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ANALYSIS OF SEASONAL CHANGES OF ZENITH TROPOSPHERIC DELAY COMPONENTS DETERMINED BY THE RADIO SOUNDING AND GNSS MEASUREMENTS DATA

The aim of the work is to analyze the change of hydrostatic and wet component values of zenith tropospheric delay (ZTD), determined for all seasons of the year. For today, ZTD components are determined mainly as follows: hydrostatic component – by using one of existing analytical models, mostly *Saastamoinen* model, and wet component – from GNSS measurements using simulated value of hydrostatic component. Also, in this study we evaluated the accuracy of the obtained values of hydrostatic and wet ZTD components for similar components, determined by radio sounding. For this purpose, we selected a pair of relatively close to each other station – aerological station and GNSS reference one. To implement the research methodology described above, we choose the Praha-Libus aerological station and the GOPE GNSS reference station. For processing and analysis, we selected the data from radio soundings of neutral atmosphere from the first station and the total values of ZTD (hydrostatic plus wet components) from the second one. Such data were selected monthly from the 1st to the 10th day of 2012 at 12 o'clock Universal Time. According to the radio sounding data, we determined the hydrostatic and the wet components of ZTD (set as reference) and the same number of total values of ZTD, derived for the same hour from GNSS measurements at the GOPE reference station. Based on these data, we determined the values of wet component of ZTD and compared them with the corresponding data, obtained from radio soundings. We found that the error of the hydrostatic component has a clear seasonal change ranging from only positive values in the range of 2–7 mm in January with a change cross zero in April (October), reaching only negative values in the range of 3–5 mm in July. As for the error of the wet component of ZTD, it should be noted that it takes only negative values during the year without clear seasonal course. Note that maximum absolute value of this error is in July, which exceeds 30 mm, due to the maximum content of water vapor in the troposphere at this time. However, only negative values of the wet component error indicate a systematic shift of its values. This paper provides recommendations for further research to improve the accuracy of determination of both hydrostatic and wet components of ZTD, as well as the reasons for seasonal changes in the accuracy of determination, especially the hydrostatic component.

Key words: zenith tropospheric delay, hydrostatic and wet components of ZTD, radio sounding of atmosphere, GNSS measurements.

Introduction

Global Navigation Satellite Systems (GNSS) play today a dominant role in surveying and navigation as location systems. In addition to the efficiency and versatility GNSS measurements provide a fairly high accuracy of the results. This accuracy is achieved by regulating a number of errors, which magnitude is either successfully corrected or eliminated [Hoffman-Wellenhof et al., 2001]. The main error that is difficult to correct in high-precision GNSS measurements is the error caused by the influence of the neutral atmosphere (troposphere and stratosphere).

This error is called tropospheric delay, which include two components – hydrostatic component and wet one. In the zenith direction, the value of total zenith tropospheric delay (hydrostatic plus wet component) at sea level varies depending on physical and geographical conditions from 2.2 to 2.5 m. Note that the value of hydrostatic component is about 90 % of the total ZTD value and it can be simulated quite accurately only by reliable atmospheric pressure measurements during observations at the GNSS receiver height. The Saastamoinen model is used the mostly for this purpose [Mendes, 1999; Saastamoinen, 1972], which is a basis of many programs for the GNSS measurement processing. However, the problem of the accurate determination of zenith tropospheric delay is the wet component, which, although it averages 10 % of the total value of ZTD, but can't be determined with sufficient accuracy using a model, because the spatiotemporal distribution of water vapor in the atmosphere does not follow any pattern [Zablotskyi et al., 2014].

Formulation of the problem

The magnitude of the wet component can be determined accurately enough with use only of too bulky and expensive technologies, such as: the neutral atmosphere radiosounding, water vapor radiometers, lidar systems, etc. [Zablotskyi, 2013]. However, in addition to cost (especially the second and third), they have disadvantages due to such reasons as time offsets caused by the duration of the measurements, weather restrictions (clouds, rain) and so on. Therefore, until recently, the wet component of the zenith tropospheric delay was determined by empirical (analytical) models, for example: *Saastamoinen, Hopfield, Chao, Ifadis, Askne and Nordius* and others [Mendes, 1999].

However, not all existing models can provide sufficient accuracy to determine the wet component of ZTD. The possibility of solving this problem appear with the introduction of a new scientific field – GPS meteorology [Bevis et. al., 1992], recently called GNSS meteorology (GNSS meteorology based on a number of theoretical principles of radio meteorology – a scientific field, which subject, on the one hand, is the influence of the atmosphere and meteorological conditions on the distribution of electromagnetic waves, and on the other – the use of electromagnetic waves to study the atmosphere).

Now, the essence of determining the wet component of the zenith tropospheric delay is as follows: from GNSS measurement, using GNSS solutions for the basic equation of code or phase pseudodistance from GNSS observations, for some interval-time solutions we get a full tropospheric delay on average zenith distance of the GNSS satellite location. Then, using the mapping function, we get a total zenith tropospheric delay [Mendes, 1999; Schueler et. al., 2002].

Then calculate the hydrostatic component of the ZTD according to an analytical mode, such as *Saastamoinen*, using a precisely measured value of atmospheric pressure at the GNSS receiver antenna height. According to the difference between the total ZTD derived from the GNSS measurements and the calculated hydrostatic component, we get the value of the wet component of ZTD at this time. This value is called the wet component of ZTD, derived from GNSS measurements [Bevis et. al., 1992]. Then, if necessary for the needs of meteorology, using the calculated wet component of ZTD according to simple calculations, you can get the value of integrated water vapor.

Note that to evaluate the accuracy of determining the total ZTD, or its components in particular, the data of radio sounding is used, if possible. Radio sounding gives quite accurate results due to direct measurements of the main meteorological variables of the atmosphere at altitudes up to 30–35 km. They contain information about vertical profiles of atmospheric pressure, temperature and characteristics of humidity, wind speed and its direction [Department of atmospheric science. University of Wyoming].

Sounding is performed at aerological stations, which are mostly designed to service airports and are the basis of the global hydrometeorological network. Radio sounding data processing allows to reliably evaluate both value of the ZTD as a whole and its components.

Analysis of recent research and publications

Scientific works on the development of methods to improve the accuracy of determining the value of ZTD, and in particular its components – hydrostatic component and wet one, have been recently published by a number of Ukrainian and foreign scientists, namely [Zablotskyi et al., 2014; Zablotskyi et al., 2021; Kablak, 2011; Palianytsia et al., 2020; Hdidon et al., 2018; Schueler et al., 2002; Zus et al., 2019] and others.

However, despite the significant number of studies in this field, the problem of accuracy of determining the components of ZTD is not solved and need further research and clarification.

Presentation of the main points

1. Input data characteristic.

As the input data in the study we choose the vertical profiles of the main meteorological variables, namely: atmospheric pressure, temperature and relative humidity, obtained from radiosounding for 1st to 10th of January – December 2012 at 12 o'clock Universal Time on the Praha-Libus aerological station CR (coordinates: φ = 50° 00', λ = 14° 27', H = 303.0 m). This station was chosen on the grounds that it is equipped with most modern equipment for measuring the main meteorological variables in troposphere and stratosphere, as well as the fact that radiosounding there are stable performing [Department of atmospheric science. University of Wyoming].

Since the procedure for determining the wet component of ZTD combines total zenith tropospheric delay derived from GNSS measurements, such data are provided by the EUREF Permanent GNSS Network Analysis Centers [NASA's Archive of Space Geodesy Data]. Therefore, in pairs to the Praha-Libus aerological station, we chose the nearest GOPE GNSS reference station (coordinates: φ = 49° 54', λ = 14° 47', H = 592.6 m). It should be noted that the GOPE station is at observatory of the Research Institute of Geodesy, Topography and Cartography at Zdiby (CR).

Since both stations are at different altitudes, to obtain reliable results it is necessary to reduce the vertical profiles of atmospheric pressure, temperature and relative humidity of Praha-Libus station to the height of GOPE station, as described in [Zablotskyi et. al., 2021]. the distance between Prague-Libus and GOPE

2. Determination of hydrostatic and wet components of ZTD according to radiosounding data.

Hydrostatic component of ZTD is determined by the formula [Zablotskyi, 2000]:

$$d_h^z = 10^{-6}\int_{H_0}^{H_d} K_1 \frac{P}{T}\left(1 - 0.378\frac{e}{P}\right)dH\,, \qquad (1)$$

where H_0 – station height, km; H_d – upper limit of the dry (hydrostatic) atmosphere height; K_1 = 77.624 – empirical coefficient according to Essen and Froome; P and e – atmospheric pressure and partial pressure of water vapor, hPa; T – air temperature, Kelvin; dH – height layer.

The wet component of ZTD is determined as follows [Mendes, 1999]:

$$d_w^z = 10^{-6}\int_{H_0}^{H_w}\left[\left(K_2 - K_1\cdot 0.622\right)\frac{e}{T} + K_3\frac{e}{T^2}\right]Z_w^{-1}\cdot dH \quad (2)$$

where H_w – upper limit of the wet atmosphere height; K_2 = 64,7 and K_3 = 371900 – empirical coefficient according to Essen and Froome; Z_w^{-1} – compressibility of water vapor coefficient for the conversion from ideal gas to real one. [Mendes, 1999].

3. Determining of the wet component of ZTD from GNSS measurements.

The total zenith tropospheric delay is determining as follows:

$$d_{trop}^z = d_h^z + d_w^z\,, \qquad (3)$$

where d_h^z – hydrostatic component of ZTD; d_w^z – wet component of ZTD.

The hydrostatic component of ZTD is determined by *Saastamoinen* formula:

$$d_{h\,SA}^z = \frac{0.002277\cdot P_0}{1 - 0.0026\cdot\cos 2\cdot\varphi - 0.28\cdot 10^{-6}\cdot H}\,, \qquad (4)$$

where P_0 – atmospheric pressure at the GNSS receiver antenna height; φ and H – latitude and height of the observation point, and the height H must correspond to the height of GNSS receiver antenna height.

Note that if in left part of formula (3) the total zenith tropospheric delay is derived from GNSS measurements, then the wet component will be also considered as obtained from the GNSS measurements.

So let's define them, respectively, as $d_{trop\ GNSS}^z$ and $d_{w\ GNSS}^z$. The hydrostatic component calculated by *Saastamoinen* formula is defined as $d_{h\,SA}^z$.Then the wet component is equal to:

$$d_{w\ GNSS}^z = d_{trop\ GNSS}^z - d_{h\,SA}^z\,. \qquad (5)$$

4. Analysis of the accuracy of the hydrostatic component values of ZTD and their seasonal changes.

The values of the hydrostatic component differences of ZTD are calculated by the formula:

$$\Delta d_{h\,SA}^z = d_{h\ sound}^z - d_{h\,SA}^z\,, \qquad (6)$$

where in the right part of the equation the first term represented the hydrostatic component determined by radiosounding, and the second term – the value calculated by the formula (4). In fact, the values

$\Delta d_{h\ SA}^{z}$ represented the accuracy of the hydrostatic component determined by the *Saastamoinen* model.

Note that if we take the value of the hydrostatic component determined by radiosounding as the reference (true) value, despite some disadvantages of radiosounding, the difference $\Delta d_{h\ SA}^{z}$ can be taken as the absolute error of the hydrostatic component determined by *Saastamoinen* model. These values correspond to the first decade of the middle month of each season of 2012 and graphically shown in Fig. 1.

As you can see, this error of the hydrostatic delay of ZTD has a clear seasonal change (shift) from exceptionally positive values in the range of 2–7 mm in January with a change cross zero in April, reaching only negative values in the range of 3–5 mm in July. Then, as you can see, the reverse process occurs (July, October, January).

On the one hand, systematic shift can be explained by significant difference in the stratification of the upper troposphere and lower stratosphere during the study periods from the neutral atmosphere stratification adopted in the *Saastamoinen* model to build a model of hydrostatic component. Thus, *Saastamoinen* based his model on the fact that the atmosphere corresponds to a static state, the air temperature drops to about 10 km evenly, 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 equal to zero, and in the stratosphere up to a height of ~50 km the temperature is constant, or slightly increases with ncreasing altitude [Saastamoinen, 1972]. Thus, Saastamoinen based its model on almost a standard model of atmosphere.

On the other hand, the distance between Prague-Libus and GOPE stations is 28 km. And this may be already the maximum distance of condition conservation of the same weather at both stations. The reason for the systematic difference in the results could be also that the heights of these stations belong to different systems. Thus, the height of the aerological station Prague-Libus is calculated from the surface of the quasi-geoid, and the height of the GNSS station GOPE from the total terrestrial ellipsod GRS80.

On the graphs in Fig. 1 clearly indicate the seasonal change of the error of the hydrostatic component of *Saastaminen*, which is obviously related to the seasonal change of the air temperature in the neutral atmosphere. Perhaps this phenomenon can be avoided by adding in formula (4) some functional dependence on air temperature, Therefore, in our opinion, it is advisable to do the same research on the several pairs of stations located in Central and Eastern Europe.

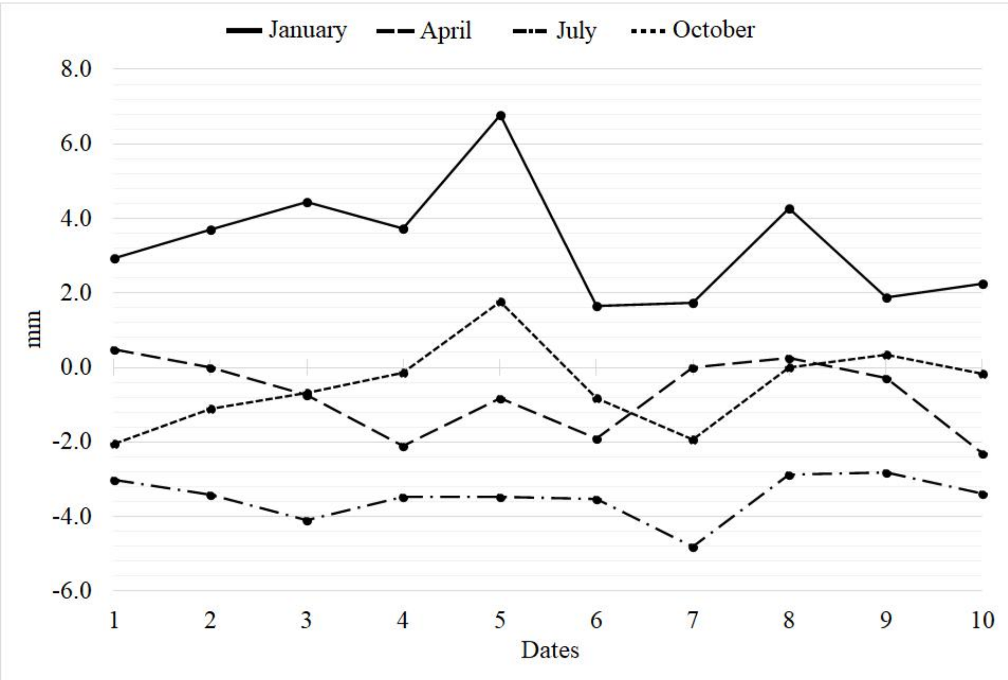

Fig. 1. The errors of $\Delta d_{h\,SA}^{z}$ *for the first decades of the middle months of the seasons*

5. Analysis of the accuracy of the wet component values of ZTD and their seasonal changes

The value of the wet component differences of ZDT is calculated by the formula:

$$\Delta d^{z}_{w\ GNSS} = d^{z}_{w\ sound} - d^{z}_{w\ GNSS}, \qquad (7)$$

where in the right part of the equation the first term represented the wet component of ZTD determined by radiosounding, and the second term – the same value derived from GNSS measurements. We take the difference $\Delta d^{z}_{w\ GNSS}$ (by analogy with the approach of determining the error of the hydrostatic component) as the absolute error of the wet component of ZTD, derived from GNSS measurements. Let's estimate this value. As you can see from formula (5), the error of the wet component of ZTD depends on the error of the total value of ZTD $d^{z}_{trop\ GPS}$ and on the error of the hydrostatic component of ZTD d^{z}_{hSA}, calculated by formula (4). The values of the errors of the wet component derived from the GNSS measurements are shown in Fig. 2, and the numerical values oh these errors are given for better readability in table 1.

As for the accuracy of the values of the wet component of ZTD and their changes, it should be noted the following:

– the maximum absolute value of this error is on July 5, exceeding -33 mm, the minimum value is on October 7 and is -6 mm;

– no patterns of seasonal changes of the error of the wet component of ZTD were found. Some exception is July, which differs among the months of the other seasons by high air temperature and, accordingly, a significant content of water vapor in the lower troposphere;

– all values of the error of the wet component are negative, which indicates a systematic shift.

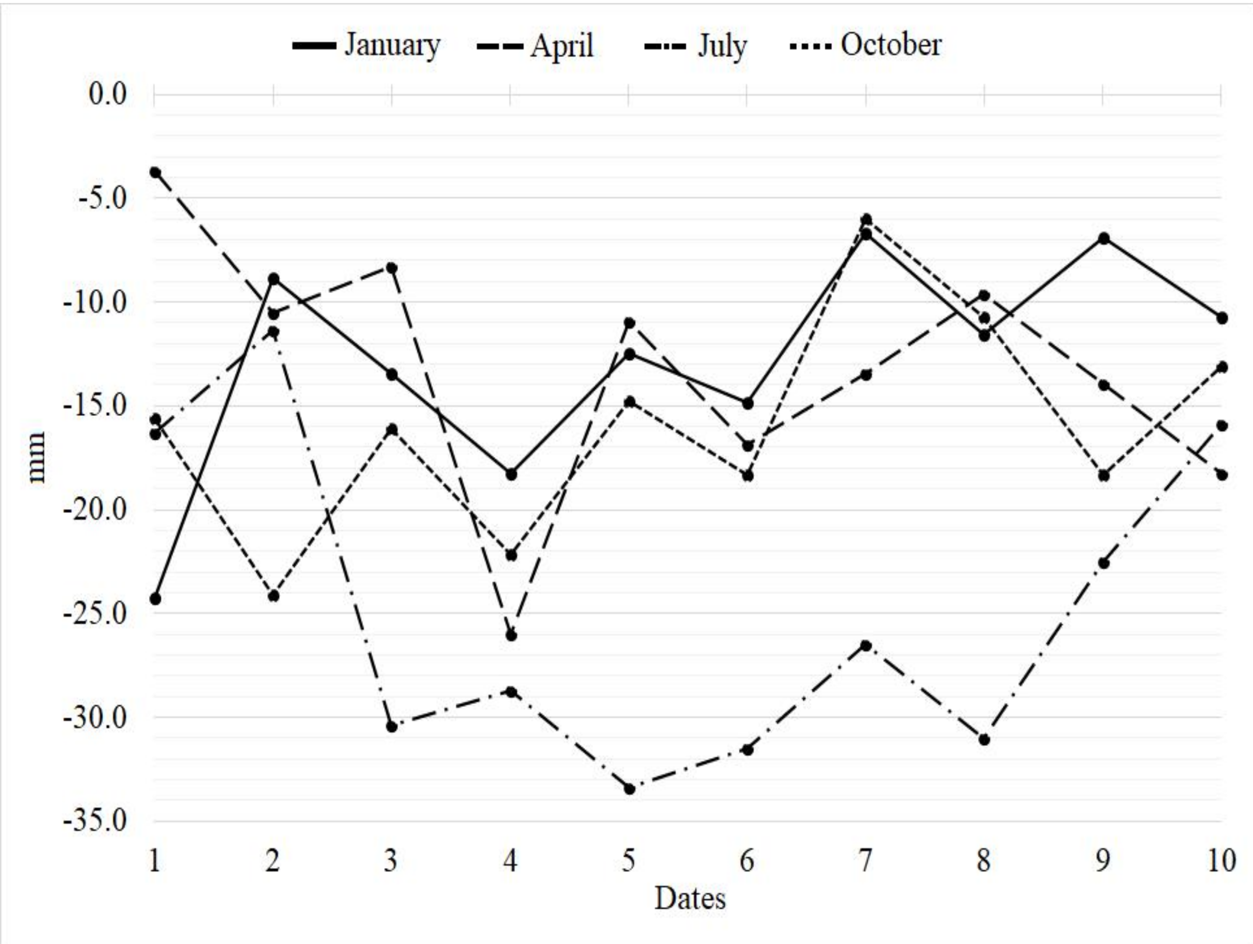

Fig. 2. The errors of $\Delta d^{z}_{w\ GNSS}$ for the first decades of the middle months of the seasons

Table 1

The errors of $\Delta d^z_{w\ GNSS}$ for the first decades of the middle months of the seasons

Dates	January			April			July			October		
	$d^z_{w\ sound}$	$d^z_{w\ GNSS}$	$\Delta d^z_{w\ GNSS}$	$d^z_{w\ sound}$	$d^z_{w\ GNSS}$	$\Delta d^z_{w\ GNSS}$	$d^z_{w\ sound}$	$d^z_{w\ GNSS}$	$\Delta d^z_{w\ GNSS}$	$d^z_{w\ sound}$	$d^z_{w\ GNSS}$	$\Delta d^z_{w\ GNSS}$
1	93.5	117.7	-24.2	32.3	36.0	-3.7	173.8	190.2	-16.3	159.4	175.0	-15.6
2	103.7	112.5	-8.8	65.7	76.2	-10.5	160.7	172.1	-11.4	116.3	140.4	-24.1
3	38.7	52.1	-13.4	64.4	72.7	-8.3	190.6	220.9	-30.4	97.1	113.2	-16.1
4	44.9	63.1	-18.2	52.4	78.4	-26.0	171.8	200.6	-28.7	115.9	138.1	-22.2
5	73.1	85.6	-12.4	102.3	113.2	-10.9	179.8	213.2	-33.4	147.3	162.1	-14.8
6	35.6	50.4	-14.8	92.2	109.0	-16.8	156.6	188.1	-31.5	102.5	120.9	-18.4
7	73.0	79.7	-6.7	64.3	77.7	-13.4	183.9	210.4	-26.5	100.6	106.6	-6.0
8	53.3	64.9	-11.6	31.3	41.0	-9.6	101.1	132.1	-31.0	62.1	72.8	-10.7
9	41.8	48.7	-6.9	36.2	50.2	-13.9	109.7	132.2	-22.5	79.0	97.3	-18.3
10	38.1	48.8	-10.7	98.6	116.9	-18.2	120.3	136.2	-15.9	76.5	89.6	-13.1

Conclusion and recommendations

In this paper we analyzed the errors of hydrostatic $\Delta d^z_{h\,SA}$ and wet $\Delta d^z_{w\ GPS}$ components of ZTD, determined by radiosounding in January, April, July and October 2012 at the aerological station Praha-Libus and zenith tropospheric delays derived from GNSS measurements at the GOPE GNSS reference station.

We found that the magnitude of the hydrostatic component error has a clear seasonal change from exceptionally positive values in the range of 2–7 mm in January with change cross zero in April (October), reaching only negative values in the range of 3–5 mm in July. This phenomenon can be avoided by adding into formula (4) some functional dependence on air temperature. However, such a recommendation needs further examination.

As for the error of the wet component of ZTD, it should be noted that it has only negative values during the year. Note thar the maximum values (30–34 mm) of this error is in July due to relatively high air temperatures, and, accordingly, the significant content of water vapor in the lower troposphere at this time. However, only negative values of the wet component errors also indicate a systematic shift in its values. Therefore, in our opinion, it is advisable to do the same research on several pairs of stations located in Central and Eastern Europe.

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АНАЛІЗ СЕЗОННИХ ЗМІН СКЛАДОВИХ ЗЕНІТНОЇ ТРОПОСФЕРНОЇ ЗАТРИМКИ, ВИЗНАЧЕНИХ ЗА ДАНИМИ РАДІОЗОНДУВАНЬ І ГНСС-ВИМІРІВ

Метою цієї роботи є проаналізувати зміну величин гідростатичної та вологої складових зенітної тропосферної затримки (ЗТЗ), визначених для усіх сезонів року. Складові ЗТЗ визначають на сьогоднішній день, переважно, так: гідростатичну – за одною із існуючих аналітичних моделей, здебільшого за моделлю *Saastamoinen*, а вологу – із ГНСС-вимірювань з використанням модельного значення гідростатичної складової. У нашому дослідженні проводилось ще оцінювання точності отриманих величин гідростатичної і вологої складових ЗТЗ за аналогічними складовими знайденими за даними радіозондування. Для цього підбиралась пара відносно близьких одна від одної станцій – аерологічної і референцної ГНСС-станції. Для реалізації викладеної методики досліджень було обрано аерологічну станцію Praha-Libus і референцну ГНСС-станцію GOPE. Для опрацювання і аналізу вибирались дані радіозондування нейтральної атмосфери з першої станції і повні величини ЗТЗ (гідростатична плюс волога складові) з другої станції. Такі дані вибирались щомісячно з 1-ї по 10-у дати 2012 року на 12-у год Всесвітнього часу. За даними радіозондування визначено гідростатичні і вологі складові ЗТЗ (прийняті надалі, як еталонні) і таку ж кількість значень повних ЗТЗ, виведених на цю ж годину із ГНСС-вимірювань на референцній станції GOPE. За ними визначено величини вологої складової ЗТЗ і порівняно їх з відповідними даними, отриманими із радіозондувань. Встановлено, що похибка гідростатичної складової має чітко виражену сезонну зміну, починаючи від виключно додатних величин в діапазоні 2–7 мм у січні з переходом через нуль у квітні (жовтні), досягаючи виключно від'ємних величин в діапазоні 3–5 мм у липні. Що ж стосується похибки вологої складової ЗТЗ, то слід зазначити що вона на протязі всього року приймає лише від'ємні значення без чітко вираженого сезонного ходу. Зауважимо, що максимальні абсолютні величини ця похибка має в липні, що переважають – 30 мм, пояснюється максимальним вмістом водяної пари у тропосфері у цей час. Проте, виключно від'ємні значення похибки вологої складової вказують і на систематичне зміщення її значень. У цій роботі подані рекомендації щодо подальших досліджень у напрямку підвищення точності визначення як гідростатичної, так і вологої складової ЗТЗ, а також причин щодо сезонних змін точності визначення, особливо, гідростатичної складової.

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

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