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Fedir ZABLOTSKYI[1a], Bohdan PALIANYTSIA[1b], Bohdan KLADOCHNYI[1c],
Olena NEVMERZHYTSKA

[1] Department of Higher Geodesy and Astronomy, Lviv Polytechnic National University, 12, S. Bandery Str., Lviv, 79013, Ukraine, email: fedir.d.zablotskyi@lpnu.ua, bohdan.b.palianytsia@lpnu.ua, bohdan.v.kladochnyi@lpnu.ua,
[1a] https://orcid.org/0000-0003-4107-2994, [1B]https://orcid.org/0000-0003-4203-1043, [1c]https://orcid.org/0000-0003-4261-0379

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ACCURACY ESTIMATION OF THE COMPONENTS OF ZENITH TROPOSPHERIC DELAY DETERMINED BY THE RADIO SOUNDING DATA AND BY THE GNSS MEASUREMENTS AT PRAHA-LIBUS AND GOPE STATIONS

The aim of this work is to evaluate the accuracy of determining the wet component of zenith tropospheric delay (ZTD) from GNSS-measurements and the accuracy of determining the hydrostatic component according to the Saastamoinen model in comparison with the radio sounding data as well. Zenith tropospheric delay is determined mainly by two methods – traditional, using radio sounding or using atmospheric models, such as the Saastamoinen model, and the method of GNSS measurements. Determination of the hydrostatic component of the zenith tropospheric delay was performed by radio sounding data obtained at the aerological station Praha-Libus in 2011–2013 and in 2018. Data were processed for the middle decades of January and July of each year at 0^h o'clock of the Universal Time. The wet component was calculated from GNSS observations. By a significant number of radio soundings at the Praha-Libus aerological station, hydrostatic and wet components of zenith tropospheric delay (ZTD) and the same number of ZTD values derived for the corresponding time intervals from GNSS measurements at the GOPE reference station were determined. The values of the wet component of ZTD were determined and compared with the corresponding data obtained from radio soundings. We found that the error of the hydrostatic component in winter does not exceed 10 mm in absolute value, and in summer it is approximately 1.5 times smaller. This is due to differences in the stratification of the troposphere and lower stratosphere in winter and summer. As for the wet component of ZTD, its errors do not exceed: in winter 15 mm, in summer – 35 mm. The resulting differences in summer have a negative sign, indicating a systematic shift, and in winter – both negative and positive. Today, there are many studies aimed at improving the accuracy of determining zenith tropospheric delay by both Ukrainian and foreign authors, but the problem of the accuracy of the hydrostatic component remains open. The study provides recommendations for further research to improve the accuracy of zenith tropospheric delay.

Key words: zenith tropospheric delay, GNSS-measurements, hydrostatic and wet components of the ZTD, atmospheric sounding.

Introduction

Zenith tropospheric delay (ZTD) can be defined by traditional and satellite methods.

The first includes

– aerological sounding, in particular, radio sounding;

– analytical models developed mainly on the basis of standard models of the atmosphere.

The second group of ZTD determination includes first of all direct GNSS measurements in a network of active reference stations.

Radio sounding gives the most accurate results of direct contact measurements of the atmospheric thermodynamic parameter at altitudes up to 30–35 km. They contain information on the vertical temperature profiles, humidity characteristics, wind speed and direction [Tropospheric GNSS measurement files]. The sounding is performed at aerological stations, which are mostly designed to serve airports and form the basis of the global aerological network. Processing of radio sounding data allows to reliably determine the value of ZTD, which makes it possible to assess the impact of neutral atmosphere on the accuracy of GNSS measurements.

However, due to a very complex organizational and costly process of radio sounding at GNSS station, in practice, ZTD is determined using analytical models. As it is known, ZTD includes hydrostatic and wet components. The hydrostatic component can be modelled relatively accurately by precise measurements of atmospheric pressure at the time of observation at the initial level, i.e. at the height of a GNSS antenna. For this purpose, the Saastamoinen model [Saastamoinen, 1972] is mostly used, which is the basis of many programs for processing GNSS measurements.

The wet component is much more difficult to model due to the uneven distribution of water vapour in the troposphere and its continuous change both in space and time [Zablotskyi, 2013].

Currently, ZTD is determined in the centres for processing GNSS measurements in reference station networks. The average values of total zenith tropospheric delay are presented on the relevant sites with 5-minute intervals throughout a day [Tropospheric GNSS measurement files]. If necessary, the user calculates the wet component as the difference between the total ZTD and the hydrostatic component calculated from the model representation, mostly Saastamoinen.

Analysis of recent research

Recently, many works have been published, in particular [Zablotskyi et al., 2002, 2011, 2013; Kablak, 2010; Palyanytsia, 2016; Kladochnyi et al., 2020; Schueler, 2002], which cover the issues of assessing the accuracy of determining the components of ZTD. Most of them focus on the evaluation of a hydrostatic component [Zablotskyi et al., 2004], as the accuracy of its determination will directly affect the accuracy of the wet component.

Also today there are many publications of foreign authors, whose research is aimed at assessing and improving the accuracy of determining the zenith tropospheric delay.

Among the studies of recent years, which are aimed at improving the accuracy of zenith tropospheric delay, the following works can be distinguished: [Hadas, et al., 2020], which investigates the accuracy of ZTD using different GNSS systems and the ability to improve accuracy by combining data from several systems. The publication [Hdidou, et al., 2018] evaluates ZTD that is determined by radio sounding at two stations. Vertical tropospheric gradients were used to improve the accuracy of ZTD interpolation in [Zus, et al., 2019]. Studies [Zheng, et al., 2018] evaluated the accuracy of ZTD using GNSS observations and determined optimal coefficients for the models used.

However, despite the large number of studies in this area, the question of the accuracy of determining a hydrostatic component of ZTD has not been completed and requires further research.

The aim

The purpose of this work is to evaluate the accuracy of determining the wet component of ZTD from GNSS measurements, evaluating at the same time the accuracy of determining the hydrostatic component according to the Saastamoinen model, in comparison with the corresponding value obtained by radio sounding.

Presentation of the main points

1. Input data.

As the input data in the study, we took the vertical profiles of main meteorological parameters, obtained from radio sounding [Department of atmospheric science – University of Wyoming, USA] for 10-day periods (mostly from the 11th to the 20th) in January and July at the Praha-Libus aerological station for the reason that it is equipped with the modern equipment for measuring main meteorological parameters in the troposphere and lower stratosphere. The GOPE GNSS station has been installed at the Pecny Geodetic Observatory of Research Institute of Geodesy, Topografy and Cartografy in 1993 (Prague).

Coordinates and heights of the Praha-Libus and the GOPE stations are presented in Table 1.

The city of Prague is located in continental Europe. It has a climate with humid continental influences. Winters are relatively cold with t average temperature of about 0 °C. The average temperature in July is +24 °C. Also in autumn and winter, in contrast to other seasons, there are frequent temperature inversions.

The region is dominated by mountainous terrain, but also there are plains, mostly along the rivers.

Table 1

Coordinates of the Praha-Libus aerological station and the GOPE GNSS station

Aerological station			GNSS station			Country	Distance, km
Latitude, 0° 00’	Longitude, 0° 00’	Height, m	Latitude, 0° 00’	Longitude, 0° 00’	Height, m		
1	2	3	4	5	6	7	8
Praha-Libus, 11520			GOPE			Czech Republic	28.0
50° 00’	14° 27’	300.0	49° 54’	14° 47	592.6		

2. A general approach to the determination of hydrostatic and wet components of ZTD.

Let’s consider a technique of calculation of the general zenith tropospheric delay and its components. When using a biexponential model of the atmosphere, the tropospheric delay includes dry (hydrostatic) d_h^z and wet (non-hydrostatic) d_w^z components (formula (2)) and it is considered as the product of the value of delay at the zenith ($z = 0°$) and the mapping function m (z) calculated for the corresponding value of zenith distance z by formula (1):

$$d_{trop} = d_h^z \cdot m_h(z) + d_w^z \cdot m_w(z)\,. \quad (1)$$

If the delay calculation is performed at the zenith, we can use a simplified version of formula (1):

$$d_{trop}^z = d_h^z + d_w^z\,. \quad (2)$$

If we decompose the components to the index of refractive index, we obtain formula (3):

$$d_{trop}^z = 10^{-6}\int_{H_s}^{H_a} N_h\,dH + 10^{-6}\int_{H_r}^{H_a} N_w\,dH\,, \quad (3)$$

were N_h and N_w – air refractive indices for hydrostatic (dry) and non-hydrostatic (wet) components of zenith tropospheric delay; H_s – the initial height of the vertical profile of the refractive index; H_a – the upper limit of the atmosphere integration; dH – height layer.

The main formula for determining of the refractive index for radio waves is the Essen-Froome formula (4). The air refractive index is a function of air temperature t, atmospheric pressure P and partial pressure of water vapour [Mendes, 1999]:

$$N = K_1\frac{P-e}{T} + K_2\frac{e}{T} + K_3\frac{e}{T^2}\,, \quad (4)$$

were K_1, K_2, K_3 – empirical coefficients. $K_1 = 77.624$ (K/hPa), $K_2 = 64.7$ (K/hPa), $K_3 = 3.719$ (10^5K^2/hPa). The first term of the formula does not depend on the content of water vapour in the atmosphere and it is called the dry component. The sum of the second and third members is the wet component of the air refractive index.

According to the Saastamoinen model, the hydrostatic component is calculated by formula (5):

$$d_{hSa}^z = \frac{0.002277 \cdot P_0}{1 - 0.0026 \cdot \cos 2\varphi - 0.0028 \cdot H}\,, \quad (5)$$

were φ and H – the latitude and altitude of the observation point; P_0 – the value of atmospheric pressure at GNSS station height.

The wet component of the zenith tropospheric delay can be calculated by the formula (6):

$$d_{wSA} = 0.002277 \cdot \left(\frac{1255}{T_s} + 0.05\right) \cdot e_0\,, \quad (6)$$

were T_s – a surface value of air temperature and e_0 – partial pressure of water vapour.

3. Analysis of the hydrostatic component values of the zenith tropospheric delay.

Values of the Δd_h^z differences of the ZTD hydrostatic component for the middle decades of January and July (in 2012 used February) are presented in tables 2 and 3. Such values are calculated as the differences between the hydrostatic component determined by radio sounding and the value calculated by the Saastamoinen formula. In fact, the values of Δd_h^z represent the accuracy of determining the zenith hydrostatic delay. As for the value of Δd_h^z we can see that they are all negative and do not exceed the absolute value of -4.1 mm.

In order to analyse the value of Δd_h^z for individual dates and in general, we presented their values in Table 2.

Table 2

Differences $\Delta d_h^z{}_{SA}$ for individual dates according to the Praha-Libus aerological station

Years	Observation days and month									
	11	12	13	14	15	16	17	18	19	20
	January (for the year 2012 –February), mm									
2011	0.5	-1.3	-0.2	1.5	-2.6	-0.8	-2.3	-1.3	-0.6	0.7
2012	2.4	4.0	3.2	1.6	3.2	0.6	3.5	0.0	1.5	3.9
2013	1.8	1.6	3.4	0.2	0.0	1.6	0.0	-0.5	-0.4	-0.6
2018	2.6	-0.7	-0.7	-1.2	0.6	-0.8	0.5	7.9	-0.9	-0.2
July, mm										
2011	-0.7	-1.4	-3.1	-2.1	-2.8	-2.6	-3.1	-2.5	-2.4	-2.5
2012	-4.8	-2.0	-3.1	-3.0	-2.7	-4.1	-2.9	-1.5	-2.5	-3.4
2013	-3.0	-1.5	-2.5	-1.4	-2.2	-2.4	-2.1	-2.2	-2.5	-1.9
2018	-4.0	-5.1	-3.2	-3.7	-3.4	-5.1	-4.1	-3.4	-6.1	-3.5

After analyzing Table 2 the differences of Δd_h^z according to the degree of change in their values, note the following:

– according to the results of observations in January 2011, 2013 and 2018, the differences of Δd_h^z have mostly negative values that do not exceed the absolute value of 3 mm. Positive values are manifested in smaller numbers, but larger in the absolute value. Thus, the maximum value, reaching 8 mm manifests itself in January 2018;

– the differences of the hydrostatic component for February 2012 look different. Compared to other years, they all have positive values;

– according to the results of July of these four years, all differences of Δd_h^z are negative but slightly larger on average in absolute terms than in winter.

The reason for this, in our opinion, is the significant difference between the stratification of the troposphere and lower stratosphere in this period from the stratification of the neutral atmosphere adopted by Saastamoinen to build a model of the hydrostatic component. Thus, Saastamoinen based his model on the fact that the atmosphere corresponds to a static state, the air temperature drops evenly to about 10 km, i.e. the temperature distribution in the troposphere is considered as a linear function of altitude. It is further assumed that in the tropopause the temperature gradient is zero, and in the stratosphere up to the height of around 50 km, the temperature is constant or slightly increases with altitude. Thus, Saastamoinen is based on an almost standard model of the atmosphere [Saastamoinen, 1972]. Since the Saastamoinen model developed almost half a century ago, the accuracy of taking into account the effect of tropospheric delay in spatial radio distancer measurements met the needs of the centimeter range, and for radar measurements- of the decimeter one.

Note that when estimating the accuracy of determining the hydrostatic component of the ZTD by comparing the data obtained by the Saastamoinen model and the data by radio sounding at both Ukrainian and Eastern European aerological stations, model errors can reach 10–15 mm. As can be seen from Table 2, these errors are, for the most part, systematically shifted toward negative values, especially in summer.

In conclusion, the question of the accuracy of determining the hydrostatic component of the ZTD, we note that it is advisable to perform additional regional research, for example, for the main operating aerological stations in Ukraine. It makes sense, in our opinion, to analyse in detail the vertical temperature gradients in the troposphere and lower stratosphere according to radiosonde data and on this basis to develop a regional model of the hydrostatic component of the ZTD.

Table 3

Differences $\Delta d_{w\,GPS}^{z}$ according to the Praha-Libus aerological station and the GOPE GNSS station

Years	Observation days and month									
	11	*12*	*13*	*14*	15	16	17	*18*	*19*	*20*
	January (for the year 2012 –February), mm									
2011	-4.5	-14.0	-2.9	-4.7	-5.1	0.9	1.0	-8.8	-7.2	-7.9
2012	-10.5	-6.4	-8.3	-5.9	-5.7	-12.9	-9.8	-1.5	-7.6	-6.7
2013	-10.2	-9.9	-7.8	-8.2	-6.9	-11.2	-11.4	-6.2	-14.0	-10.3
2018	-1.9	-13.6	-10.2	-6.3	-5.6	-0.1	1.9	-8.4	5.7	-10.1
July, mm										
2011	1.4	1.6	-25.2	-12.2	-18.6	-11.4	-15.1	-3.8	-13.4	-15.1
2012	-20.4	-16.8	-18.7	-18.3	-30.3	-16.8	-14.9	1.5	-31.4	-13.2
2013	-11.1	-5.7	-17.1	-12.8	-22.8	-19.1	-4.4	-8.7	-6.9	-19.5
2018	12.4	-9.2	-6.3	-13.7	-9.8	-9.7	-8.1	-17.8	-27.6	-34.7

Let's estimate the error of the wet component of ZTD. As it is known, it includes the error of the total value of the ZTD, derived from the basic equation of code or phase pseudo-distances. As it can be seen from the formula (1), the error of the wet component of the ZTD depends on the error of the complete zenith tropospheric delay $\Delta d^{z}_{tropGPS}$ and the error of the hydrostatic component of the ZTD calculated by the formula (5). Note that according to Table 2 the error of the hydrostatic component $\Delta d_{h\,SA}^{z}$ in the winter in absolute value does not exceed 10 mm. In summer, it is about 1.5 times smaller. This is due, as already mentioned, to some other real stratification of the troposphere and lower stratosphere in winter and summer.

As for the wet component of ZTD, its errors do not exceed: in winter 15 mm, in summer – 35 mm.

Conclusion and recommendations

The article covers the differences between the values of the hydrostatic component of ZTD obtained by radio sounding and the Saastamoinen model for 10 days in January and July 2011-2013 and 2018 at the Praha-Libus aerological station and the GOPE GNSS station. Actually, the differences between the hydrostatic component $\Delta d_{h\,SA}^{z}$ and the wet component $\Delta d_{w\,GPS}^{z}$ show the accuracy of these components. In summer, they have a negative sign, indicating a systematic shift, and in winter – both negative and positive.

We recommended analysing in detail the vertical temperature gradients in the troposphere and the lower stratosphere according to the radio sounding data and on this basis to develop a regional model of the hydrostatic component of ZTD. In this case of increasing accuracy of determining the hydrostatic component of ZTD, the accuracy of the wet component from GNSS measurements will also increase.

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Федір ЗАБЛОЦЬКИЙ[1a], Богдан ПАЛЯНИЦЯ[1b], Богдан КЛАДОЧНИЙ, Олена НЕВМЕРЖИЦЬКА

[1] Кафедра вищої геодезії та астрономії, Національний університет "Львівська політехніка", вул. С. Бандери, 12, Львів, 79013, Україна, ел. пошта: fedir.d.zablotskyi@lpnu.ua, bohdan.b.palianytsia@lpnu.ua, bohdan.v.kladochnyi@lpnu.ua,
[1a] https://orcid.org/0000-0003-4107-2994, [1В]https://orcid.org/0000-0003-4203-1043, [1C]https://orcid.org/0000-0003-4261-0379

ОЦІНКА ТОЧНОСТІ СКЛАДОВИХ ЗЕНІТНОЇ ТРОПОСФЕРНОЇ ЗАТРИМКИ ВИЗНАЧЕНИХ ЗА ДАНИМИ РАДІОЗОНДУВАННЯ ТА ГНСС-ВИМІРЮВАНЬ НА СТАНЦІЯХ PRAHA-LIBUS І GOPE

Мета цієї роботи полягає в оцінюванні точності визначення вологої складової зенітної тропосферної затримки (ЗТЗ) із ГНСС-спостережень та точності визначення гідростатичної складової за моделлю

Саастамойнена у порівнянні зі значеннями, отриманими за радіозондуванням. Зенітну тропосферну затримку прийнято визначати, в основному, двома методами – традиційним, а саме радіозондуванням, та використовуючи моделі атмосфери, наприклад, модель Саастамойнена, а також методом ГНСС-вимірювань. У цьому дослідженні визначення гідростатичної складової зенітної тропосферної затримки виконувались за даними радіозондування, отриманими на аерологічній станції Praha у 2011–2013 рр та 2018 р. Дані опрацьовано для середніх декад січня і липня кожного року на 0 год Всесвітнього часу. Волога складова обчислювалась за даними ГНСС-спостережень. За даними значної кількості радіозондувань на аерологічній станції Praha-Libus визначено гідростатичні та вологі складові зенітної тропосферної затримки (ЗТЗ) і такої ж кількості значень ЗТЗ, виведених для відповідних часових інтервалів із ГНСС-вимірювань на референцній станції GOPE. За ними визначено величини вологої складової ЗТЗ і порівняно їх із відповідними даними, отриманими із радіозондувань. Встановлено, що похибка гідростатичної складової в зимовий період не перевищує 10 мм за абсолютною величиною, а в літній період – приблизно в 1,5 рази є меншою. Це пояснюється відмінностями у стратифікації тропосфери та нижньої стратосфери у зимовий і літній періоди. Що ж стосується вологої складової ЗТЗ, то її похибки не перевищують: взимку 15 мм; влітку – 35 мм. Отримані різниці у літній період мають від'ємний знак, що вказує на систематичне зміщення, а в зимовий – як від'ємний, так і додатний. Сьогодні є багато досліджень, спрямованих на підвищення точності визначення зенітної тропосферної затримки українських та іноземних авторів, однак питання точності визначення гідростатичної складової досі залишається відкритим. У цьому дослідженні подані рекомендації щодо подальших вивчень у напрямку підвищення точності визначення зенітної тропосферної затримки.

Ключові слова: зенітна тропосферна затримка; ГНСС-спостереження; гідростатична і волога складові ЗТЗ; радіозондування атмосфери.

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