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ANALYSIS OF THE TROPOSPHERIC DELAY ESTIMATES IN SOFTWARE PACKAGE – GIPSYX BASED ON MULTI-GNSS OBSERVATIONS

The emergence and establishment of the Global Navigation Satellite System (GNSS), namely the USA Global Positioning System (GPS), the Russian Global Navigation Satellite System (GLONASS), the European Galileo and the Chinese BeiDou systems, have led to wide possibilities of their application not only for positioning tasks, but also for atmospheric research. The **purpose** of this work is to study the accuracy of tropospheric delay estimates based on multi-GNSS observations data with using a GipsyX software package. **Methodology**. In this work it was analyze the multi-GNSS data, obtained from observations on the GNSS station GANP during July of 2018. Data processing was performed in the GipsyX software package, based on the Precise Point Positioning (PPP) method. The processing strategy of multi-GNSS observations envisaged five solutions: four separate – "GPS only", "GLONASS only", "Galileo only" and "BDS only", and one combined, which included "GPS + GLONASS+ Galileo + BDS" observations data. The gotten values of Zenith Tropospheric Delay (ZTD) were compared with the corresponding values from the atmosphere radio sounding data from located near aerological station – 11952 Poprad-Ganovce. **Results.** The values obtained from the data of multi-GNSS observations indicate that they are highly consistent with atmospheric radio sounding data within 30 days. The results of this experiment confirm that the use of all possible full-fledged satellite navigation systems provides better accuracy than "only GPS", "only GLONASS", "only Galileo" or "only BDS", with the accuracy of the definition increased by 25 %. **Scientific novelty and practical significance.** It was established that the accuracy of tropospheric delay estimates based on multi-GNSS observations exceeds the accuracy of tropospheric products obtained during GNSS observations processing from one satellite navigation system. This result are a novelty product for the GNSS community.

Key words: Global Navigation Satellite Systems (GNSS); Zenith Tropospheric Delay (ZTD); Precise Point Positioning (PPP); multi-GNSS, atmospheric research.

Introduction

Over the last one-two years began a new era of significant change and innovation in the field of geodesy and navigation with multi-channel Global Navigation Satellite System (GNSS). A few years ago the USA Global Positioning System (GPS) was actually the only fully functional system that dominated in positioning and navigation around the world, but now the situation has changed and three other satellites constellation attracted the attention of the international community. Since 2011 began full operation of GLONASS, and in recent years China and Europe have built their own independent global navigation systems BeiDou and Galileo. To improve the accuracy, reliability and availability of data from GNSS it was also developed satellite additions SBAS (Satellite Based Augmentation System) at continental and regional levels.

Currently GNSS is the standard generic term for satellite navigation systems that provide autonomous geospatial positioning with global coverage. As this term also includes a constellation of global navigation systems satellites (GPS, GLONASS, Galileo, BeiDou) and SBAS GEO-satellites from regional navigation systems, then it is interpreted as multi-GNSS.

To date, in the operation are the following satellite navigation systems:

– American GPS;
– Russian GLONASS (GLObal NAvigation Satellite System);
– European Galileo;
– Chinese BDS (BeiDou System);
– Indian IRNSS (Indian Regional Navigation Satellite System), with the operating name NAVIC;
– Japanese QZSS (Quasi-Zenith Satellite System).

The total number of working satellites that are available for multi-GNSS observations, reaching to 120 units.

At the initiative of the International GNSS service (IGS) in the 2012 appeared the project Multi-GNSS-Experiment (MGEX) [http://mgex.igs.org], the main objective of which is tracking, comparison and analysis of all available GNSS signals. Within this project, to users became available: multi-GNSS final ephemeris and clock corrections of satellites; combined multi-GNSS broadcast ephemeris; Earth orientation parameters, multi-GNSS biases. Now they cover up to six global or regional navigation satellite systems (ie GPS, GLONASS, Galileo, BDS, QZSS, NAVIC).

Most of the stations in the MGEX network track signals of GPS, GLONASS, and at least another of Galileo, BDS etc. [Montenbruck et al., 2017].

The success of multi-GNSS significantly improved operational flexibility of positioning; however, this system also increased the number of applications that use GNSS, for example, atmospheric research.

In recent years, Precise Point Positioning (PPP) are increasingly being used for high-precision processing of GNSS observations data, as it allows to assess accurately the coordinates of GNSS-station and does not require nearest base station. The PPP method based on using the precise ephemeris and clock corrections of satellites [Zumberge et al., 1997]. This method is implemented in software products that meet the different strategies and use precise ephemeris from different sources, but, so far, PPP mainly associated with the software package GIPSY-OASIS, or rather, its improved version– GipsyX [https://gipsy-oasis.jpl.nasa.gov/], that was developed by Jet Propulsion Laboratory (JPL) of California Technical Institute. JPL began developing of this software package in 1985, and since that time it has developed and improved. The current version running on operating system UNIX and can be used to study not only the data of GNSS, but also Satellite Laser Ranging (SLR), Doppler Satellite Positioning (Détermination d'Orbite et Radiopositionnement Intégré par Satellite, DORIS) and others [Gregorius, 1996]. In case of zenith troposphere delay (ZTD) estimates, PPP method has significant advantages in efficiency and flexibility of processing.

Aim

The aim of this work is to study the accuracy of tropospheric delay estimates by multi-GNSS observations in software package GipsyX.

Methodology

In this study data of multi-GNSS observations from the station of MGEX project processed in PPP mode with using a software package GipsyX. Observed signals processed using linear combinations of GNSS-observations that are free from the influence of the ionosphere (Ionosphere-Free, IF) [Seeber, 2008]. Obtained in this way ZTD values compared with the corresponding results of atmosphere radio sounding data, to assess the accuracy of gotten values of the tropospheric delay.

Generalized model of GNSS- data processing has been extended for multi-GNSS observations with regard to the identified displacements between different constellations of satellites. So, IF -combination of each satellite navigation systems separately for code (pseudo-distance P) and phase (pseudo-distance L) observations between GNSS-station r and corresponding satellite s (conventionally marked as G – GPS, R – GLONASS, E – Galileo and C – BDS), can be structured in the form of formulas (1) and (2).

$$\begin{cases} P_{r,IF}^{G} = \rho_r^G + c\left(t_r - t^G\right) + c\left(b_{r,IF}^{G} - b_{IF}^{s,G}\right) + T_r^G + e_{r,IF}^{G} \\ P_{r,IF}^{R} = \rho_r^R + c\left(t_r - t^R\right) + c\left(b_{r,IF}^{R} - b_{IF}^{s,R}\right) + T_r^R + e_{r,IF}^{R} \\ P_{r,IF}^{E} = \rho_r^E + c\left(t_r - t^E\right) + c\left(b_{r,IF}^{E} - b_{IF}^{s,E}\right) + T_r^E + e_{r,IF}^{E} \\ P_{r,IF}^{C} = \rho_r^C + c\left(t_r - t^C\right) + c\left(b_{r,IF}^{C} - b_{IF}^{s,C}\right) + T_r^C + e_{r,IF}^{C} \end{cases} \tag{1}$$

$$\begin{cases} L_{r,IF}^{G} = \rho_r^G + c\left(t_r - t^G\right) + \lambda_{IF,G}\left(N_{r,IF}^{G} + B_{r,IF}^{G} - B_{IF}^{s,G}\right) + T_r^G + e_{r,IF}^{G} \\ L_{r,IF}^{R} = \rho_r^R + c\left(t_r - t^R\right) + \lambda_{IF,R}\left(N_{r,IF}^{R} + B_{r,IF}^{R} - B_{IF}^{s,R}\right) + T_r^R + e_{r,IF}^{R} \\ L_{r,IF}^{E} = \rho_r^E + c\left(t_r - t^E\right) + \lambda_{IF,E}\left(N_{r,IF}^{E} + B_{r,IF}^{E} - B_{IF}^{s,E}\right) + T_r^E + e_{r,IF}^{E} \\ L_{r,IF}^{C} = \rho_r^C + c\left(t_r - t^C\right) + \lambda_{IF,C}\left(N_{r,IF}^{C} + B_{r,IF}^{C} - B_{IF}^{s,C}\right) + T_r^C + e_{r,IF}^{C} \end{cases} \tag{2}$$

where $P_{r,IF}^{s}$ – ionosphere-free code pseudo-distances; $L_{r,IF}^{s}$ – ionosphere-free phase pseudo-distances; ρ_r^s – geometric distance between GNSS-station and satellite; c – speed of light in vacuum; t_r – clock displays at the station; t^s – clock displays at the satellite; $\lambda_{IF,G}$ – wavelength of IF -combinations; $b_{r,IF}^{G}$ and $b_{IF}^{s,G}$ – delays in equipment for code observations; $B_{r,IF}^{G}$ and $B_{IF}^{s,G}$ – delays in equipment for phase observations; $N_{r,IF}^{s}$ – phase ambiguity; T_r^s – tropospheric delay, which is in the main interest in this study; $e_{r,IF}^{s}$ – disregarded effects (noise of receiver, multiply beam, etc.).

Important is that delays in equipment for code observations ($b_{IF}^{s,G}, b_{IF}^{s,R}, b_{IF}^{s,E}, b_{IF}^{s,C}$) and phase observations ($B_{IF}^{s,G}, B_{IF}^{s,R}, B_{IF}^{s,E}, B_{IF}^{s,C}$) of different satellite navigation systems vary across of different frequencies. These delays in GPS system equal to zero, for BDS and Galileo systems input Inter-System Biases (ISBs), and Inter-Frequency Bias (IFB) determined for each frequency of GLONASS in data processing mode of multi-GNSS observations [Cuixian et al., 2018].

Uncalibrated phase delay (UPD), that distort integer character of ambiguity, must be clearly defined for reliable fixation for ambiguity. In the case of processing data from various navigational systems the values of UPD should be evaluated primarily [Li et al., 2013].

The above processing algorithm of multi-GNSS observations laid in the foundation of software package GipsyX that in recent years has been expanded and improved in order to study data from different satellite navigation systems on capabilities level of existing GPS-observations processing. Figure 1 shows the simplified flowchart of this software package.

The result of *gd2e.py* run is not only the final coordinates of the observation point, which is concentrated in a file called *smoothFinal.tdp*, but also three other important files.

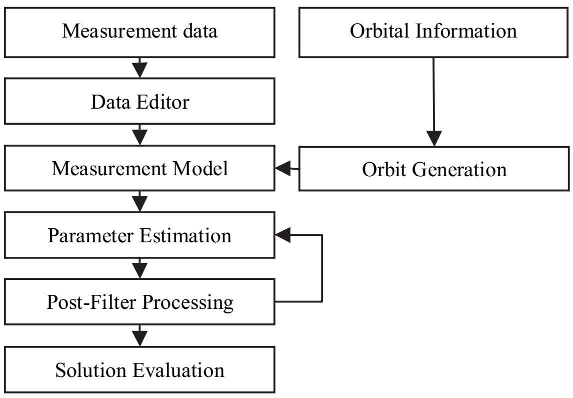

Fig. 1. GipsyX flowchart

To restart subroutines it creates an executable script called *runAgain*, allowing the user to save previous settings or make changes. In addition, errors are going to save in *rtgx_ppp_0.tree.err0_0*, and *rtgx_ppp_0.tree.log0_0* file gathers information on processing.

An important aspect in GipsyX data processing is configuration of the program tree functions. It is necessary to prescribe the types of observational data in accordance with the possibilities of selected GNSS-station. Tree functions fragment for processing multi-GNSS observations in the software package GipsyX shown in Fig. 2.

Since this work aims is to explore the possibilities of tropospheric delay estimates by the PPP method based on multi-GNSS observations it is necessary to choose GNSS-station, which would be close in location to the aerological station and was able to receive data from several satellite navigation systems. Based on these requirements, it was selected GNSS-station from MGEX project – GANP (Gánovce, Slovakia), as this station is located in 1 km from the aerological station 11952 Poprad-Ganovce and can track satellites of four constellations – GPS, GLONASS, Galileo and BDS. Location of those stations is shown on Fig. 3, and their geographic coordinates φ and λ, absolute heights H and the distance between them D given in the Table 1.

```
...
IonoFreeL_1C_2W
...
IonoFreeC_1C_2W
...
          Platforms. * GPS. *
...
IonoFreeL_2I_7I
...
IonoFreeC_2I_7I
...
          Platforms. * C. *
...
IonoFreeL_1X_8X
...
IonoFreeC_1X_8X
...
          Platforms. * E. *
...
IonoFreeL_1C_2P
...
IonoFreeC_1P_2P
...
          Platforms. * R. *
...
```

Fig. 2. Tree functions fragment of GipsyX

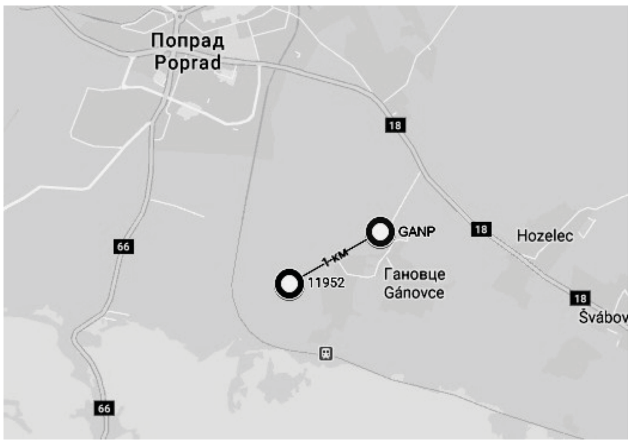

Fig. 3. Location of GNSS-station GANP and aerological station 11952Poprad-Ganovce

Table 1

Station coordinates

Aerological station 11952 Poprad-Ganovce			GNSS-station *GANP*			D, km
φ, °	λ, °	H, *m*	φ, °	λ, °	H, *m*	
49.0	20.3	706	49.0	20.3	745	<1

Since these stations are of different heights, respectively, meteorological parameters and height of the aerological station were reduced to the GNSS-station by interpolation method. During the processing of radio sounding data, a special program was used – *atmsound.exe* – developed by LPI Analysis Center

(Department of Higher Geodesy and Astronomy, Lviv Polytechnic National University, Ukraine). In this program radio sounding data downloaded from the Website of the Atmospheric Research Service of the University of Wyoming (Canada) [http://weather.uwyo.edu/upperair/sounding.html]. After this downloading, ZTD values is calculated ZTD by integrating vertical profiles of sounding data with the addition of the standard model of the atmosphere. The main window of calculations in *atmsound.exe* is shown on Fig. 4.

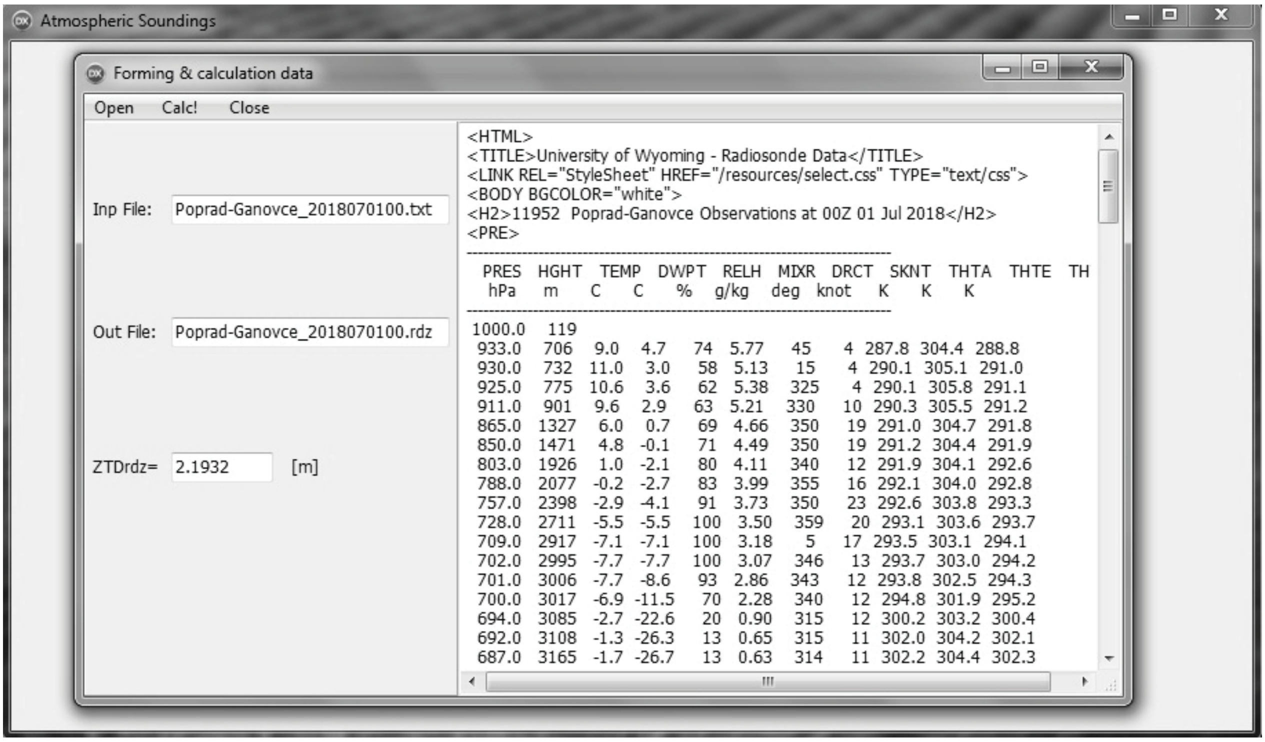

Fig. 4. Main window of calculations in atmsound.exe

GNSS-station GANP is tracking four satellite constellations from the middle of 2018. Therefore, we have processed multi-GNSS observations on July of 2018 (182–212 GPS-days). Observations data from the GANP station was selected in format RINEX (Receiver INdependent EXchange) Version 3.03 [ftp://igs.org/pub/data/format/rinex303.pdf], because for processing multi-GNSS, files must contain tracking data of several satellite navigation systems, each with different types of observations. Despite the fact, that JPL not produces ephemeris and clock corrections for four constellations, GipsyX has the ability to process multi-GNSS observations using other data sources. As precise ephemeris and clock corrections of satellites there were used files of Analysis Center CODE (Center for Orbit DEtermination) – CodeMGEX3. Required data was downloaded from MGEX FTP servers [http://mgex.igs.org].

Results

Data obtained from GNSS-station GANP and Analysis Center CODE, were processed in PPP mode using a software package GipsyX. To determine ZTD values there were used combined empirical model of Global Pressure and Temperature GPT2 [Lagleretal., 2013] and Global Mapping Function GMF [Boehmetal., 2006]. The value cut of angle was set to 7.

To obtain reliable ZTD values by processing data of multi-GNSS observations it is the necessary condition the phase ambiguity solution. The criterion for such discrepancies is the numerical characteristics of the differences between phases ambiguity. On Fig. 5 is shown difference between the phase ambiguity on GNSS-station GANP on 00.00 hour of each day during July 2018, resulting in processing of multi-GNSS observations: vertical – the difference between the phase ambiguity (residuals) in mm; horizontally – GPS-day.

From Fig. 5 it is clear that for all available satellite navigation systems, the differences between phases ambiguity are in one order and within ± 0.04 mm. Such result allows to assert, that in the processing of multi-GNSS observations, other unknown parameters can be evaluated, in particular ZTD.

ZTD values obtained in the processing with using GipsyX compared with their corresponding values obtained from radio sounding data calculation in program *atmsound.exe.* The resulting differences in the corresponding values at 00.00 during July 2018 at the GNSS station GANP and aerological station 11952 Poprad-Ganovce are summarized in Table 2.

As can be seen from Table 2, full exhaustion of satellite navigation systems (multi-GNSS) provides the best accuracy of the results processing.

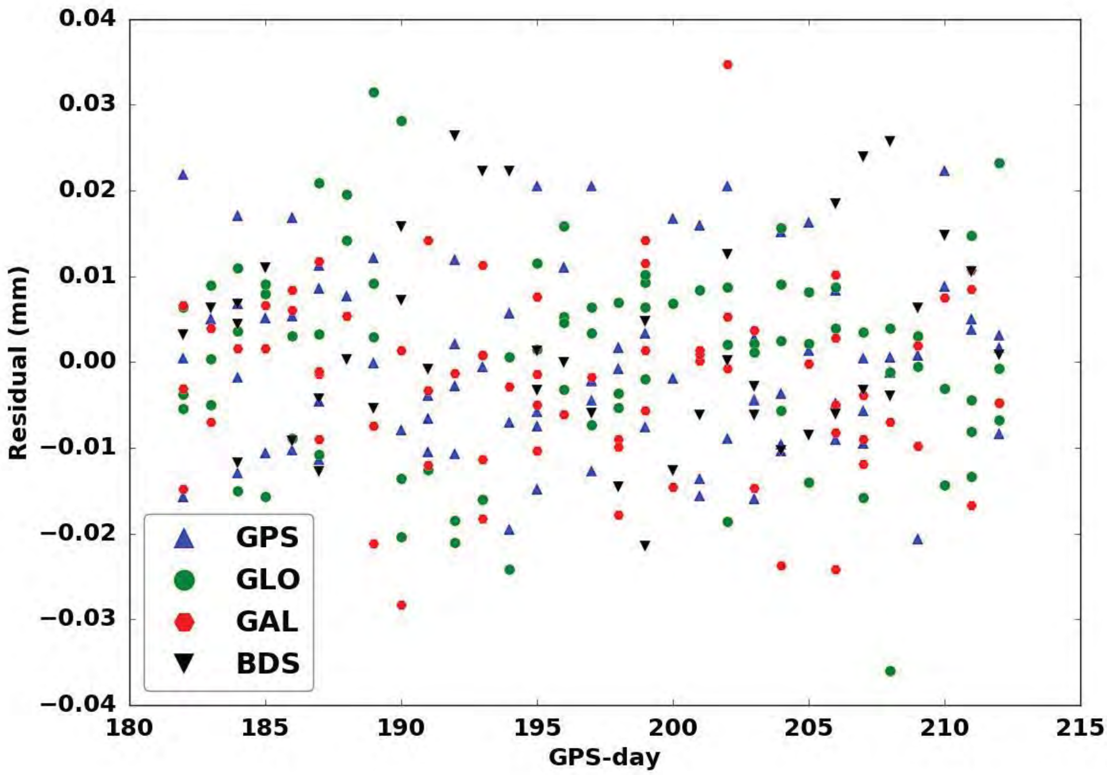

Fig. 5. Differences between the phase residuals of the GNSS station GANP during July 2018 at 00.00

Table 2

ZTD **value differences**

GPS-day	*182*	*183*	*184*	*185*	*186*	*187*	*188*	*189*	*190*	*191*
Multi-GNSS	**0.000**	**.0155**	**0.008**	**0.014**	**0.012**	**0.015**	**0.018**	**0.015**	**0.022**	**0.022**
GPS	-0.009	.0049	-0.004	0.009	0.006	0.010	0.006	0.010	0.016	0.025
GLO	0.008	.0158	0.007	0.019	0.010	0.011	0.012	0.013	0.017	0.018
GAL	-0.006	.0190	0.007	0.015	0.005	0.013	0.021	0.014	0.027	0.026
BDS	-0.016	-0.1328	-0.012	0.010	0.006	-0.003	0.009	-0.009	-0.021	0.015
GPS-day	*192*	*193*	*194*	*195*	*196*	*197*	*198*	*199*	*200*	*201*
Multi-GNSS	**0.004**	**0.025**	**0.013**	**0.017**	**0.002**	**0.009**	**-0.008**	**0.011**	**0.011**	**0.012**
GPS	0.006	0.039	0.006	0.014	-0.009	-0.004	-0.013	-0.018	0.004	0.002
GLO	0.003	0.028	0.010	-0.320	0.007	0.007	-0.008	0.009	0.011	0.011
GAL	0.007	0.057	0.012	0.018	0.002	0.023	0.002	0.003	0.007	0.007
BDS	0.026	0.072	0.033	-0.011	0.003	-0.012	-0.023	-0.010	0.011	0.002
GPS-day	*202*	*203*	*204*	*206*	*207*	*208*	*209*	*210*	*211*	*212*
Multi-GNSS	**0.015**	**0.029**	**0.022**	**0.029**	**0.012**	**0.020**	**0.014**	**0.001**	**0.006**	**-0.008**
GPS	0.007	0.012	0.019	0.016	0.000	-0.001	0.000	-0.013	-0.011	-0.012
GLO	0.016	0.028	0.021	0.027	0.024	0.017	0.016	0.004	0.013	-0.004
GAL	0.013	0.020	0.030	0.034	0.013	0.011	0.010	0.006	0.012	-0.005
BDS	0.004	-0.006	0.010	0.032	0.021	0.014	0.001	0.001	0.007	0.012

Scientific novelty and practical significance

The results of this experiment suggest that the accuracy of the tropospheric delay estimates based on multi-GNSS observations exceeds the accuracy of tropospheric products obtained as a result of the processing of GNSS observations from a single satellite navigation system. Thus, the results of the study show that on 0.00 hour during July of 2018 compared to systems “only GPS” and “only GLONASS”, the average number of effective signals for multi-GNSS increases 3 times, “only Galileo” – in 7 , and “only BDS” – almost 10 times. Accordingly in our experiment, the accuracy of tropospheric delay estimates based on GNSS observations from four satellite navigation systems at the same time points as compared with the results of processing from a separate satellite system increases by about 25 %.

The results are a novelty product for the GNSS community, which improves the accuracy and reliability of observations data.

Conclusions

This paper presents studies of the tropospheric delay estimates accuracy based on data from multi-

GNSS observations using the software package – GipsyX. For research was used GNSS-station of project MGEX–GANP (Gánovce, Slovakia) and newly products CODE, and the obtained results were compared with radio sounding data.

Overall, the tropospheric delays obtained by data of multi-GNSS observations show a high consistency with the radio sounding data.

The results show that compared with the system "GPS only", "only GLONASS", "only BDS", "Galileo only" average number of effective signals for multi-GNSS increases in 5.7 times on 0.00 hour during the July of 2018, the accuracy of tropospheric delay estimates increases by 25 %.

Considering that the number of GNSS-signals using four satellite navigation systems increases significantly, it is obvious that the combined multi-GNSS system can greatly improve the spatial and temporal resolution imaging tropospheric tomography, which has potential for applications in the future.

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АНАЛІЗ ВИЗНАЧЕННЯ ТРОПОСФЕРНИХ ЗАТРИМОК У ПАКЕТІ ПРОГРАМНОГО ЗАБЕЗПЕЧЕННЯ GIPSYX НА ОСНОВІ МУЛЬТИ-GNSS СПОСТЕРЕЖЕНЬ

Поява і становлення багатоканальних глобальних навігаційних супутникових систем (Global Navigation Satellite System, GNSS), а саме Глобальної системи позиціонування США (Global Positioning System, GPS), російської Глобальної навігаційної супутникової системи (ГЛОНАСС), європейської Galileo і китайської BeiDou систем зумовили можливість широкого їх застосування не тільки для завдань позиціонування, а також і для проведення атмосферних досліджень. **Метою** цієї роботи є дослідження точності визначення тропосферних затримок із мульти-GNSS спостережень із використанням пакета програмного забезпечення GipsyX. **Методика.** У роботі проаналізовано дані мульти-GNSS, отримані зі спостережень на GNSS-станції GANP впродовж липня 2018 р. Опрацювання даних виконано у пакеті програмного забезпечення GipsyX, в основу якого покладено абсолютний метод точного позиціонування (Precise Point Positioning, PPP). Стратегія опрацювання мульти-GNSS спостережень передбачала п’ять розв’язків: чотири окремих – “тільки GPS”, “тільки ГЛОНАСС”, “тільки Galileo” та “тільки BDS” і один комбінований, що містив дані спостережень “GPS+ГЛОНАСС+Galileo+BDS”. Отримані значення зенітної тропосферної затримки (Zenith Tropospheric Delay, ZTD) порівняно з відповідними значеннями за даними радіозондування атмосфери розташованої неподалік аерологічної станції 11952 Poprad-Ganovce. **Результати**. Отримані за даними мульти-GNSS спостережень значення ZTD демонструють високу узгодженість із даними радіозондування атмосфери упродовж 30 днів. Результати цього експерименту підтверджують, що використання усіх можливих повноцінних супутникових навігаційних систем забезпечує вищу точність опрацювання порівняно з “тільки GPS”, “тільки ГЛОНАСС”, “тільки Galileo” чи “тільки BDS”, а точність визначення ZTD збільшується на 25 %. **Наукова новизна та практична значущість.** Встановлено, що точність визначення тропосферних затримок на основі мульти-GNSS спостережень перевищує точність тропосферних продуктів, отриманих у результаті опрацювання даних GNSS-спостережень від однієї супутникової навігаційної системи. Отримані результати є новинним продуктом для спільноти GNSS.

Ключові слова: глобальні навігаційні супутникові системи (Global Navigation Satellite Systems, GNSS); зенітна тропосферна затримка (Zenith Tropospheric Delay, ZTD); абсолютний метод точного позиціонування (Precise Point Positioning, PPP); мульти-GNSS, атмосферні дослідження.

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