The GIM technology was developed in several research centres, providing the construction of global maps of absolute vertical TEC value of the ionosphere by interpolating data received from the IGS international service. Ionospheric maps are distributed in the format of IONEX, containing the values of vertical TEC for different regions of the globe with the discreteness: 2.5 – in latitude, 5 – in longitude and 2:00 – by time [Krankowski, 2010; Schaer, 1998]. Global ionospheric maps by the density of electron content are produced in real time by comparing the data obtained from the stationary terrestrial GPS stations. The given maps are formed in order to check the indicators in real time by marking the received data on the map. The present display of information allows the precise calibration for navigation systems. The given maps are also used to monitor the ionosphere state used to forecast ionospheric perturbations, which often arise in response to the influence of the Earth's magnetic field on the flow of a solar wind [Alizadeh, et al., 2011; Todorova, et al., 2008; Alizadeh, et al., 2015].

The results of using global ionospheric maps (GIM) in the tasks of high-precision GNSS-positioning are presented in the work of [Zhelanov, & Bezsonov, 2011]. It is shown that the use of the IGS model in the tasks of high-precision GNSS-positioning provides an acceptable level of accuracy of ionospheric delay compensation when using single-frequency observations and makes it possible to reduce the systematic component of ionospheric error two or more times, compared to the widely used Klobuchar model.

In the work of [Tereshchenko, et al., 2015] the method of operative TEC determination by the signals from GLONASS satellites was presented. The comparison of the calculated TEC values by the signals from GLONASS satellites was carried out with the TEC values obtained by the calculations of the global numerical model of the upper atmosphere of the Earth UAM and the data of global ionospheric map GIM.

Considering the fact that, according to GIM data, the spatial distribution of TEC has mostly a smooth character, as well as taking into account two-hour discreteness of the given data by time, it is quite difficult to investigate relatively fast and local processes, occurring in the ionosphere. Therefore, it is necessary to find out whether it is possible to consider such fleeting and small-scale processes due to the measured values of the TEC. In our opinion, the measured values of TEC instead of the GIM model shall also be used because of the fact that the global ionospheric maps essentially represent a degree grid of TEC values and do not include all GNSS-stations (for example, in order to produce GIM, only the data from the SULP station are used from the GNSS-stations network located in Western Ukraine). It is worth noting that the TEC nodal values interpolation slightly distorts the real values of total electron content, and a real state of the ionosphere is not always accurately displayed as a result of such a modeling. Instead, a well-developed local network ZAKPOS provides sufficient density and continuity of GNSS data, which, in its turn, allows us to more accurately describe the true character of the ionosphere at the local level.

The main purpose of the given research was to define and compare the differences between the measured values of total electron content (TEC) and the corresponding TEC values obtained from global ionospheric maps (GIM) data in different periods of solar activity.

Methodology and results

For our study, the data of total electron content (TEC) and the data of global ionospheric maps (GIM) were used, as well as the data from the Ionolab website were applied for better clarity [Ionospheric Research Laboratory: IONOLAB], where the TEC nodal values were essentially used, from the same global ionospheric maps (GIM). The data for September 2013 and July 2018 for the SULP station were processed. The time of observations was chosen, according to the cycle of solar activity. According to the data of the following website [the amount of sunspots of the progression], the minimum in the cycle of solar activity fell on 2018, and the maximum was observed in 2013 (Fig. 1). The data were taken for each day in September 2013 and July 2018 with an interval of 2 hours.

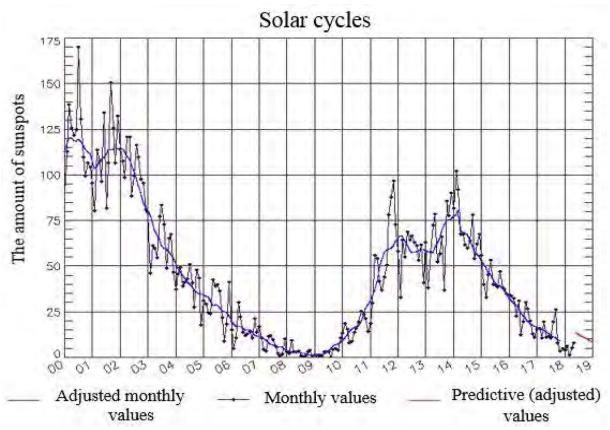

Fig. 1. The amount of sunspots of the progression

In order to analyze total electron content (TEC), it was complicated to use the data from the file, the fragment of which is presented in Fig. 2, since it is provided for each satellite separately, and over time the satellites replaced each other. Therefore, we used the program Station TEC 07102013, which was created at the Department of Higher Geodesy and Astronomy. The given program converts the VTEC data from a file, for example: [LP_ATMO_2150.16TEC], into the working files at observation stations. In Fig. 3, a sample of such a file is provided:

```
Total Electron Content (TEC)
FileName: lpi_iono_0050.18TEC
Epoch rate (sec): 15

#[Year] [Month] [Day] [Hour] [Minute] [Second] [Number of stations]
[Station code] [Number of satellites]
[Satellite id];[Vertical TEC value];[Pierce point Lat[rad]];[Pierce point Long[rad]]

#2018 01 05 12 25 45.0000000  29
SULP 14
G02;9.659;0.828601759;0.198084207
G05;10.446;0.915068084;0.299084424
G07;12.016;0.859213941;0.423104307
G09;14.621;0.863441412;0.485682797
G16;7.431;0.992132464;0.604613910
G23;10.050;0.835742118;0.621987013
G30;12.863;0.831518352;0.378857413
R01;9.823;0.906672504;0.358476652
R07;14.400;0.773683854;0.566332427
R08;13.499;0.859731803;0.443176765
R09;8.578;0.951027079;0.534958759
R10;12.959;0.862405755;0.438476240
R11;13.773;0.776843112;0.373156474
R17;12.243;1.029795572;0.186943054
DORO 13
G02;11.527;0.802068602;0.232228114
G05;10.252;0.890130397;0.337209662
```

Fig. 2. The fragment of a daily file
of total electron content (TEC)

Fig. 3: The given file was automatically generated by the program of Station TEC 07102013. The program performs VTEC data conversion from the file [lpi_iono_0050.18TEC] into the working files at the observation stations, located in [c:\TEMP\]. The working file contains the assignment operator in Matlab language. SULP_VTEC is an array of VTEC values of the SULP station. The first column of the SULP_VTEC array – is the time [0-24], in the fractions of hours of a day. The second column of the SULP_VTEC array – is the VTEC values

```
1.243e+001 1.1597e+001
1.243e+001 1.1242e+001
1.244e+001 1.1489e+001
1.244e+001 1.1722e+001
1.245e+001 1.2206e+001
1.245e+001 1.2403e+001
1.245e+001 1.2501e+001
1.246e+001 1.2493e+001
1.246e+001 1.2488e+001
1.247e+001 1.2489e+001
1.247e+001 1.2473e+001
1.248e+001 1.2150e+001
1.248e+001 1.2094e+001
1.248e+001 1.2063e+001
1.249e+001 1.2013e+001
1.249e+001 1.1994e+001
1.250e+001 1.1962e+001
1.250e+001 1.1953e+001
1.250e+001 1.1944e+001
1.251e+001 1.1937e+001
1.251e+001 1.1930e+001
1.252e+001 1.1932e+001
1.252e+001 1.1952e+001
```

Fig. 3. The fragment of a file at observation stations

It was difficult to directly use the data for the analysis from the file of global ionospheric maps (GIM), a part of which is presented in Fig. 4, because the values of in the vertical TEC are given in latitude every 2.5°, and every 5° in longitude and 2:00 – by time. Therefore, a program to simplify computations was created in the software environment of Delphi, a fragment of which is presented in Fig. 5.

```
 50.0-180.0 180.0   5.0 450.0                    LAT/LON1/LON2/DLON/H
 89  92  96 101 103 103  99  92  84  76  69  67  68  69  71  70
 67  61  56  51  47  45  44  44  44  44  44  43  42  39  35  32
 30  31  32  35  39  45  51  58  66  74  80  83  85  88  90  93
 95  96  96  96  97  98  99 100 100 100 101  99  98  95  91  88
 85  84  84  85  86  86  87  88  89
 47.5-180.0 180.0   5.0 450.0                    LAT/LON1/LON2/DLON/H
 89  93  98 104 108 108 106 100  91  83  76  72  71  72  72  71
 67  63  58  54  51  49  48  48  49  49  48  47  45  41  37  34
 32  33  34  37  41  46  53  61  70  78  84  88  90  92  95  99
102 103 103 103 103 104 106 107 107 107 107 106 104 101  97  94
 91  88  87  87  86  86  85  86  89
```

Fig. 4. The fragment of a file
of global ionospheric map (GIM)

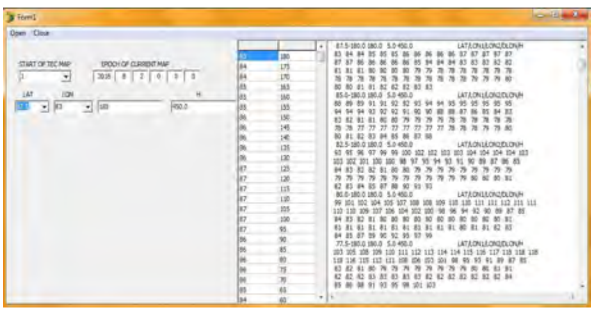

Fig. 5. A fragment of the program

The essence of our research was to compare the values of total electron content (TEC) and the global ionospheric maps (GIM), that is, in determining its differences. Also, as it was already stated, the data from the Ionolab website were provided for better clarity. According to the obtained data, the charts for September 2013 and July 2018 were created, which are represented in Fig. 6 and 7.

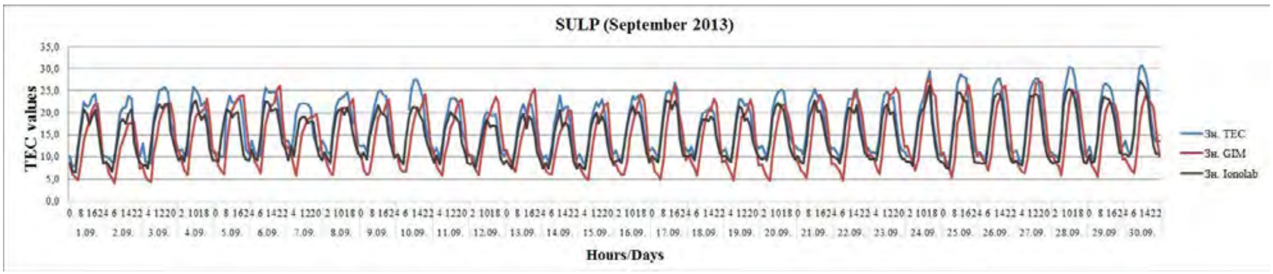

Fig. 6. Variations of the values of total electron content for the SULP station for September 2013

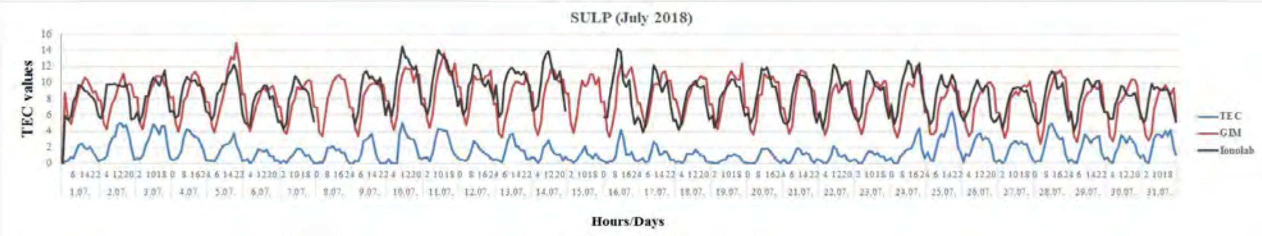

Fig. 7. Variations of the values of total electron content for the SULP station for July 2018

Analyzing the given charts, it may be stated that at a low solar activity, which was observed in 2018, the TEC values generally fluctuated between 0 and 14.9 TECU. Taking it into account, the measured TEC values prevail over the model values by more than 20 % and mainly do not exceed ≈6 TECU (see Fig. 7). As to the results, obtained in September 2013, both the measured and the model TEC values are close to each other and roughly vary in the range from 4 to 31 TECU, that is, in our opinion, directly related to the peak of the solar activity, which, as it was already noted, fell in 2013.

With the help of the MYSTAT software, we obtained the statistical characteristics of the averaged differences of TEC values, which are given in Table 1.

Table 1

Statistical characteristics of the averaged differences of TEC

	Averaged differences	
	September 2013	July 2018
Amount	30	31
Minimum	-0.1	-8.2
Maximum	6.8	-4.2
Arithmetic mean value	2.68	-6.65
Standard deviation	0.25	0.18

During the analysis of the data, it was revealed that the TEC differences for the chosen station for September 2013 are mostly positive and range from 0.3 to 6.8 TECU with a standard deviation of 0.2. In July 2018, the indicators of TEC differences are basically negative, and reach ≈8 TECU, since there was a minimum of solar activity in the given year and the measured TEC values were significantly lower than its corresponding model indexes. It should be noted that the standard deviation for the given month was also 0.2.

In Fig. 2 and 3, the statistical characteristics of the measured and model TEC values for September 2013 and July 2018, respectively, are presented.

Table 2

Statistical characteristics of the measured TEC values

	0h	2h	4h	6h	8h	10h	12h	14h	16h	18h	20h	22h
	September 2013											
Amount	29	30	30	30	30	30	30	30	30	29	29	29
Minimum	9.5	7.8	8.1	8.5	15.1	19.1	20.2	17.5	14.0	15.0	12.5	10.5
Maximum	13.7	20.9	25.4	27.5	27.4	30.4	30.8	30.0	29.5	25.1	19.7	17.5
Arithmetic mean value	11.52	10.86	10.18	13.70	20.13	23.36	24.36	23.77	23.93	21.31	15.75	12.63
Standard deviation	1.15	2.20	3.17	3.52	2.68	2.72	2.63	2.99	2.98	2.10	1.84	1.52
	July 2018											
Amount	31	31	31	31	31	31	31	31	31	31	31	31
Minimum	0.0	0.0	0.0	0.0	0.5	0.6	0.9	0.9	0.8	0.7	0.1	0.0
Maximum	1.4	1.3	0.9	2.2	3.5	5.1	5.0	5.0	6.0	6.4	4.6	2.1
Arithmetic mean value	0.43	0.34	0.24	0.91	1.99	2.74	2.86	2.45	2.38	2.24	1.96	0.87
Standard deviation	0.30	0.28	0.29	0.64	0.90	1.09	1.12	1.16	1.24	1.43	1.29	0.65

According to the data in Tabl. 2, it is clear that in September the measured TEC values are in the range from 7.8–30.8 TECU with a standard deviation of 1.1–3.5 TECU. In July, the measured TEC values varied from 0 to 6.4 TECU, and the standard error of the arithmetic mean value varied from 0.3 to 1.4 TECU.

Table 3

Statistical characteristics of the model TEC values

	0h	2h	4h	6h	8h	10h	12h	14h	16h	18h	20h	22h
	September 2013											
Amount	30	30	30	30	30	30	30	30	30	30	30	30
Minimum	7.6	5.5	4.8	4.1	8.9	12.2	13.4	15.9	17.5	17.7	17.9	12.5
Maximum	12.5	10.3	8.8	7.0	12.3	18.3	22.3	26.8	27.9	26.9	26.3	19.2
Arithmetic mean value	9.92	7.91	6.74	5.62	10.28	15.37	19.17	21.34	22.24	22.84	21.92	15.83
Standard deviation	1.34	1.21	1.01	0.78	0.84	1.54	2.21	2.77	2.55	2.12	2.04	1.73
	July 2018											
Amount	31	31	31	31	31	31	31	31	31	31	31	31
Minimum	5.5	3.4	2.4	3.8	6.6	7.7	8.1	8.5	8.9	9.2	8.5	8.6
Maximum	9.5	6.6	4.9	6.3	9.7	11.2	12.5	13.7	13.2	12.9	14.9	12.5
Arithmetic mean value	7.36	4.64	3.70	5.12	7.69	8.99	9.89	10.28	10.50	10.44	10.20	10.20
Standard deviation	0.96	0.81	0.62	0.77	0.74	1.03	1.07	1.18	0.92	0.88	1.15	1.02

As it is shown in Tabl. 3, the model TEC values during high solar activity (September 2013) range approximately from 4 to 28 TECU with a standard error ≈0.8–2.8 TECU. During low solar activity (July 2018), the standard error of the arithmetic mean value was 0.6–1.2 TECU, and the model values ranged from 2.4 to 14.9 TECU.

Conclusions

On the basis of the conducted research, which consisted in identifying and comparing the differences between the measured values of total electron content (TEC) and the corresponding TEC values, obtained according to the global ionospheric maps (GIM) data, the following was established:

1) during low solar activity the absolute TEC values – the measured ones, prevail over the corresponding model values by more than 20 % and, on average, do not exceed 6 TECU, and the indicators of TEC differences are basically negative, and reach ≈8 TECU;

2) during high solar activity, both model and measured values are practically the same and range from 4 to 31 TECU, its differences are mostly positive and range from 0.3 to 6.8 TECU;

3) when considering the ionospheric correction using global ionospheric maps, the maximum and the minimum solar activity should be taken into account.

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ПОРІВНЯННЯ ВИМІРЯНИХ ВЕЛИЧИН ЗАГАЛЬНОГО ВМІСТУ ЕЛЕКТРОНІВ (TEC) З ВІДПОВІДНИМИ ЗНАЧЕННЯМИ TEC, ОТРИМАНИХ ЗА ДАНИМИ ГЛОБАЛЬНИХ ІОНОСФЕРНИХ КАРТ (GIM)

Мета роботи полягає у визначенні та порівнянні різниць між виміряними величинами загального вмісту електронів (TEC) та відповідними значеннями TEC, отриманих за даними глобальних іоносферних карт (GIM) у різні періоди сонячної активності. **Методика.** У роботі використано дані загального вмісту електронів (TEC) та дані глобальних іоносферних карт (GIM) для станції SULP, а також для кращої наочності взято дані з сайту Ionolab, де по суті використано вузлові значення TEC, з тих самих глобальних іоносферних карт (GIM). Суть досліджень полягала у порівнянні значень (TEC), отриманих двома вищевказаними методами в різні періоди сонячної активності (висока сонячна активність – дані за 2013 рік, низька сонячна активність – 2018 рік). **Результати.** Визначено, що різниці (TEC) за малої сонячної активності здебільшого від’ємні і сягають ≈8 TECU, а за піку сонячної активності і виміряні, і модельні значення TEC переважно однакові і коливаються в межах від 0.3 до 6.8 TECU. **Наукова новизна.** Отримано та наведено варіації значень загального вмісту електронів TEC для станції SULP на різні періоди прояву сонячної активності та встановлено, що за низької сонячної активності виміряні величини TEC переважають модельні значення більш ніж на 20 % і не перевищують ≈6 TECU, а за високої сонячної активності і модельні, і виміряні значення практично однакові і приблизно коливаються в межах від 4 до 31 TECU. **Практична значущість.** Отримані результати можна використати для побудови регіональних карт та швидкостей і напрямку руху іоносферних плям, вирішення деяких завдань для певного регіону.

Ключові слова: загальний вміст електронів (TEC), глобальні іоносферні карти (GIM), іоносфера Землі; GNSS-вимірювання.

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