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COMPARISON OF APPROACHES TO ZENITH TROPOSPHERIC DELAY DETERMINATION BASED ON DATA OF ATMOSPHERE RADIO SOUNDING AND GNSS OBSERVATION

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Currently, Global Navigation Satellite Systems (GNSS) are increasingly used in atmospheric monitoring tasks. To determine tropospheric delays, two approaches are most often used: the calculation of atmospheric radio sounding data and the processing of GNSS observations. GNSS processing is, generally, based on two methods, namely precise point positioning (PPP) and double-differencing (DD). PPP is a potent data analysis instrument sensitive to a variety of parameters. This paper demonstrates that PPP can be used not only for positioning and navigation but also for other atmospheric monitoring tasks. **Purpose.** Realization of a comparative analysis of various approaches for tropospheric delays determination based on the results of GNSS observations processing by the PPP and DD methods, and on atmospheric radio sounding data. **Methodology.** The observation data from following GNSS stations were used: BUCU (Bucharest, Romania), GANP (Ganovce, Slovakia) and GLSV (Kyiv, Ukraine), as well as, located nearby, aerological stations 15420 (Bucharest, Romania), 11952 (Poprad-Ganovce, Slovakia), 33345 (Kiev, Ukraine). Therefore, in this work the zenith tropospheric delay (ZTD) determination is performed according to GNSS observation data using the PPP method with the application of the software package GIPSY-OASIS and the DD method by means of the Bernese GNSS Software and GAMIT-GLOBK software packages. The obtained results were compared with the corresponding radio sounding data. **Results**. The ZTD values obtained using different approaches correspond to a sub-centimeter level of accuracy with respect to radio sounding data, while the best results were obtained by the PPP method at Slovak stations (millimeter level), where the distance between the location of the aerological and GNSS stations is less than 1 km, i.e. they are in the same atmospheric conditions. This suggests that the PPP method provides a better level of accuracy and can be used precisely to determine tropospheric delays. **Scientific novelty, practical significance.** The technology of continuous atmospheric monitoring using GNSS stations and observations processing technology from these stations based on the absolute positioning PPP. The obtained results after their completion can be used in thoughtful investigations of tropospheric effects through GNSS observations and for numberous atmospheric monitoring applications.

Key words: precise point positioning (PPP), zenith tropospheric delay (ZTD), atmospheric radio sounding, GNSS-observation, atmospheric monitoring.

Introduction

At the present stage of space geodesy development, Global Navigation Satellite Systems (GNSS) are becoming increasingly widespread for atmospheric monitoring. The propagation delays of the GNSS signal through atmospheric layers depends on the properties of these layers, such as the troposphere's temperature, pressure and water vapor. However, the numerical characteristics of the signal which are delayed in the troposphere only provide information about the integral properties of the atmosphere [Kablak & Savchuk, 2012].

Different approaches are used to analyze the tropospheric delay, the most common of which are the atmosphere radio sounding and processing of GNSS observations. The radio sounding is conducted at aerological stations, providing information about vertical profiles of pressure, temperature and relative humidity. This is the sole approach for directly obtaining atmospheric parameters. Its significant disadvantage is a long period of one session usage during which abrupt changes of meteorological conditions are possible [Savchuk & Zablotskyj, 2014].

In turn, GNSS observations are characterized by high accuracy of results and independence on meteorological conditions. The analysis of data obtained from GNSS observations is based on the precise point positioning (PPP) method and the classical method of double differences (DD). PPP does not need any synchronous observations from a nearby GNSS station, but can reproduce the positioning accuracy with a high computational efficiency [Zumberge et al., 1997], while DD method require at least two stations. PPP has not been widely used because of its sensitivity to all error sources: errors of satellite coordinates, the influence of propagation environment and external influences. At present, PPP method can provide 1 millimeter accuracy of the processing results and can be used to solve various monitoring tasks, including atmosphere monitoring. A number of specialized programs exist that allow data processing using PPP, namely GIPSY-OASIS and Bernese GNSS Software.

For example, most E-GVAP analysis centers use DD processing, not PPP. In the majority, this is because for all tasks almost all European centers use Bernese GNSS Software, which satisfy the high accuracy of the DD method, while the PPP method in this software package is not well-developed.

The joint work of Uzhhorod National University (Lead Partner) and its partners – University of Miskolc (Miskolc, Hungary), Vihorlat Observatory (Humenne, Slovakia), Association Center for Research, Innovation and Technology Transfer "NORDTech" (Baia Mare, Romania), and International Association of Regional Development Institution “IARDI” (Uzhhorod, Ukraine) has resulted in the project HUSKROUA/1101/252 (SES project) [http://meteognss.net/]. At present, the system of remote monitoring the atmosphere of the cross-border area is processing observations from about 40 active reference stations of Borsod-Abaúj-Zemplén region (Hungary), Prešovsky region (Slovakia), Maramures county (Romania) and western part of Ukraine (Transcarpathian and Ivano-Frankivsk regions as well as part of Lviv region) [Kablak et al., 2016]. The process of obtaining data of the spatial and temporal distribution of the water vapor based on the values of tropospheric are delayed over the indicated region the ALBERDING GNSS STATUS Software package as a part of the SES project has been developed and tested.

The ALBERDING GNSS STATUS Software package uses streams of initial data of reference GNSS stations in real time and PPP approach for the determination of tropospheric delay values of each observation station. The given package is based on the ALBERDING EURONET software module and uses additional external software components RTCM3EPH, IGS01, CLK11 [Alberding, 2016-1017].

The PPP method can be widely used in meteorological application because it does not require the baseline length constraint and calibration such as the relative positioning. The problem arises from the fact that in PPP, the tropospheric estimates are greatly affected by the fractional ambiguity parts. In the case that a successfully ambiguity resolution has been made, the tropospheric estimates are determined more accurately [Nistor &, Buda, 2016].

Nowadays, PPP is basically associated with the GIPSY-OASIS software package [Zumberge et al., 1997]. The developer and owner of this software product is the Jet Propulsion Laboratory (JPL) of the California Institute of Technology. The original GIPSY-OASIS package consists of FORTRAN programs and UNIX scripts [Gregorius, 1996]. This software is not free but some government subcontractors are able to have a free license in order to perform work under a certain state contract. In this paper, we demonstrate the use of the PPP method not only for positioning tasks, but also for many others, as the observation model should take into account different factors influencing GNSS signals.

Our results demonstrate the satisfactory accuracy of determining values of tropospheric delay between the results of processing in such software packages as GIPSY-OASIS, Bernese GNSS Software, GAMIT-GLOBK, and the results of atmospheric radio sounding. The conducted studies confirm that the proposed approach can be used for determining the values of tropospheric delay.

Purpose

The main aim of this research is conducting a comparative analysis of various determination approaches for determining the values of tropospheric delay based on the results of GNSS observation processed by the PPP and DD methods and atmospheric radio sounding data, in order to assess the accuracy of the parameters obtained.

Methodology

The troposphere is the lowest region of Earth's atmosphere ranging from 0 to 50 km. It is the seat of all meteorological phenomena's (clouds, rain, hydrometeors) and contains approximately 75 % of the atmosphere's mass and almost all (99 %) of its water vapor and aerosols. For the computation of the total zenith tropospheric delay (ZTD), the tropospheric delay is divided into two components: dry (hydrostatic) – ZHD and wet – ZWD. According to [Nistor, Buda, 2016], a total ZTD may be represented as follows:

$$ZTD = ZHD \cdot m_h(z) + ZWD \cdot m_w(z)\,, \qquad (1)$$

Typically, ZHD can be determined at the millimeter level of accuracy, since it depends mainly on the distribution of atmospheric pressure, but ZWD is determined only approximately, since it depends on the unknown distribution of water vapor in the atmosphere. Here $m_h(z)$ and $m_w(z)$ are the mapping functions of dry and wet components, according to the direction to zenith.

The values of total tropospheric delay are determined from the data of atmospheric radio sounding by integrating the vertical profile of the air refraction index [Turchin &, Zablotskyj, 2013]:

$$ZTD = 10^{-6}\int_{H_s}^{h_d} N_{h(d)}\,dH + 10^{-6}\int_{H_s}^{h_w} N_{w(d)}\,dH\,, \qquad (2)$$

where H_s is the initial height of the vertical profile of air refraction index; h_d is the layer height of dry air; h_w is the height of layer containing water vapor; $N_{h(d)}$ is the hydrostatic (dry) component of air refraction index; $N_{w(d)}$ is the wet component of air refraction index; dH is the height within the layer.

In turn, the air refraction index is calculated by the following formulas [Turchin &, Zablotskyj, 2013]:

$$N = K_1 \frac{P}{T}(K_2 - K_1)\frac{e}{t} + K_3 \cdot 10^5\,\frac{e}{T^2}\,, \qquad (3)$$

$$N = K_1 \frac{P_d}{T} Z_d^{-1} + \left(K_2 \frac{e}{T} + K_3 \frac{e}{T^2}\right) Z_d^{-1}\,, \qquad (4)$$

$$\begin{gathered} N = K_1 \frac{P}{T}\left(1 - 0.378\frac{e}{P}\right) + \\ + \left((K_2 - K_1 \cdot 0.622)\frac{e}{T} + K_3 \frac{e}{T^2}\right) Z_w^{-1}, \end{gathered} \qquad (5)$$

where K_1, K_2, K_3 are the empirical coefficients of Essen and From; T is the absolute temperature in K; P is the atmospheric pressure of humid air; e is the partial pressure of water vapor; Z_d^{-1}, Z_w^{-1} – coefficients of compressed dry air and water vapor for the transition from ideal gas to not ideal one, respectively.

In general, the tropospheric delay is defined as a sum of the dry and wet components. Since the dry component is more predictable, an important point is the analysis of wet component values. Using GNSS observations, the determination of wet component of ZTD is defined as the difference between the total and dry components of ZTD. Thus, first, we determine the total tropospheric delay for a certain average zenith distance by means of the basic GNSS equation. Second, we transform the total tropospheric delay into its zenith projection by means of the mapping function. Last, we determine the hydrostatic component by means of an analytical model. For this purpose, various tropospheric models, such as the Saastamoinen model, can be used [Saastamoinen, 1972]:

$$ZHD_{SA} = \frac{0.0022768 \cdot P_0}{1 - 0.0026\cos 2j - 0{,}00028H_0}\,, \qquad (6)$$

where ZHD_{SA} is the hydrostatic component of ZTD, calculated by Saastamoinen model; j – is the station latitude; P_0 is the surface value of atmospheric pressure; H_0 is the height above the sea level.

At the final stage, the wet component of ZTD is defined as the difference between total tropospheric delay and its hydrostatic component [Paziak, Zablotskyj, 2015].

In the experimental phase, atmospheric radio sounding data were used at three aerological stations 15420 (Bucharest, Romania), 11952 (Poprad-Ganovce, Slovakia), 33345 (Kyiv, Ukraine) and, located near, three GNSS stations BUCU (Bucharest, Romania), GANP (Ganovce, Slovakia) and GLSV (Kyiv, Ukraine). The spatial locations scheme of the selected stations are shown in Figure 1. In tables 1 and 2, the coordinates of the selected stations are shown.

Atmospheric radio sounding data were downloaded from the web resource of Atmospheric Research Service at the University of Wyoming [http://weather.uwyo.edu/upperair/sounding.html]. The sounding profiles were supplemented by data from a Standard atmospheric model (SMA-81). The calculation of the dry and wet components of ZTD was conducted by means of the integral method based on this data.

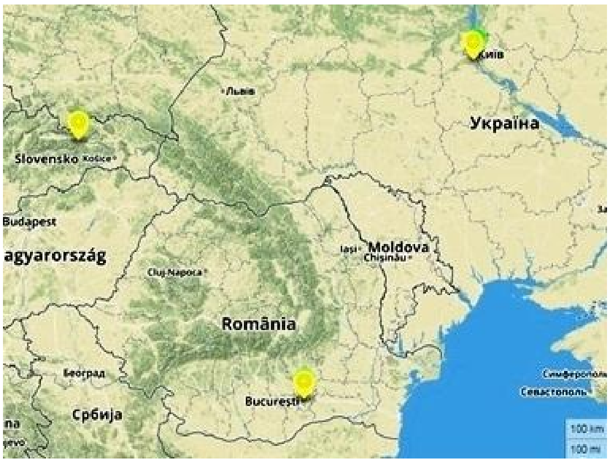

Fig. 1. Spatial locations of aerological and GNSS stations

Table 1

Coordinates of aerological stations

Station name	Latitude, °	Longitude, °	Height, m
Bucharest	44.50	26.13	91.0
Poprad	49.03	20.31	706.0
Kyiv	50.40	30.56	167.0

Table 2

Coordinates of GNSS stations

Station name	Latitude, °	Longitude, °	Height, m
BUCU	44.46	26.13	143.2
GANP	49.03	20.32	745.2
GLSV	50.36	30.56	226.8

Selected GNSS stations are included in the EUREF Permanent GNSS Network(EPN), so their data observations were downloaded from the ftpserver of the EUREF Permanent GNSS Network, which included observation data in the territory of Europe [http://epncb.oma.be/ftp/obs/].

Since in each pair, aerological and GNSS stations have different elevations, elevation and meteorological parameters of the aerological station were brought to elevation of GNSS station by interpolation.

The results of GNSS observations were obtained through the following scientific software packages:

– GIPSY-OASIS (version 6.4) [Ries et al., 2015];

– Bernese GNSS Software (version 5.2) [Dach et al., 2015];

– GAMIT-GLOBK (version 10.6) [Herring et al., 2016].

It should be noted that the Bernese GNSS Software [http://www.bernese.unibe.ch/download/] and GAMIT-GLOBK software [http://www-gpsg.mit.edu/~simon/gtgk/] performed GNSS observations basing on DD method, and GIPSY-OASIS – on PPP method.

In the framework of this research, we calculated the ZTD independently in the software packages GIPSY-OASIS and GAMIT-GLOBK. We obtained the corresponding values calculated by Bernese GNSS Software from the FÖMI Satellite Geodetic Observatory (SGO, Budapest, Hungary).

The dry component is caused by the dry gases present at the troposphere. In each of the abovementioned software packages, the harmonization of all parameters and models of processing was necessary. The dry delays were calculated based on the station height *h* by using the following equation [Ries et al., 2015]:

$$\mathrm{ZHD} = 1.013 \times 2.27 \times \exp(-0.166 \times 10^{-3} \times \mathrm{h}) . \quad (7)$$

As a mapping function, the Niell function [Niell, 1996] was applied. The elevation cut-off of 5 – was used.

As we noted earlier, GIPSY-OASIS software was set it to run in PPP mode, using script gd2p – GNSS Data to Position – with a recommended high level GIPSY interface for processing data from a single GNSS receiver [Zumberge et al., 1997]. As previously mentioned, in PPP method, the exact values of ephemeris and corrections of satellites clocks are used, which were downloaded from the JPL server [ftp://sideshow.jpl.nasa.gov/pub/].

Comparison of tropospheric delays at selected aerological and GNSS stations is based on the analysis of four atmospheric radio sounding and GNSS observations experiments on July 15, 2016; October 15, 2016; January 17, 2017, and April 16, 2017. The wet component value of ZTD obtained by the PPP method in GIPSY-OASIS software at GNSS stations BUCU, GANP, GLSV on the given days is shown in Figures 2–13.

Analyzing Figures 2–13 we can conclude that distribution of ZWD values is characterized by seasonal nature of change and, in general, the wet component is higher in value in the summer than in winter.

In Tables 3–6, differences $ZTD_{software} - ZTD_{sounding}$ of the total tropospheric delays, between the results of processing by means of GIPSY-OASIS, Bernese GNSS Software, GAMIT-GLOBK software packages and the results of atmospheric radio sounding are summarized in Tables 3–6.

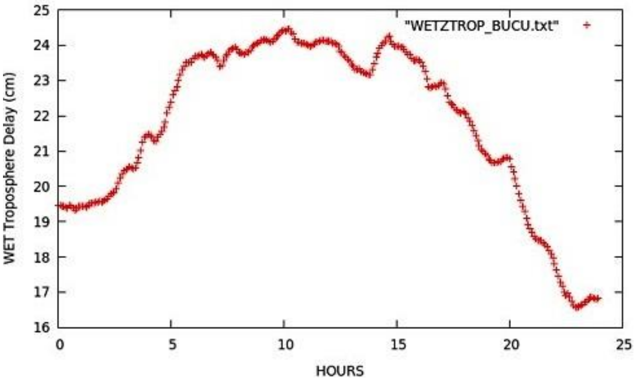

Fig. 2. ZWD values at the station BUCU 15.07.2016

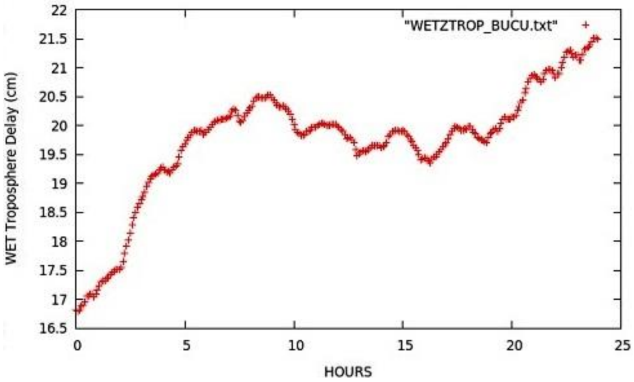

Fig. 5. ZWD values at the station BUCU 15.10.2016

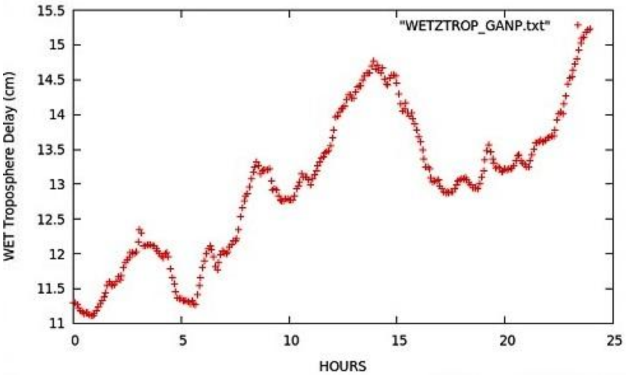

Fig. 3. ZWD values at the station GANP 15.07.2016

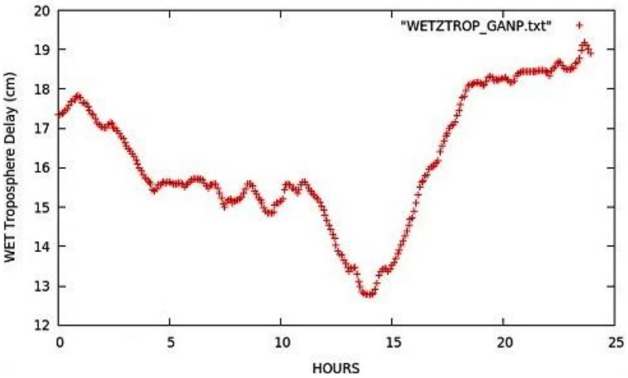

Fig. 6. ZWD values at the station GANP 15.10.2016

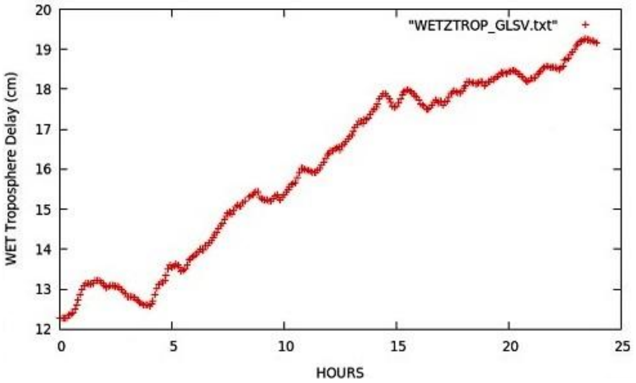

Fig. 4. ZWD values at the station GLSV 15.07.2016

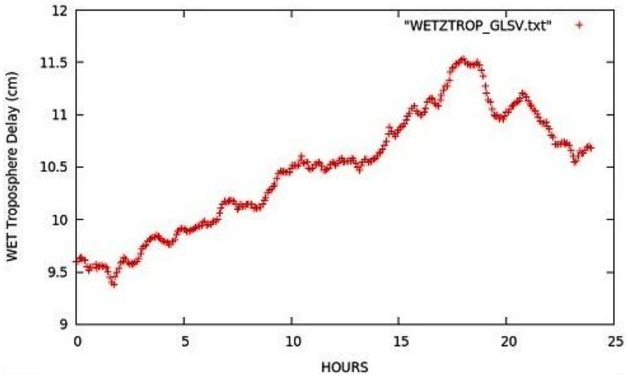

Fig. 7. ZWD values at the station GLSV 15.10.2016

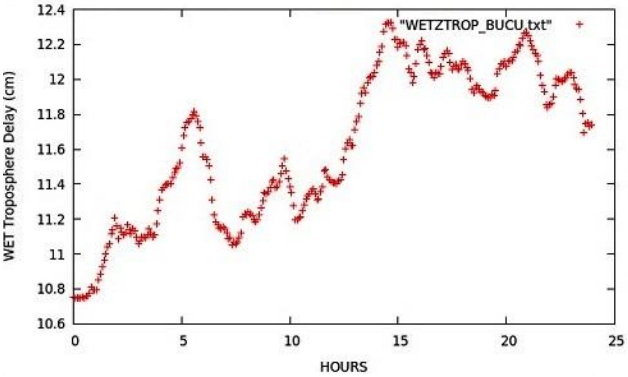

Fig. 8. ZWD values at the station BUCU 17.01.2017

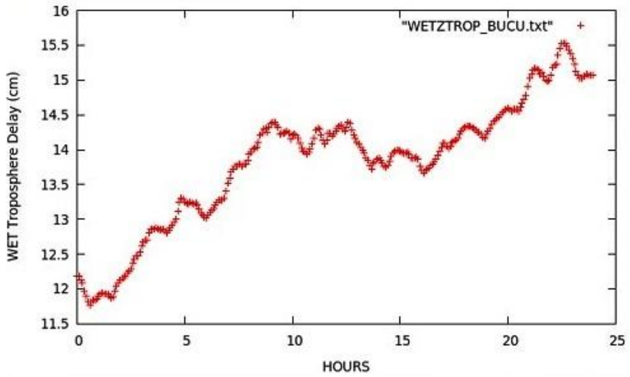

Fig. 11. ZWD values at the station BUCU 16.04.2017

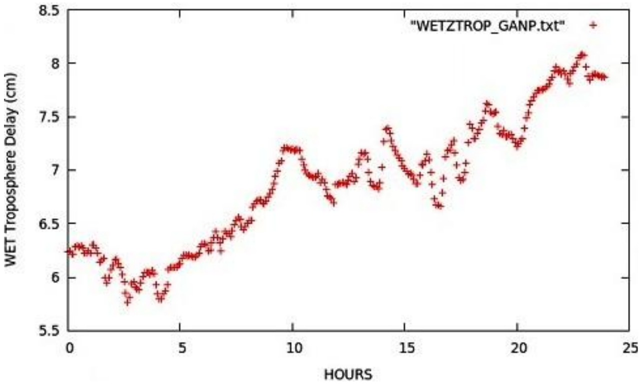

Fig. 9. ZWD values at the station GANP 17.01.2017

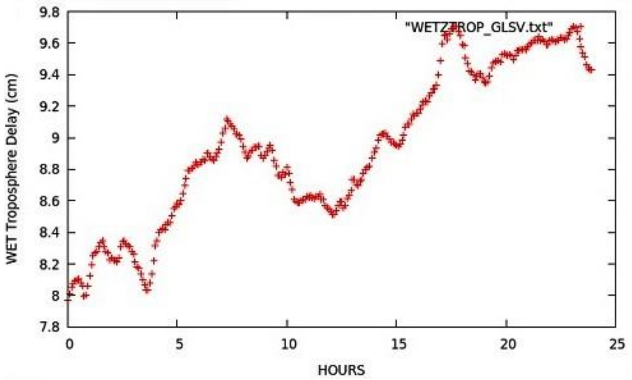

Fig. 10. ZWD values at the station GLSV 17.01.2017

Table 3

Differences in the calculation of the total *ZTD* on 15.07.2016

Station name	ΔGIPSY-OASIS, mm	ΔBERNESE, mm	ΔGAMIT-GLOBK, mm
BUCU-Bucharest	–2	4	8
GANP-Poprad	0	-2	3
GLSV-Kyiv	12	15	5

Table 4

Differences in the calculation of the total *ZTD* on 15.10.2016

Station name	ΔGIPSY-OASIS, mm	ΔBERNESE, mm	ΔGAMIT-GLOBK, mm
BUCU-Bucharest	10	14	–31
GANP-Poprad	–1	–5	0
GLSV-Kyiv	11	19	8

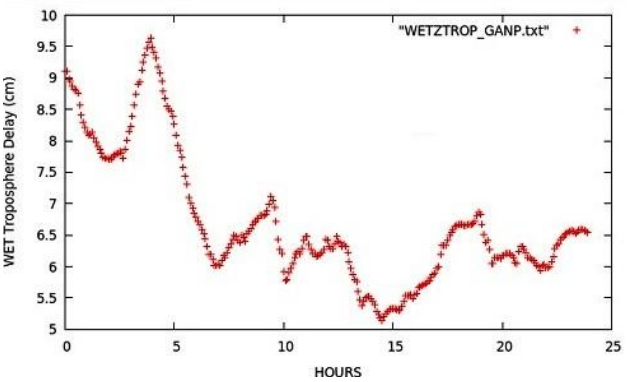

Fig. 12. ZWD values at the station GANP 16.04.2017

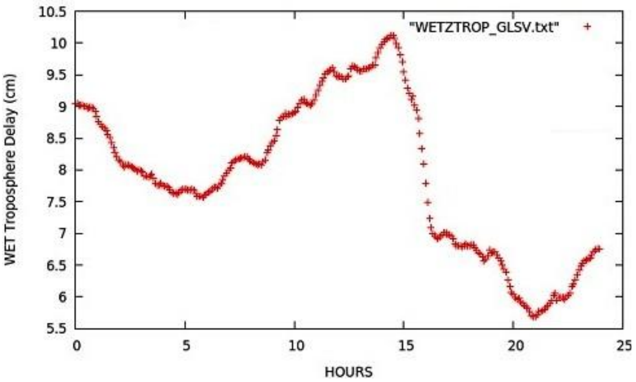

Fig. 13. ZWD values at the station GLSV 16.04.2017

Table 5

Differences in the calculation of the total *ZTD* on 17.01.2017

Station name	ΔGIPSY-OASIS, mm	ΔBERNESE, mm	ΔGAMIT-GLOBK, mm
BUCU-Bucharest	4	11	11
GANP-Poprad	0	–12	9
GLSV-Kyiv	17	23	21

Table 6

Differences in the calculation of the total *ZTD* on 16.04.2017

Station name	ΔGIPSY-OASIS, mm	ΔBERNESE, mm	ΔGAMIT-GLOBK, mm
BUCU-Bucharest	7	13	17
GANP-Poprad	–3	4	–9
GLSV-Kyiv	5	11	9

After analyzing the results, we see that the best results are obtained at the Slovakian stations. It is explained by smallest distance between the locations of the aerological and GNSS stations. Regarding the Ukrainian stations, the results are somewhat poorer, but the primary reason for this is the equipment of the aerological station with sounding data.

As can be seen from Tables 3–6, differences in the calculation of the total ZTD vary within a few centimeters that may be caused by various technical equipment of the stations or different weather conditions. In order to compare the way of changes in ZTD obtained at various stations using different approaches, the average values of the obtained data are calculated (Table 7).

Table 7

Average differences between total ZTD during the research period

Station name	ΔGIPSY-OASIS, mm	ΔBERNESE, mm	ΔGAMIT-GLOBK, mm
BUCU-Bucharest	8	13	22
GANP-Poprad	2	8	8
GLSV-Kyiv	14	20	14

As can be seen from Table 7, the smallest differences in the results of atmospheric radio sounding data and GNSS observations give the data processed in the GIPSY-OASIS software. In addition, it has demonstrated close differences between the data obtained from the software packages of Bernese GNSS Software and GAMIT-GLOBK. This is because the first software during processing uses the absolute PPP method, while the other two – relative DD method.

The time series of ZTD values of approximately 40 GNSS stations involved in the SES project [http://meteognss.net/] are one of the tropospheric products of the ALBERDING GNSS STATUS Software (see Fig. 14). Tropospheric delay values determined at stations of the ZAKPOS/UA□EUPOS network in real time by means of PPP method are interpolated at any point location (both horizontally and vertically) [Kablak et al., 2016].Tropospheric delays from 10 stations of the ZAKPOS/UA□EUPOS network, obtained during 1 month in real time (RT-PPP ALBERDING GNSS STATUS Software) and near-real time (NRT-DD Bernese GNSS software) were selected for comparison. According to the comparison, the mean values of differences and their standard deviations were calculated for each station. The resulting analysis shows that the mean difference values ranged within 1–2 cm, and standard deviations were within 0.6–2.3 cm.

Scientific novelty and practical significance

To solve the problem of atmospheric monitoring, we have proposed and experimentally investigated an approach based on the PPP method, which allows scientifically substantiated to replace the expensive radio atmosphere radio sounding on the existing network of GNSS stations. The technology for conducting continuous atmospheric monitoring with the use of GNSS stations and the methodology for processing observational data may be useful.

Data processing in several different approaches enables us to assess the quality of the results obtained, which can be used in the future, with their complement to predict troposphere effects on GNSS observation and for many other atmospheric monitoring tasks.

Conclusions

The ZTD values that allow one to determine integrated water vapor are important in the GNSS-meteorology. The reliability of the estimates of the integrated water vapor from the GNSS data analysis is one of the main problems in the use of these results. Accordingly, strategy of the GNSS data analysis should provide ZTD estimations which meet the requirements of the GNSS-meteorology. Based on the processed data, we obtained the modeled dry component values, as well as the calculated wet component values of ZTD. The obtained results demonstrate the satisfactory accuracy of determining the value of ZTD between the results of processing using such software packages as GIPSY-OASIS, Bernese GNSS Software, GAMIT-GLOBK, and results of the atmospheric radio sounding. The conducted studies confirm that the proposed approach can be used for determination of the value of ZTD. Although the results obtained are quite good, there is a clear need for further research to determine the cause of unwarranted large differences and to improve the strategy for determining the value of ZTD using the PPP method.

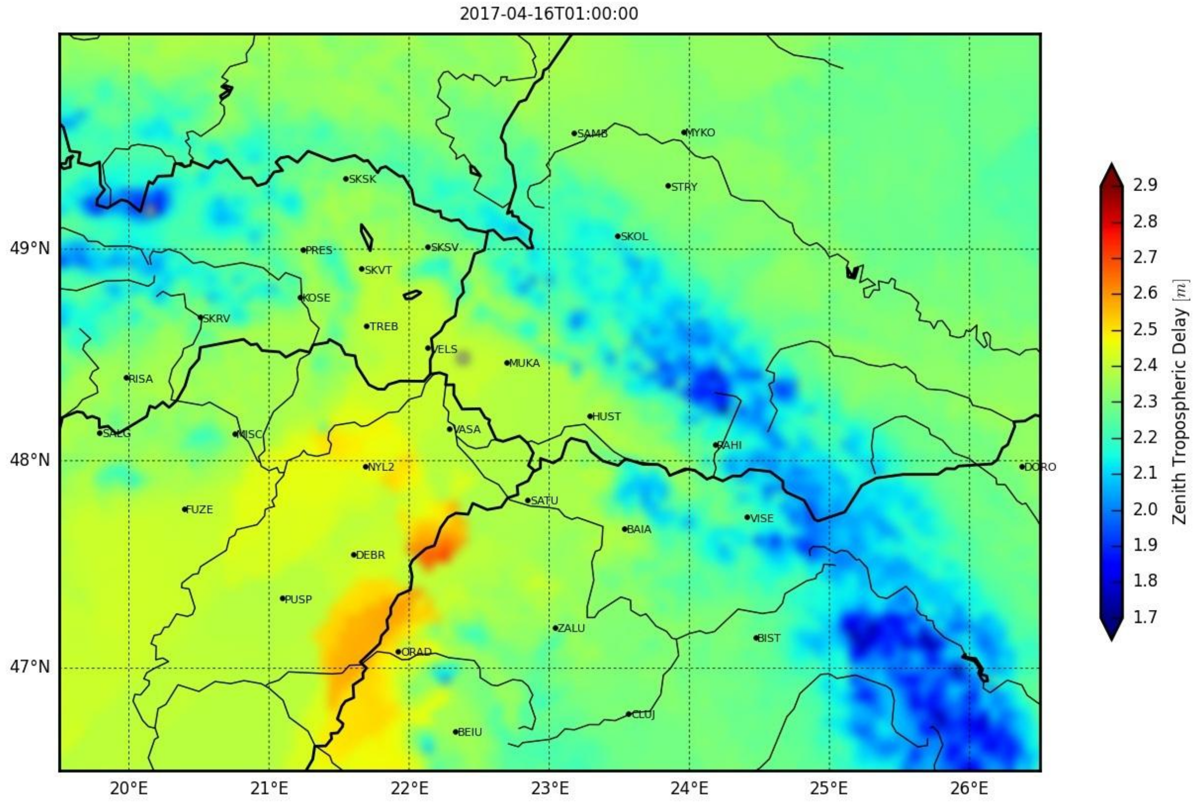

Fig. 14. ZTD in the Carpathian Region (Romania, Ukraine,Slovakia, Hungary) on 16.04.2017

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ПОРІВНЯННЯ ПІДХОДІВ ВИЗНАЧЕННЯ ЗЕНІТНОЇ ТРОПОСФЕРНОЇ ЗАТРИМКИ ЗА ДАНИМИ РАДІОЗОНДУВАННЯ АТМОСФЕРИ ТА GNSS-СПОСТЕРЕЖЕНЬ

Глобальні навігаційні супутникові системи (GNSS) на даний час все частіше використовуються в задачах моніторингу атмосфери. Для визначення тропосферних затримок найчастіше застосовують два підходи: обчислення даних радіозондування атмосфери та опрацювання даних GNSS-спостережень. GNSS-опрацювання, зазвичай, виконуються двома методами: абсолютним методом точного позиціонування (Precise Point Positioning, PPP) і методом подвійних різниць (Double Differences, DD). PPP – це потужний інструмент для аналізу даних, що чутливий до різних параметрів. Дана публікація показує, що PPP метод може використовуватися не тільки для позиціонування та навігації, але й для інших завдань, а саме моніторингу атмосфери. **Мета**. Проведення порівняльного аналізу різних підходів визначення тропосферних затримок за результатами опрацювання GNSS-спостережень PPP і DD методами, та за даними радіозондування атмосфери. **Методика.** В роботі використовувалися дані спостережень з таких GNSS-станцій: BUCU (Бухарест, Румунія), GANP (Ганове, Словаччина) і GLSV (Київ, Україна), а також дані радіозондування, розташованих неподалік, аерологічних станцій 15420 (Бухарест, Румунія), 11952 (Попрад-Гановце, Словаччина), 33345 (Київ,Україна). Визначення зенітної тропосферної затримки (Zenith Tropospheric Delay, *ZTD*) проводилося за даними GNSS-спостережень абсолютним PPP методом за допомогою програмного пакету GIPSY-OASIS і відносним методом DD із програмними пакетами Bernese GNSS Software і GAMIT-GLOBK. Отримані результати порівнювалися з відповідними даними радіозондування. **Результати.** Значення *ZTD* отримані з використанням різних підходів, відповідають субсантиметровому рівню точності відносно даних радіозондувань, при цьому найкращі результати були отримані методом PPP на словацьких станціях (міліметровий рівень), де відстань між розташуванням аерологічної і GNSS-станції є менше 1 км, тобто вони знаходяться в однакових атмосферних умовах. Це дозволяє стверджувати, що PPP метод забезпечує кращий рівень точності і може використовуватися саме для визначення тропосферних затримок. **Наукова новизна, практична значущість.** Технологія проведення неперервного моніторингу атмосфери з використанням GNSS станцій та методика опрацювання даних спостережень з цих станцій на основі абсолютного позиціонування PPP. Отримані результати, при їх доповненні, можуть використовуватись для вирішення багатьох задач моніторингу атмосфери і замінити у перспективі дорого вартісне радіозондування.

Ключові слова: абсолютний метод точного позиціонування (Precise Point Positioning, PPP), зенітна тропосферна затримка (Zenith Tropospheric Delay, *ZTD*), радіозондування атмосфери, GNSS-спостереження, моніторинг атмосфери.

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