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RESEARCH OF OSCILLATIONS IN THE COMPONENTS OF ZENITH TROPOSPHERIC DELAY DURING THE YEAR IN UKRAINE

The aim of this work is to study the fluctuations of the components of the zenith tropospheric delay during the annual period according to the ground meteorological measurements in Ukraine. **Methodolodgy**. The surface values of meteorological values at the stations: Lviv, Kyiv, Kharkiv and Odesa, obtained in 2019 with an interval of 3 hours were used for the research. A total amount of 2020 measurements at each of the stations has been presented. The calculation of the components of the zenith tropospheric delay was performed according to the Saastamoinen formula. According to the calculated values of the components, graphs of changes in the dry and wet components of the zenith tropospheric delay for each of the stations during constructed. Subsequently, the monthly average and annual average values of the components were calculated and compared with each other. **Results**. Based on studies of changes in delay values at four Ukrainian meteorological stations for the period of 2019, it was found that the monthly average values of ZHD component are higher at stations whose altitude is lower. The wet component of ZWD during the year acquires the biggest values in summer. Annual fluctuations of the dry component of ZHD have a much smaller amplitude than the wet ZWD. The amplitude of the change in the total delay is determined by the amplitude of the change of the wet component, which at different stations is almost two times bigger than the amplitude of the change of the dry component, although ZWD is only up to 10% of ZTD. Thus, the variations in the total tropospheric delay, which indirectly reflects the weather and climatic processes due to variations in the wet component**. Scientific novelty and practical significance** consist in identifying the features of the annual change in the components of tropospheric delay at stations in different climatic and weather conditions. The performed research can be used in the tasks of monitoring of large hydraulic structures by GNSS methods to create regional models of the atmosphere and further studies of tropospheric delay, as they relate to its changes in space and time.

Key words: tropospheric delay, neutral atmosphere, satellite measurements, methods for determining the components of ZHD and ZWD zenith tropospheric delay ZTD.

Introduction

Tropospheric delay is one of the main factors deteriorating the accuracy of GNSS measurements. Geodetic methods, to which GNSS technologies are actively involved today, are widely used to monitor deformations of large engineering structures, so there is always the question of improving the accuracy of such measurements by reducing errors and their correct consideration, including tropospheric delay.

The International GNSS Service (IGS), which traces more than 500 permanent worldwide stations, regularly generates daily files in RINEX format containing total zenith troposphere delay (ZTD). Further, these files are analyzed and also the files accumulated over different years are compared, identifying trends in the volumes, including ZTD [Jin, et al., 2007]. Seasonal fluctuations of the correction and features of ZTD change during many years at stations with different climatic conditions are among the studied parameters.

Many Ukrainian and foreign scientists have studied and continue to research the influence of the troposphere on satellite measurements in the radio engineering range, which include GNSS measurements with centimetre wavelengths. Among the scientific works in which the research of dry (ZHD) and wet (ZWD) components of zenith tropospheric delay has been conducted, the following can be mentioned [Mendes, 1999; Ifadis, et. al., 2006; Jin, et. al., 2007; Kablak, 2011; Zablocki, et. al., 2001].

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The aim

The aim of this work is to study the fluctuations of the components of the zenith tropospheric delay during the annual period according to the ground meteorological measurements in Ukraine.

Output data

To study the annual changes in the components of the zenith delay, the data of the ground meteorological observations for 2019 from the resource [National Climatic Data Center], were used. The surface values of meteorological values (air temperature t, atmospheric pressure P, and relative humidity f) received at the stations: Lviv, Kyiv, Kharkiv and Odesa in the period of 2019 with an interval of 3 hours, were selected. Total amount of 2020 measurements of each of the meteorological quantities at each of the stations is being deducted.

The above-mentioned cities as well as almost the entire territory of Ukraine are in zone of temperate continental climate with certain features. Namely:

Lviv typically has the highest rainfall and the lowest summer temperatures among all regional centres of Ukraine, which is caused by almost the lowest continentality of the local climate among the major cities of Ukraine. Lviv climate is mild in winter and warm in summer. The average monthly air temperature is −4 °C in January and +18 °C in July. On average, 740 mm of precipitation falls per year: the least in January and the most in July. During the year, the city has an average of 174 days of rainfalls.

The climate of Kyiv also has mild winters and warm summers. The average monthly temperatures vary: in January it is lower than −3.5 °C, in July it is higher than +20.5 °C.

Kharkiv typically has cold and snowy, but changeable winters and hot summers. The average annual temperature is +6.9 °C (-6.9 in January, +20.3 in July). The average annual rainfall is 513 mm, the highest – in June and July. The city is located almost on the border of forest-steppe and steppe zones, evaporation in summer significantly exceeds precipitation. Kharkiv is situated on five hills and has a height difference between the upper and lower stations of more than 115 meters. Therefore, cold air moves from the upper stations down, usually in river valleys, where it lowers the temperature.

Although the climate of Odesa is moderately continental, it has the features of subtropical one, with mild winters, relatively long springs, warm and long, often hot summers, as well as long and warm autumns. The average annual air temperature is + 10.1 °C, the lowest in January (-1.7 °C), the highest in July (+ 21.4 °C). On average, 464 mm of precipitation falls in Odesa per year, the least in October and the most in July. [http://prima.franko.lviv.ua/faculty/geology/phis_geo/ fourman/E-books-FVV/]. In our data for 2019, the values of extreme temperatures have slight differences from the above values obtained from long-term observations (Table 1). In addition, temperature records have been fixed on some days in 2019, a particular attention has not been paid to this, as the investigation was directed towards the search of general trends.

Method

Tropospheric delay (ZTD) is supposed to be considered as the sum of dry (hydrostatic) and wet (non-hydrostatic) components:

$$d_{trop}^{z} = d_{h}^{z} + d_{w}^{z} \tag{1}$$

Saastamoinen formulas used to calculate the components [Saastamoinen J., 1972]. For the dry component (ZHD):

$$d_{hSA} = \frac{0.002277 \cdot P_s}{\left(1 - 0.0026\cos 2\varphi - 28 \cdot 10^{-8} H_S\right)} \tag{2}$$

and for the dry (ZWD):

$$d_{wSA} = 0.002277 \cdot \left(\frac{1255}{T_s} + 0.05\right) \cdot e_0 \tag{3}$$

In formulas (2) and (3): φ *i* H_s – the latitude and altitude of the observation station; T_s,P_s, e_s – surface values of air temperature, atmospheric and partial pressure, respectively.

After the calculations carried out according to the specified formulas, the graphs of change of ZHD and ZWD for each of the stations have been constructed.

Research results

The surface values of the main meteorological parameters T_s, P_s, e_s are characterized by slow changes due to the processes of diurnal and

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seasonal course, and fast changes are associated with the turbulence in the atmosphere.

The average seasonal changes in atmospheric pressure are relatively small. They are only 1–3 mbar. The minimum value of pressure is observed during the cyclone and reaches 935 mbar for the territory of Eurasia, which includes the territory of Ukraine. The maximum value of pressure makes 1050 mbar and is observed during the anticyclones which happen 36 times a year, that is almost twice less than cyclones. The amplitude of daily pressure changes is 0,5 mbar, but it is strongly veiled by rapid changes in the magnitude of atmospheric pressure [Tverskoj, 1962].

As for the air temperature, it has a pronounced annual course. The character and amplitude of annual changes depend on the properties of the underlying surface, types of air masses, the peculiarities of atmospheric circulation. The amplitude of the annual temperature on monthly average values reaches almost 30 °C. In addition to the annual changes, the temperature undergoes characteristic of daily changes, the magnitude of which depends on season. The maximum amplitude of the daily temperature change is observed on the earth's surface. The nature of its vertical distribution in the lower troposphere layers is associated with the annual and daily change in the surface value of temperature [Kazakov, Lomakin, 1976].

The annual course of both absolute and relative humidity is generally ordinary (according to average data): absolute humidity repeats the course of temperature, and relative humidity – on the contrary – the reverse of this course. The values of their annual amplitudes also correspond to the values of temperature: in summer the absolute humidity is the highest and the relative humidity is the lowest and in winter – the opposite [Jordan V., et al. 1971].

In northern latitudes, the relative humidity is highest in winter and is 80–90 %, in summer it drops to 60–70 %, and in the eastern regions of Ukraine – up to 45 %. The elasticity of water vapour (e), on the contrary, is low in winter (2–3 mbar) and much higher in summer (its average value is 12–15 mbar), so that the average annual amplitude is 10–12 mbar [Kazakov, Lomakin, 1976].

With altitude, the annual fluctuations in humidity decrease and are insignificant in the upper troposphere part.

It is known that there is an inverse relationship between atmospheric pressure and altitude. Taking into account the evaluation of the initial data it can be noted that the greater the height of the meteorological station is, the smaller are the surface values of atmospheric pressure obtained on it. Approximately the same trend should continue to average and extreme values. In our case, the average annual value of atmospheric pressure for the specified period (2019) is the highest in Odesa (h = 42 m) – 1011.3 mVar (Table 1), and the lowest in Lviv (h = 42 m) – 947.3 mVar. In general, the pressure at Lviv station is lower than at other stations, and at Odesa station on the contrary. Two other stations have not been an exception. In Kharkiv, the average annual value is P_s = 997.6 mVar at h = 152 m, and in Kyiv P_s = =995.6 mVar at h = 168 m. The dry component of ZHD changes accordingly.

According to the data used in the calculations for 2019, the annual average minimum value of air temperature was in Lviv (9.9 °C), and the maximum in Odesa (12.9 °C). The air temperature reached a maximum in 2019 in Odesa (34.20 °C), and the minimum at Kharkiv station (-16.6 °C). The largest amplitude of annual temperature fluctuations was observed in Kharkiv (50.1 °C), and the smallest – in Odesa (44.1 °C), due to the mild sea climate.

The partial pressure **e** was the highest in Kyiv – 26.2 mbar, and the lowest in Kharkiv – 1.4 mbar. The average annual value **e** is the highest in Odesa (11.3 mbar), and the lowest also in Kharkiv (9.1 mbar). The amplitude of the partial pressure varies from 20.8 mbar in Kharkiv to 24.4 mbar in Kyiv.

Therefore, all these variations of meteorological magnitudes are fully reflected in the formation of the values of the components ZHD and ZWD, calculated by formulas (2) and (3).

In accordance with the obtained values, graphs of variations in ZHD and ZWD are being constructed, which show the change of components at stations with different climatic features during the summer period (Fig. 1–8).

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It is known that the GNSS signals of the radio range passing the path from the satellite to the receiver through a neutral atmosphere delay due to the influence of dry air and water vapour. ZHD is proportional to the surface value of atmospheric pressure, and ZWD is proportional to the surface value of partial pressure [Palianytsia, et. al., 2020; Kladochnyi, & Palianytsia, 2018; Jin, et. al., 2007; Kablak, 2011].

Subsequently, the monthly average values of dry and wet components of the zenith tropospheric delay were calculated. Graphs are constructed, being based on these values (Fig. 9–16). The average annual magnitudes of the corresponding components are shown on the graphs by solid lines.

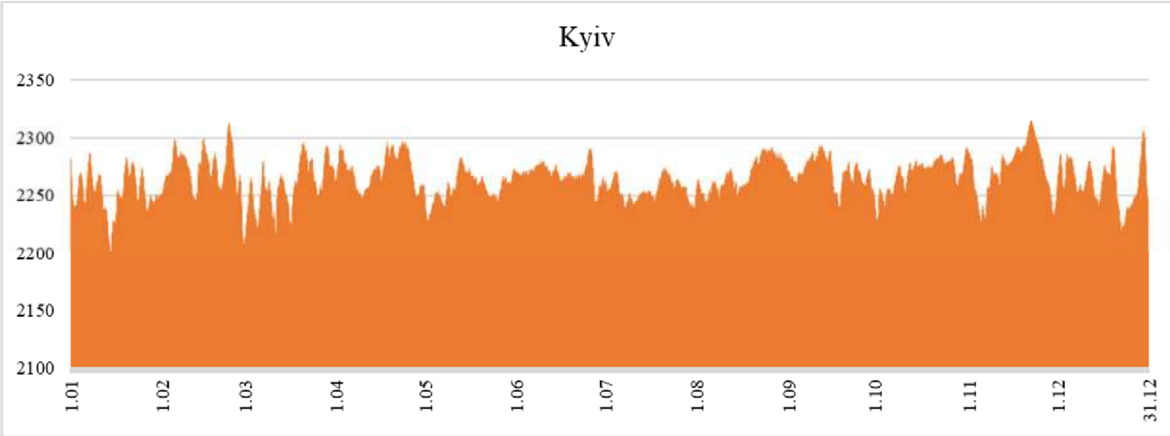

Fig. 1. Change of d_h^z component (in mm) at Kyiv station during 2019

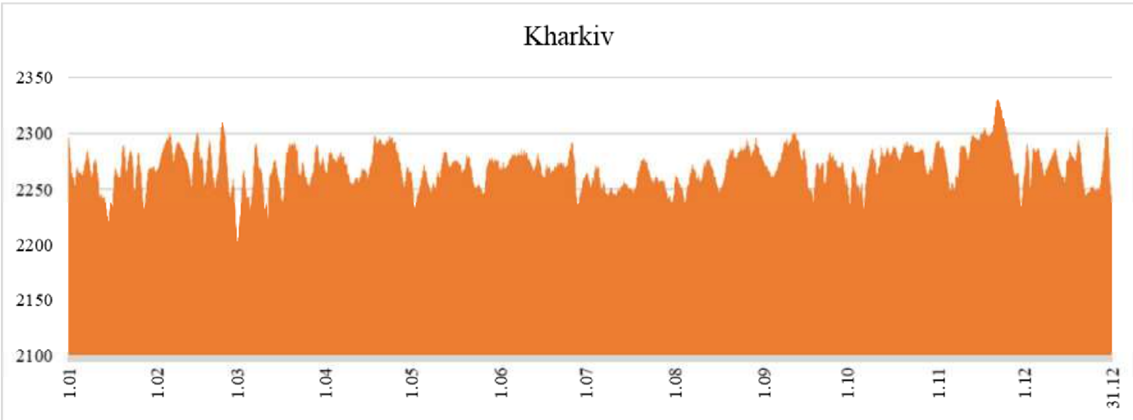

Fig. 2. Change of d_h^z component (in mm) at Kharkiv station during 2019

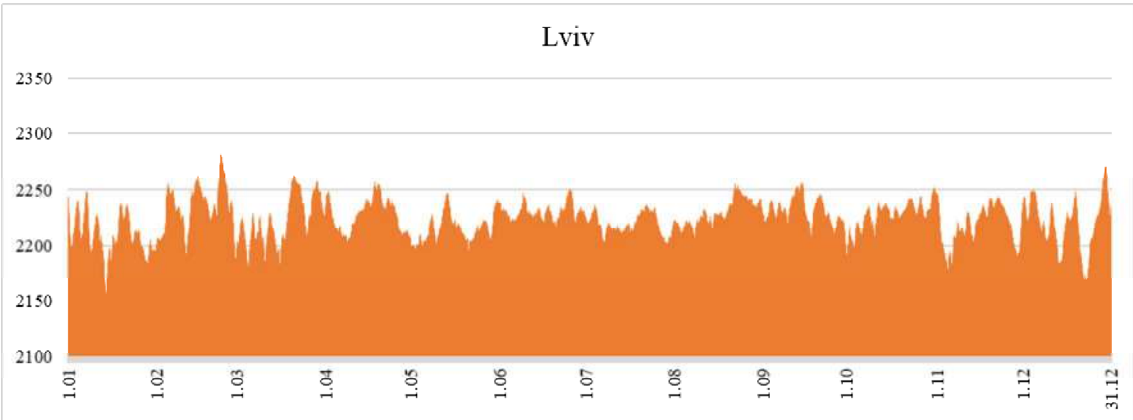

Fig. 3. Change of d_h^z component (in mm) at Lviv station during 2019

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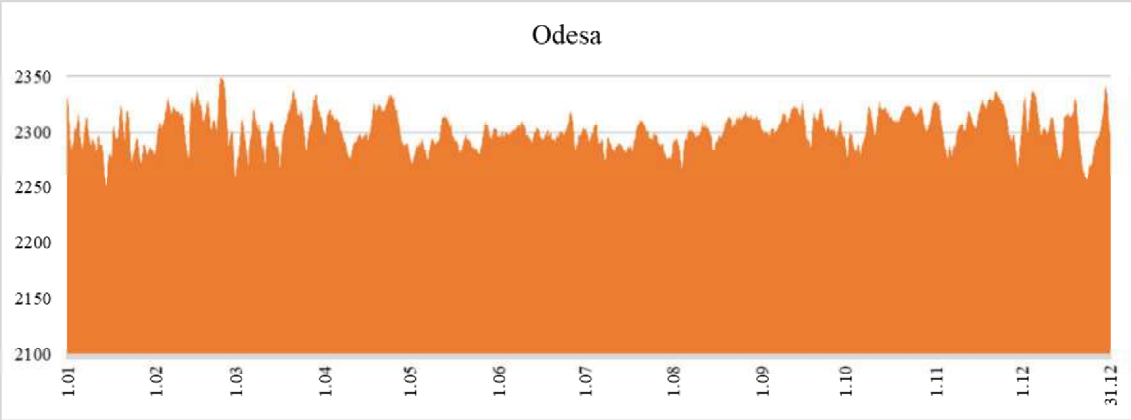

Fig. 4. Change of $\mathbf{d}_h^z$ *component (in mm) at Odesa station during 2019*

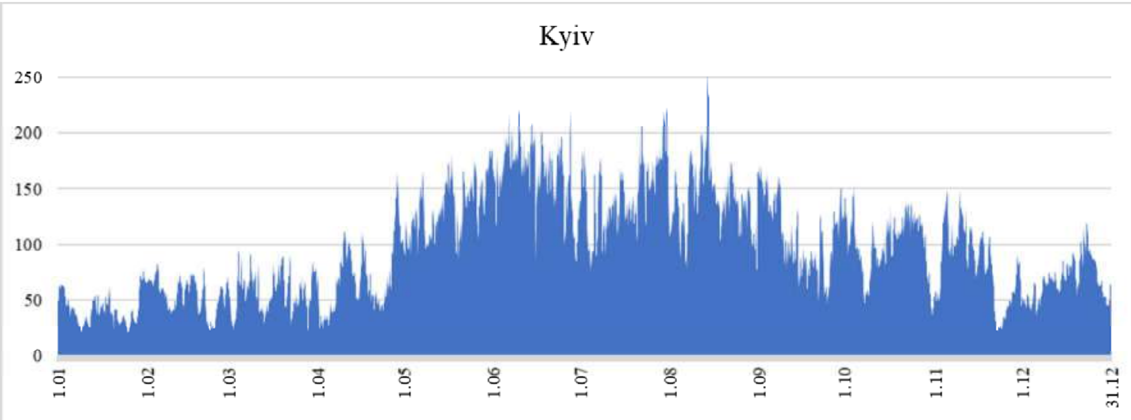

Fig. 5. Change of $\mathbf{d}_w^z$ *component (in mm) at Kyiv station during 2019*

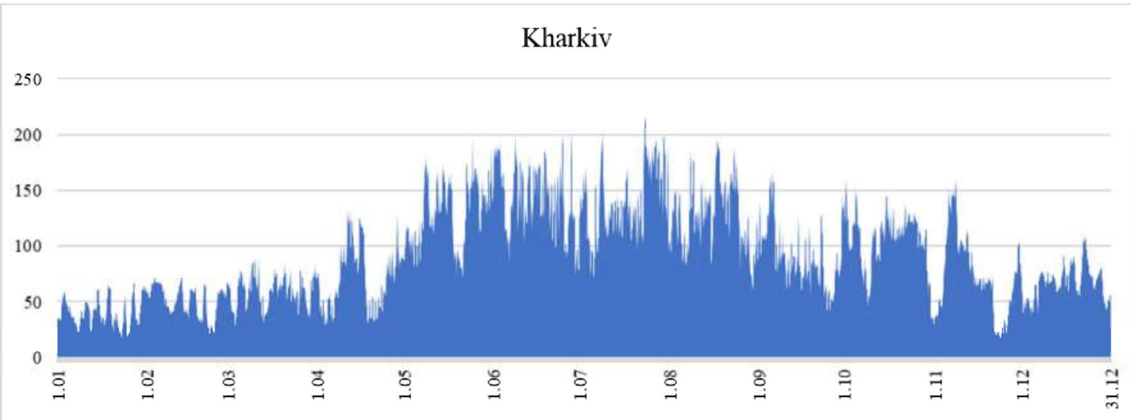

Fig. 6. Change of $\mathbf{d}_w^z$ *component (in mm) at Kharkiv station during 2019*

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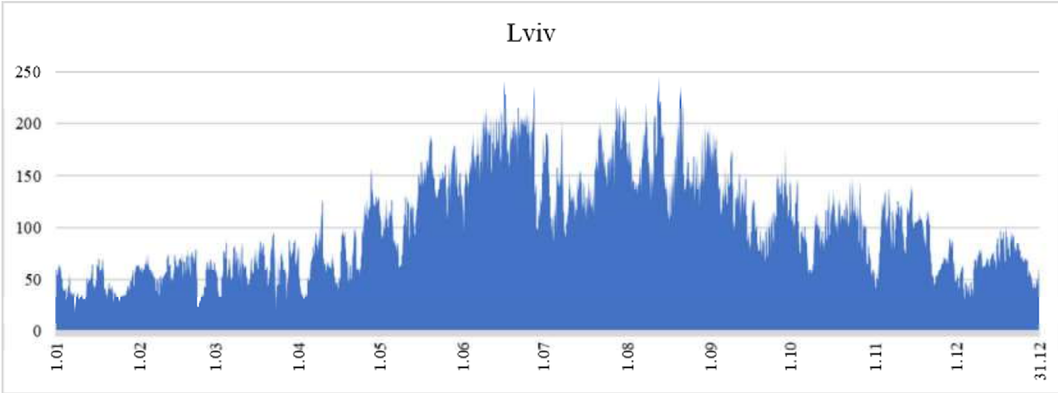

Fig. 7. Change of $\mathbf{d}_w^z$ component (in mm) at Lviv station during 2019

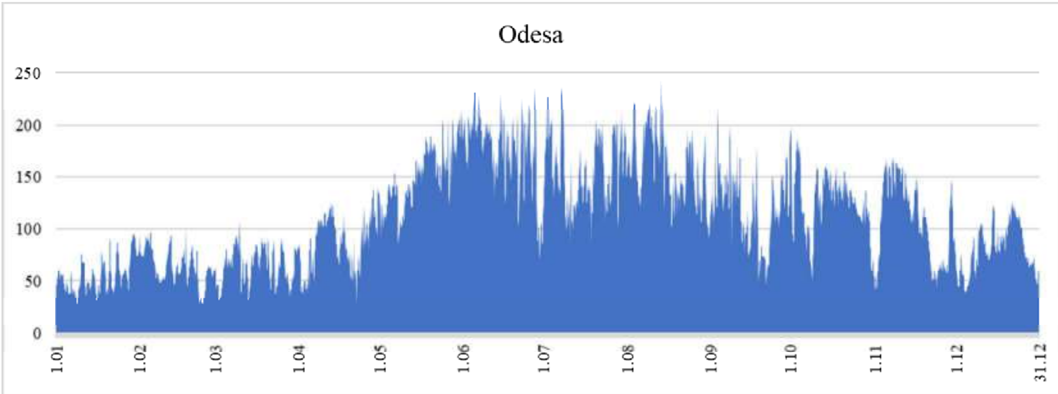

Fig. 8. Change of $\mathbf{d}_w^z$ component (in mm) at Odesa station during 2019

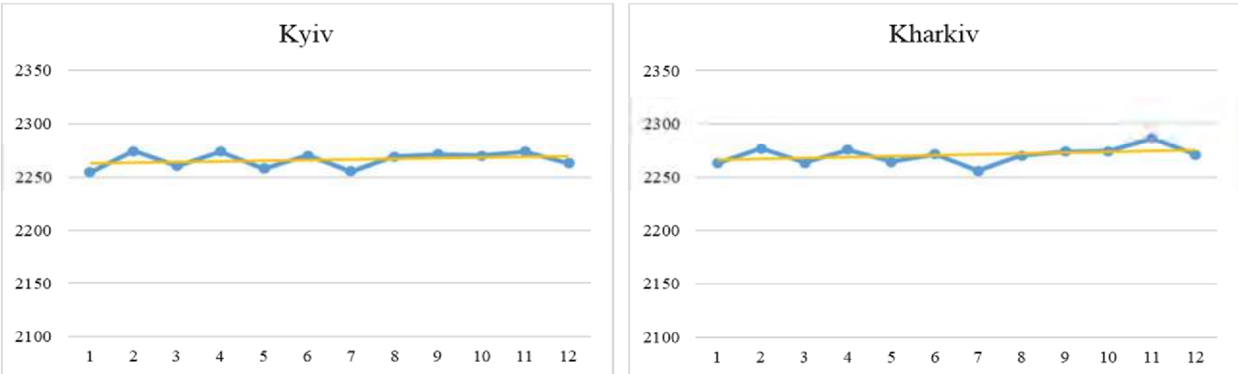

Fig. 9, 10. Average monthly and annual average value of the dry component (in mm)

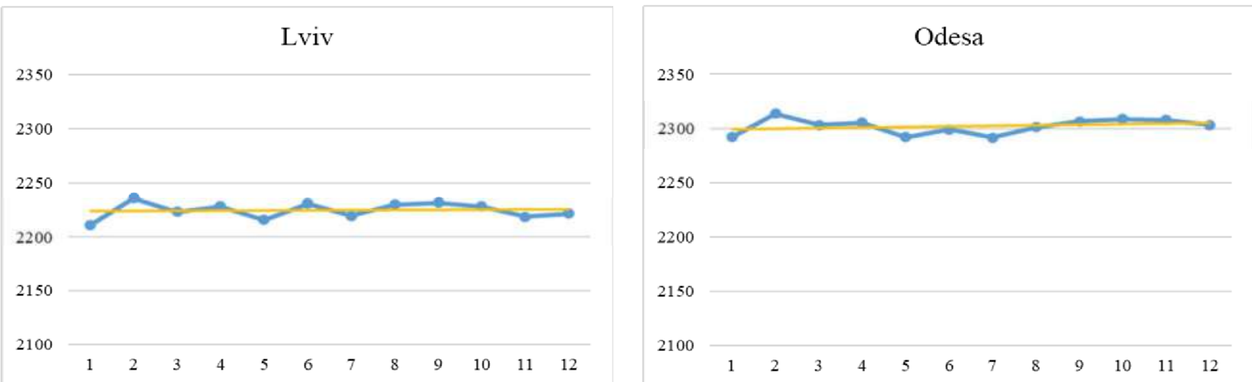

Fig. 11, 12. Average monthly and annual average value of the dry component (in mm)

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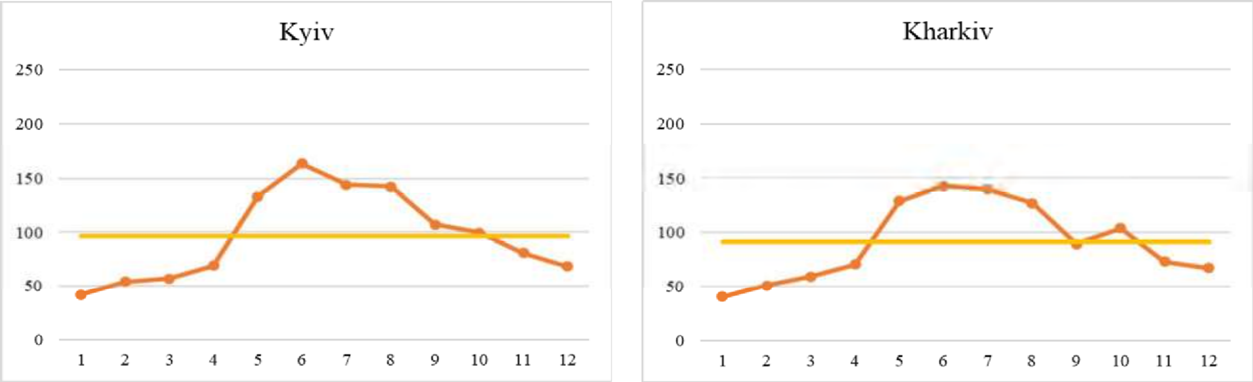

Fig. 13, 14. Average monthly and annual average value of the wet component (in mm)

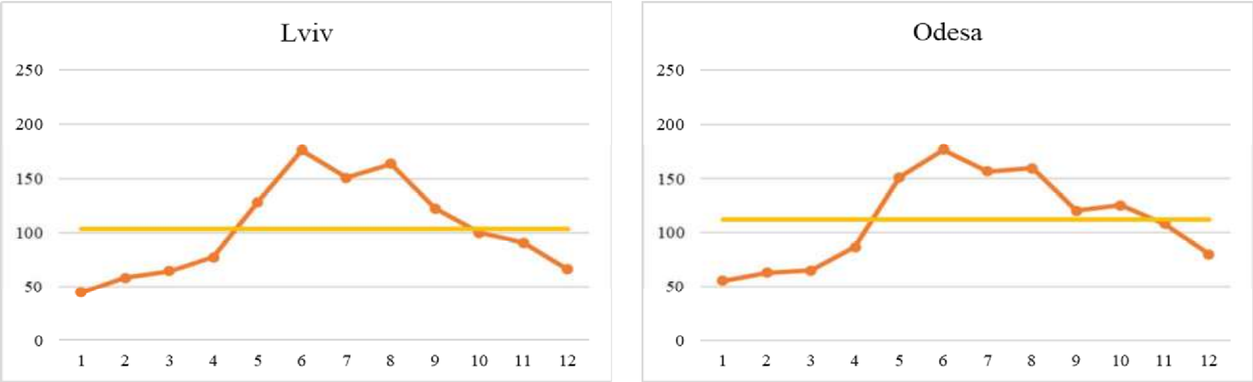

Fig. 15, 16. Average monthly and annual average value of the wet component (in mm)

Table 1

The main characteristics of meteorological quantities and the obtained values of the components

Station name, altitude, coordinates	Value	P, mBar	t, °C	f, %	e, mBar	d^{Z}_{h}, mm	d^{Z}_{w}, mm
1	2	3	4	5	6	7	8
Lviv	Avg.	977.4	9.9	77.9	10.3	2224.8	103.8
h = 318 m	Max.	1002.4	31.8	100.0	25.6	2281.8	247.5
$\varphi = 49{,}83^{O}$	Min.	947.3	-15.3	14.0	1.6	2156.1	17.9
$\lambda = 24{,}03^{O}$	Max.-Min.	55.2	47.1	86.0	24.0	125.6	229.6
Kyiv	Avg.	995.6	10.6	70.4	9.7	2266.1	97.1
h = 168 m	Max.	1017.8	34.0	100.0	26.2	2316.5	255.5
$\varphi = 50.4^{O}$	Min.	967.1	-14.0	18.0	1.8	2201.2	20.0
$\lambda = 30.52^{O}$	Max.-Min.	50.7	48.0	82.0	24.4	115.3	235.5
Kharkiv	Avg.	997.6	10.3	69.6	9.1	2270.7	91.7
h = 152 m	Max.	1024.3	33.5	100.0	22.2	2331.4	217.5
$\varphi = 49.92^{O}$	Min.	968.1	-16.6	17.0	1.4	2203.4	15.2
$\lambda = 36.23^{O}$	Max.-Min.	56.3	50.1	83.0	20.8	128.1	202.4

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Cont. Table 1

1	2	3	4	5	6	7	8
Odesa	Avg.	1011.3	12.9	71.8	11.3	2302.5	112.9
h = 42 m	Max.	1032.0	34.2	100.0	25.9	2349.7	249.8
φ = 46.43°	Min.	988.4	-9.9	17.0	2.5	2250.4	27.4
λ = 30.73°	Max.-Min.	43.6	44.1	83.0	23.4	99.3	222.4

Having analyzed the obtained time series, it should be noticed that the annual change in the dry component of ZHD has a much smaller amplitude than the wet ZWD.

The graphs show that ZHD becomes more significant in winter, as well as in the first months of spring and late autumn. It is visible at Kyiv and Odesa. At other stations, this change is not so noticeable. The average values of the component are the largest in Odesa, which is explained by the lowest height of the station – h = 42 m. The minimum average magnitude of ZHD at Lviv – 2224.8 mm, where the station is at a height h = 318 m and is the highest among the studied ones.

The wet component of ZWD, in contrast to ZHD, acquires the maximum values in summer (or rather – from early May to November). ZWD changes are more noticeable than ZHD changes. It can change for a short time up to 200 mm, while short-term changes in ZHD at different times of the year do not exceed 50 mm.

The highest value of ZWD was noticed at Odesa station (112.9 mm) and the lowest – at Kharkiv station (91.7 mm). At the other two points, the values are smaller, but there are temporary increases of up to 250 mm in summer. The wet component is characterized by a decrease in size in mid-summer. This is due to changes of weather conditions during this period, namely – a decrease of air temperature and relative humidity.

The obtained results were compared with the results obtained in [Palyanytsia, et al., 2016]. The difference lies in the fact that much more data is taken in the presented work, as the discreteness of data collection is 3 hours, but only the surface values of meteorological magnitudes (for 2019). Aerological sounding data for 10 days for each month as well as at night (in 2015) were selected in [Palyanytsia, et al., 2016]. Thus, in order to obtain average monthly values, the average magnitude for 10 days was calculated.

Comparing the average annual values of ZHD and ZWD for 2019 and 2015, we can find out that:

– the difference between the average annual values of ZHD in Kyiv is 8.9 mm, in Lviv – 7.7 mm, in Odesa – 4.9 mm;
– the difference between the average annual values of ZWD in Kyiv is 4.3 mm, in Kharkiv – 10.0 mm, in Lviv – 5.8 mm, in Odesa – 1.3 mm;
– in general, the average annual values of ZHD and ZWD for 2019 were lower than in 2015 due to weather conditions.

The variations in general tropospheric delay indirectly reflecting the weather and climatic processes, are caused by variations in the wet component. The amplitude of the change in the general delay is determined by the amplitude of change in the wet component, which at different points is almost two times bigger than the amplitude of change of the dry component. Graphs of the average monthly values of ZHD and ZWD confirme the same. Although ZWD is only up to 10 % of the value of ZTD, the influence of ZWD on the change of ZTD is obvious, because the scales of the vertical axes on the graphs are the same.

Scientific novelty and practical significance

The scientific novelty consists in identification of the features of annual change in the components of tropospheric delay at points in different climatic and weather conditions.

The practical significance of the conducted research is that they can be used in the monitoring tasks of large hydraulic structures by GNSS methods in order to create regional models of the atmosphere and further studies of tropospheric delay, as they relate to changes in space and time.

Conclusions

Based on researches of changes in delay values at four Ukrainian weather stations for the period of 2019, it is notable that the average monthly

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magnitudes of the ZHD component are higher at points whose altitude is lower.

The wet component of ZWD during the year acquires the maximum values in summer.

Annual fluctuations of the dry component of ZHD have a much smaller amplitude than the wet ZWD.

Although ZWD is only up to 10 % of the value of ZTD, the influence of ZWD on the change of ZTD is obvious, because the scales of the vertical axes on the graphs are the same.

Thus, the variations in total tropospheric delay, which indirectly reflects the weather and climatic processes, are caused by variations in the wet component.

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ДОСЛІДЖЕННЯ КОЛИВАНЬ СКЛАДОВИХ ЗЕНІТНОЇ ТРОПОСФЕРНОЇ ЗАТРИМКИ ПРОТЯГОМ РОКУ НА ТЕРИТОРІЇ УКРАЇНИ

Мета цієї роботи – дослідження коливань складових зенітної тропосферної затримки протягом річного періоду за даними наземних метеорологічних вимірювань на території України. **Методика.** Для досліджень використано приземні значення метеорологічних величин на пунктах: Львів, Київ, Харків та Одеса, отримані в 2019 році з інтервалом у 3 години. Всього по 2920 вимірювань на кожному з пунктів. Обчислення складових зенітної тропосферної затримки виконано за формулою Саастамойнена. За обчисленими значеннями складових побудовано графіки зміни сухої та вологої складових зенітної тропосферної затримки для кожного з пунктів. Надалі обчислювалися середньомісячні та середньорічні значення складових і порівнювалися між собою. **Результати**. На основі проведених досліджень зміни значень затримки на чотирьох українських метеостанціях за період 2019 року встановлено, що середньомісячні значення складової ZHD більші на пунктах, висота яких над рівнем моря є меншою. Волога складова ZWD протягом року найбільших значень набуває в літній період. Річні коливання сухої складової ZHD мають значно меншу амплітуду, ніж вологої ZWD. Амплітуда зміни сумарної затримки визначається амплітудою зміни вологої складової, що у різних пунктах майже вдвічі є більшою за амплітуду зміни сухої складової, незважаючи на те, що ZWD складає всього до 10 % від величини ZTD. Таким чином, варіації загальної тропосферної затримки, що опосередковано відображає погодно-кліматичні процеси, обумовлені варіаціями вологої складової. **Наукова новизна та практична значущість** полягають у виявленні особливостей річної зміни складових тропосферної затримки на пунктах, що знаходяться у різних кліматичних і погодних умовах. Виконані дослідження можуть використовуватися в задачах моніторингу крупних гідротехнічних споруд ГНСС-методами для створення регіональних моделей атмосфери та подальших досліджень тропосферної затримки, оскільки стосуються її зміни у просторі й у часі.

Ключові слова: тропосферна затримка; нейтральна атмосфера, супутникові виміри; методи визначення складових ZHD і ZWD зенітної тропосферної затримки ZTD.

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