УДК 528.18:629.783

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https://doi.org/10.23939/istcgcap2021.93.048

CONSTRUCTION OF 3D MODELS OF THE DISTRIBUTION OF ZENITHAL TROPOSPHERIC DELAY COMPONENTS FOR THE TERRITORY OF UKRAINE

The purpose of this work is to build 3D models of components of zenith tropospheric delay (ZTD) according to the surface measurements of meteorological values obtained at 100 points, which is almost evenly distributed throughout Ukraine. Method. Saastamoinen formulas calculated dry and wet components of the zenith tropospheric delay. According to the obtained results, the fields of dry and wet components of tropospheric delay were compiled, the fields of their change were constructed using a different number of studied points. Also, with the help of a graphic editor, 3D models of the magnitude one-moment distribution of dry and wet components of the zenith tropospheric delay for the territory of Ukraine were built. Results. Built 3D models of ZTD components; constructed zenith tropospheric delay fields for the territory of Ukraine; a comparison of the distribution of delay components for the specified area and its change during the day are the results of this work. It is established that the dry component becomes more important in the southern and central territory of Ukraine, where the observation points are lower in height and where there is a higher atmospheric pressure, which dominates in the calculation of this component. Accordingly, the wet component is also higher in the southern part of Ukraine, but this is due to higher relative humidity. As a result of the compaction of the network to 100 points, more accurate models of component distribution were obtained, which allowed Ukraine to assess in more detail the value of tropospheric delay for the territory of Ukraine. Further compaction of the network for the territory of Ukraine did not lead to the expected increase in the accuracy of tropospheric delay, as the location of meteorological stations in the country is not uniform enough, and some values of meteorological magnitudes are obtained not by direct measurements but by interpolation. It is necessary to compact the model with reliable meteorological measurements evenly and to control the calculation of components by integrating according to the aerological soundings carried out at individual points to obtain a more detailed model. Scientific novelty and practical significance. The scientific novelty is to build 3D models of tropospheric delay components for the territory of Ukraine at a certain point in time. The practical significance of the performed research is that they can be used as an initial step to build a Spatio-temporal model of tropospheric delay, reflecting the spatial changes of the delay in real-time for a particular area.

Key words: tropospheric delay; methods for determining tropospheric delay; determination of tropospheric delay components; tropospheric delay modeling; GNSS observations.

Introduction

One of the sources of errors in measuring pseudo-distances from the satellite to the GNSS receiver, due to the influence of the atmosphere, is the uneven passage of radio waves through the neutral, non-ionized part of the Earth's atmosphere containing layers of the troposphere and stratosphere. Moreover, although the whole atmosphere is involved in this error, a significant part is formed by the lower part. For example, a 10 km layer determines approximately 74 % of its value simulated [Palianytsia, 2001]. Therefore, the error of the impact on satellite measurements of the lower non-ionized part of the atmosphere is called tropospheric delay. Tropospheric delay is a significant factor that impairs the accuracy of GNSS measurements.

Methods of geodetic measurements based on GNSS technologies continue to be actively developed. They are widely used in various fields of science, including research of deformations of the earth's crust, monitoring of large engineering objects, hydraulic structures, and many others. All this requires high-precision measurements, and accordingly, there is a question of the possibility of accurately determining the magnitude of tropospheric delay and taking it into account in the measurement results. The study of the influence of the troposphere often involves the creation of new, selection, or modification of existing models to determine the delay [Mendes, et al., 2000; Zablocki, et al., 2004]. The state of the atmosphere, the processes that take place in it, the distribution of meteorological quantities with altitude, the vertical distribution of water vapor in the troposphere, the amount of deposited water vapor in the atmosphere, or the distribution of tropospheric delay components over a particular area are also simulated [Yang,, et al. 2020; Palianytsia, et al., 2020a; Palianytsia, et al., 2020b].

There is now a large amount of work devoted to studying the influence of the troposphere on the results of GNSS measurements. In recent years, many studies concern the determination of the amount of deposited vapor in the atmosphere at a particular tropospheric delay, the construction of troposphere models for weather forecasting [Bevis, et al., 1992; Kablak, 2011; Zablotskyi, et al., 2017; Paziak, 2019].

Many articles have assessed the effect of tropospheric delay on the accuracy of GNSS measurements performed in different parts of our planet with different climatic conditions. Among other works [Abdel-Ghany, et al., 2019; Ashraf EL-Kutb Mousa, 2016; Zablocki; et al., 2004; Zablocki, et al., 2006], in which studies were performed in Europe, America, Asia, Africa, and Antarctica. The results of meteorological studies conducted near Beijing to determine the ZTD for measurements of the Chinese navigation system BeiDou (BDS) were compared in [Yang, et al. 2020; Aigong, et al., 2013] with similarly defined using software packages of the International GNSS Service (IGS). The resulting displacements and standard deviations are about 2 mm and 5 mm, respectively.

In addition, research related to the creation of global models of tropospheric delay is exceptionally relevant. Recently, many approaches have been developed to model tropospheric delay and its components, especially wet, which is quite challenging to predict and model [Kablak, et. al., 2016]. For example, the Nevada Geodetic Laboratory (NGL) created an empirical model of the GPT3 (Global Pressure and Temperature) troposphere using data from 16,000 meteorological stations ten-year period, which is successfully used to calculate tropospheric delay. Due to the large number of stations, the long time series of data acquisition, and the different locations of the stations, the Spatio-temporal properties of the empirical model gave good results [Junsheng, et al., 2020].

The purpose

The work aims to build 3D models of tropospheric delay components based on surface measurements of meteorological values obtained at 100 points, which are almost evenly distributed on the territory of Ukraine.

Input data

To study the change in the magnitude of the components of the ZTD and the construction of the tropospheric delay field were used summary data of ground meteorological observations and from the resource [National Climatic Data Center] and data from the archive of the resource [Raspisaniye Pogodi Ltd.], namely: surface meteorological measurements (air temperature in ^{0}C, atmospheric pressure in hPa and relative humidity in%), carried out at meteorological stations and airports in July 2020, because the largest daily fluctuations in temperature and humidity are exactly in this period

Data were selected to ensure that the points were evenly distributed throughout Ukraine. For the study in the first case, meteorological data with a density of 240 km were used. This density approximately corresponds to the location of regional centers. Therefore, meteorological measurements are taken from observations conducted at meteorological stations in regional airports of Ukraine. The calculations performed on these data were used to build models of components, which are in the future referred to as "sparse." A network of 100 points was used to build "compacted" models, which are almost as dense as district centers in Ukraine (currently 136), and where meteorological observations are conducted and also the points outside Ukraine. The result is a network where the points are located at a distance of up to 80 km (Fig. 1).

Method

The accuracy of determining the tropospheric delay depends on the amount of meteorological data that can be used to calculate it. It is best if the aerological soundings data of the atmosphere obtained near the observation point were available at the GNSS measurements. However, since there is no such possibility, it is necessary to model the meteorological situation at the time of measurements, using the available data. Most often, surface measurements of meteorological quantities and analytical models are used to calculate the components of tropospheric delay. More than thirty such analytical models are known today. Nevertheless, for several decades the most popular model remains Saastamoinen [Saastamoinen, 1972]. According to research by many authors, including [Zablotsky, et al., 2004; Palyanytsia, et al., 2016], it is established that it gives good results for our region. Therefore, the calculations of the components of the tropospheric delay were calculated according to this model. According to it, the formula for the dry component of the zenith tropospheric has the following form:

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

and for wet – such:

$$d_{wSA} = 0.002277 \cdot \left(\frac{1255}{T_s} + 0.05\right) \cdot e_0 \quad (2)$$

In the formulas (3) and (4): φ *i* H_s – latitude and altitude of the observation station; T_s, P_s, e_0 – ground values of air temperature, atmospheric and partial pressure, respectively.

Research results

According to the calculated values of the delay components, grid files were created based on which the delay fields for the dry and wet components were constructed. Also, during the construction, different methods of interpolation were evaluated, and the most optimal one has been chosen.

In the beginning, according to the meteorological data selected for the grid built for points in the regional centers of Ukraine (sparse model, see Fig. 1a), delay fields were constructed for the dry and wet component for two days with an interval of 12 hours, as in [Masonry, et al., 2018].

The next step of the study was to seal the network of points (construction of a compacted model – Fig. 1b). Thus, another 75 points located on the territory of Ukraine were added to the existing network of 25 points and meteorological stations located outside its borders but not far from it. This makes it possible to avoid extrapolation in border areas not covered by the network of points located in our country. Thus, a network of points was obtained, the distance between which in most cases is less than 80 km. Figure 1 shows the observation points used to build the grid.

To illustrate the dynamics of changes in the dry and wet components and the difference between the compacted network of points, Figures 2–17 show the fields of change of dry and wet components. They were obtained within two days with an interval of 12 hours, i.e., at 00 and 12 hours on July 6 and at 00 hours and 12 hours on July 7 Kyiv time, i.e., two images fall on the night period and two – during the day.

Comparing the results presented in the figures, we can see that the compaction of the model had a positive effect on the result. The right figures show a more detailed picture of the distribution of components in the covered area.

Further compaction of the model did not always lead to a better result. The reason may be that the meteorological data were obtained by simple interpolation, and therefore the picture has not changed significantly. In addition, an anticyclone was observed throughout the country during the study period, and therefore the picture changed insignificantly in two days. Still, when the network is compacted, it is possible to estimate the field of delay components in more detail. Considering the field of the dry component, the use of a condensed network allows a more accurate assessment of the situation in areas with significant differences in atmospheric pressure (areas of the Carpathians and the Crimean Mountains).

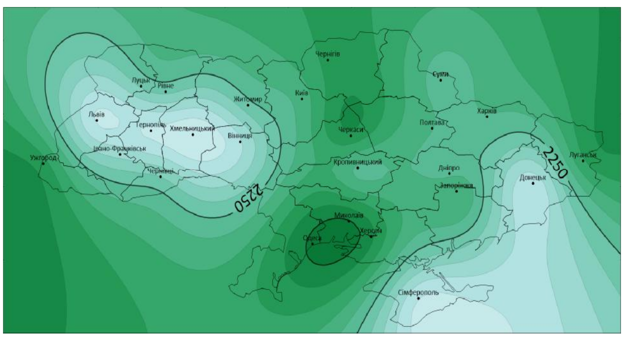
In the wet component, the model thickening makes it possible to assess the situation in more detail in areas with sharper changes in temperature and humidity (regions located near the sea). It can also be seen that using points outside the border, the field of components throughout Ukraine can be estimated by avoiding extrapolation.

If we consider the dynamics of change, the figures show that the change in the dry component is insignificant, and within two days, its values decrease almost evenly regardless of the period of the day. Concerning the wet component, the dynamics of its change are more significant, and the value during the study period is also significantly reduced.

a

b

Fig. 1. Comparison of sparse and compacted network:
a – Sparse network; b – Compacted network



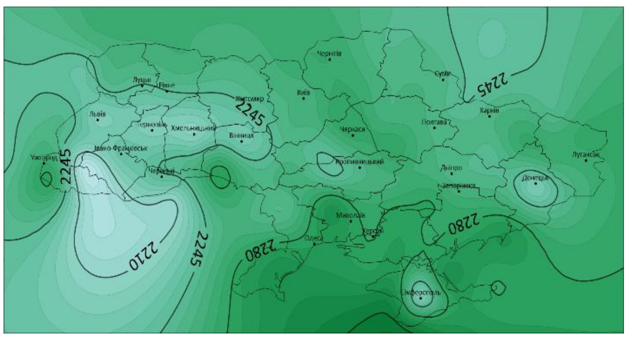


*Fig. 2, 3. The field of the dry component of the delay (mm) according to the rarefied model (left) and to the compacted model (right) as of **00 h July 6, 2020.** Isolines are drawn through 7 mm*

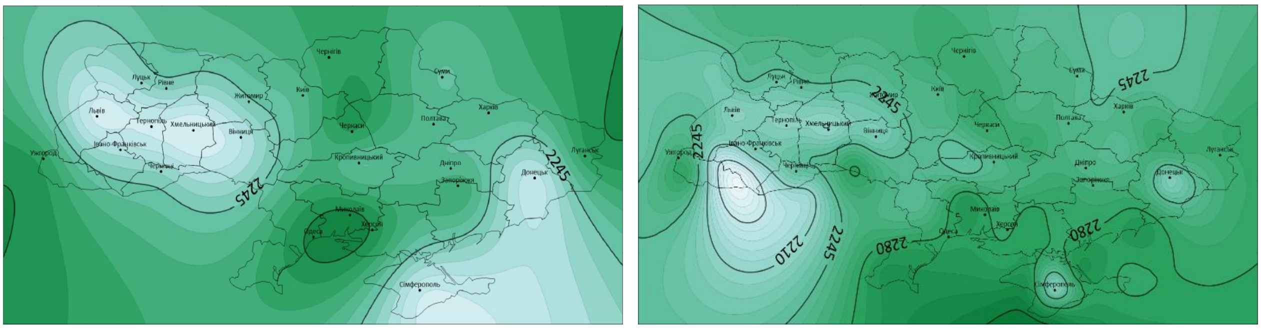


*Fig. 4, 5. The field of the dry component of the delay (mm) according to the sparse model (left) and to the compacted model (right) as of **noon on July 6, 2020.** Isolines are drawn through 7 mm*

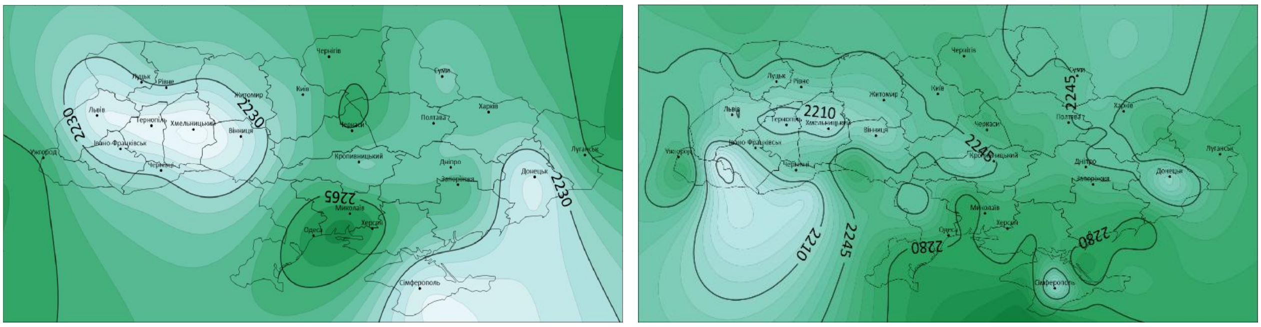


*Fig. 6, 7. The field of the dry component of the delay (mm) according to the sparse model (left) and to the condensed model (right) as of **00 h July 7, 2020.** Isolines are drawn through 7 mm*

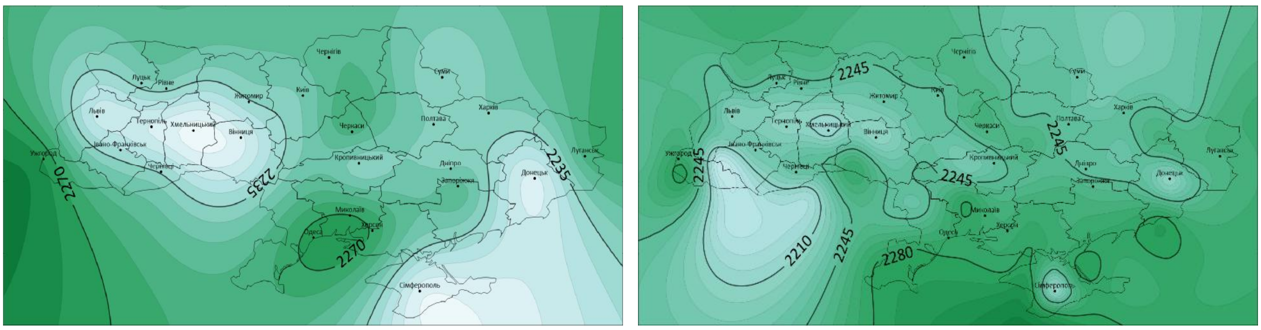


*Fig. 8, 9. The field of the dry component of the delay (mm) according to the sparse model (left) and to the compacted model (right) as of **noon on July 7, 2020.** Isolines are drawn through 7 mm*

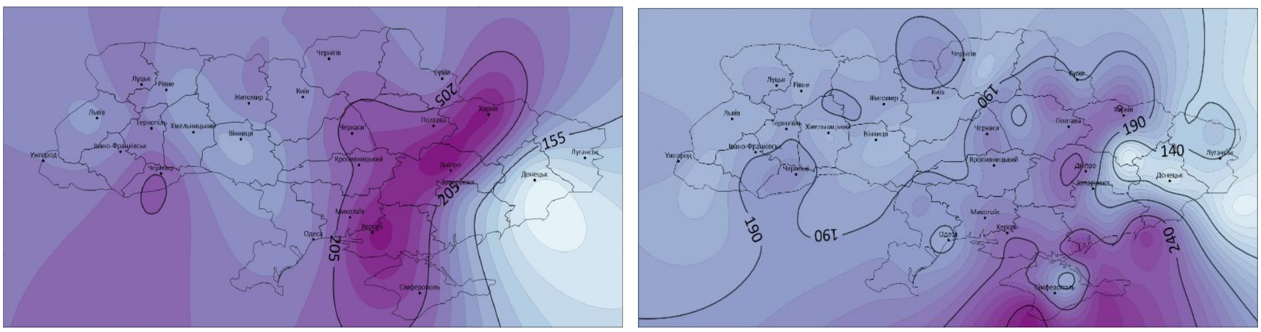


*Fig. 10, 11. The field of the wet component of the delay (mm) according to the sparse model (left) and to the compacted model (right) as of **00 h July 6, 2020.** Isolines are drawn through 10 mm*

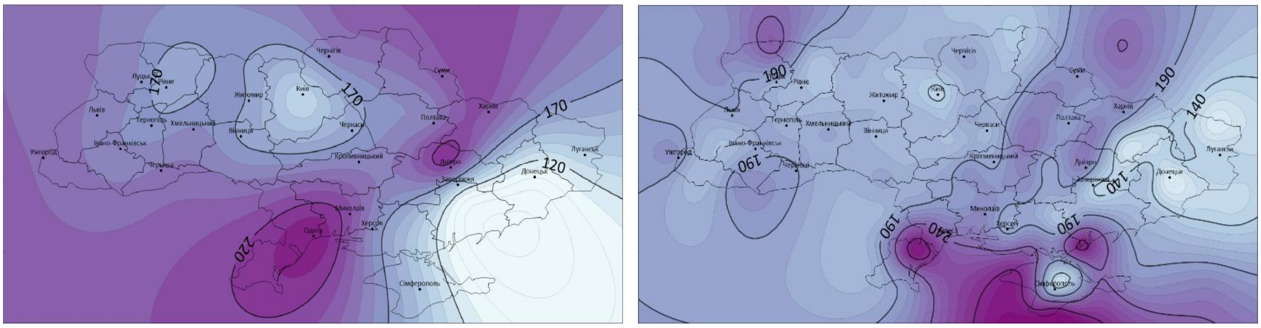


Fig. 12, 13. The field of the wet component of the delay (mm) according to the rarefied model (left) and to the compacted model (right) as of ***noon on July 6, 2020.*** *Isolines are drawn through 10 mm*

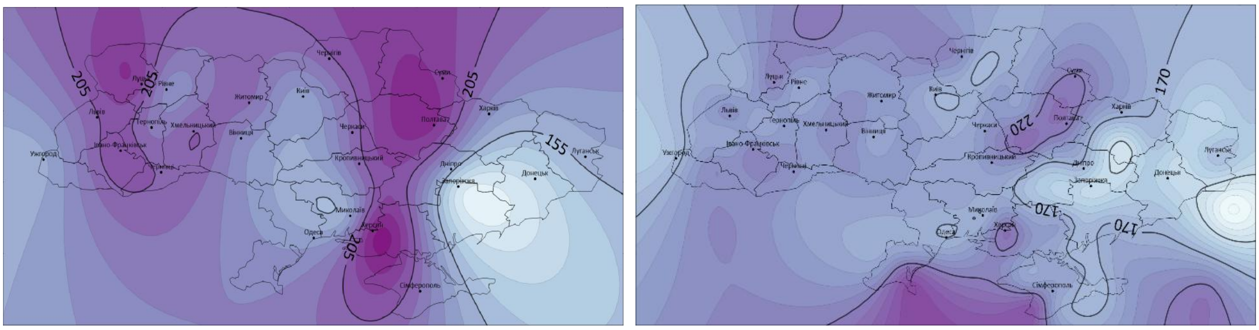


Fig. 14, 15. The field of the wet component of the delay (mm) according to the sparse model (left) and the compacted model (right) as of ***00 h July 7, 2020.*** *Isolines are drawn through 10 mm*

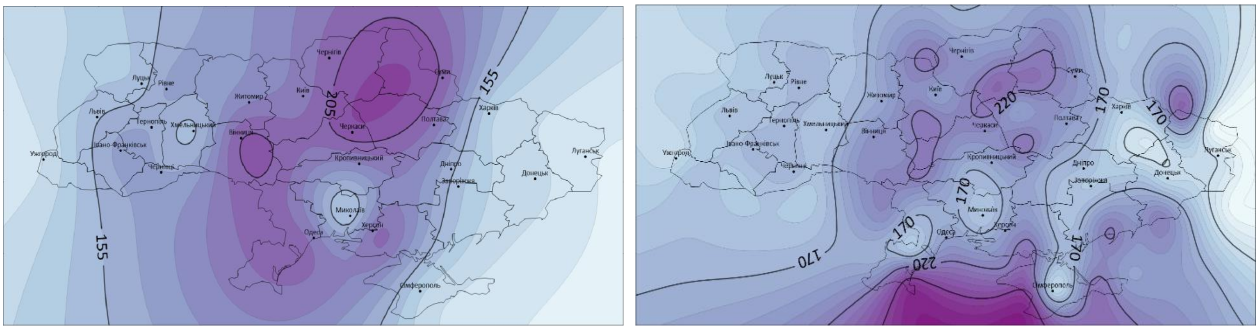


Fig. 16, 17. The field of the wet component of the delay (mm) according to the sparse model (left) and according to the compacted model (right) as of ***noon on July 7, 2020.*** *Isolines are drawn through 10 mm*

In addition to the general downward trend, it is also noticeable that the values of the components increase in the middle of the day and decrease at night, especially in areas located by the sea.

To better compare the results obtained with different densities of points, we have built spatial 3D models of the distribution of tropospheric delay components for the territory of Ukraine at a certain point in time. Figures 19–20 show hydrostatic (dry) models, and Figures 21–22 – non-hydrostatic (wet) component of ZTD. They are also built on the data of a sparse model (left) and compacted (right).

On models with a compacted network, points with significant differences in altitude and, accordingly, the values of meteorological quantities (particularly the Carpathian region) are excluded, which is due to significant differences in meteorological values significantly complicate this model and require separate, more detailed consideration.

If we compare the left and right figures for both components, i.e., models built on compacted and sparse models, it is evident that the condensed model gives a more regular picture with more minor differences in the south-eastern part of the covered area.

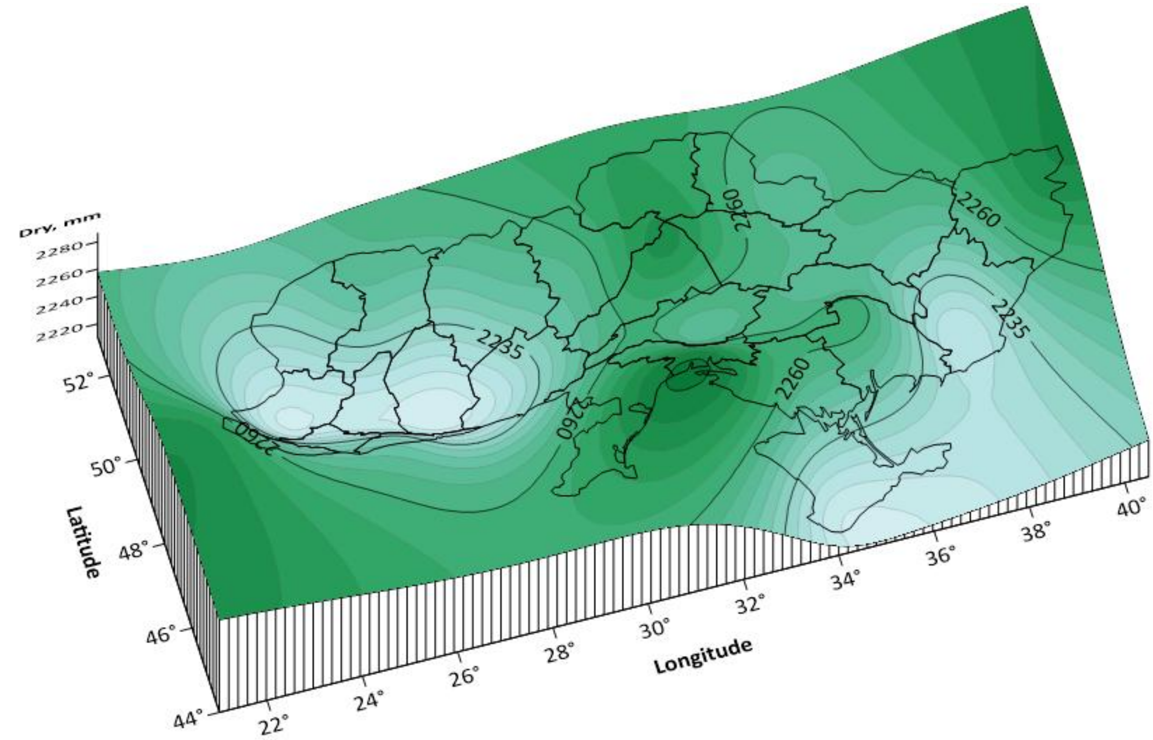


Fig. 19. 3D model of the dry component of the delay (mm) on the sparse model. Isolines are drawn through 7 mm

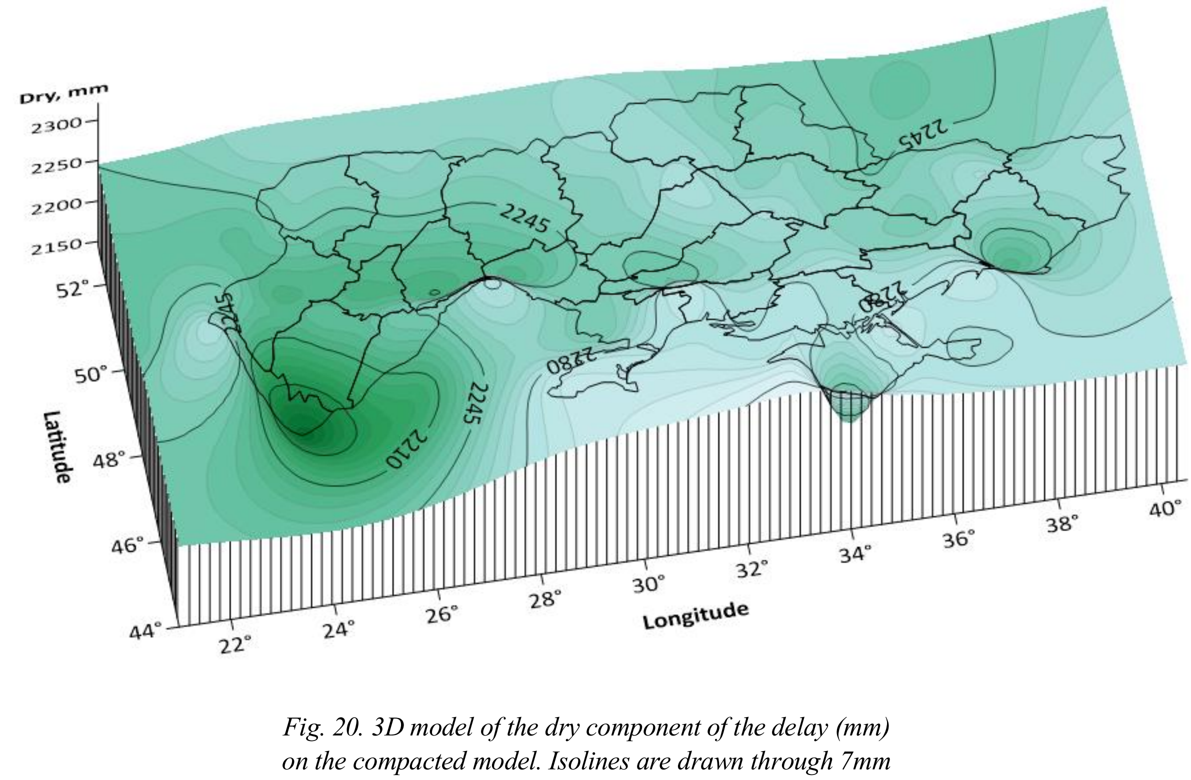


Fig. 20. 3D model of the dry component of the delay (mm) on the compacted model. Isolines are drawn through 7mm

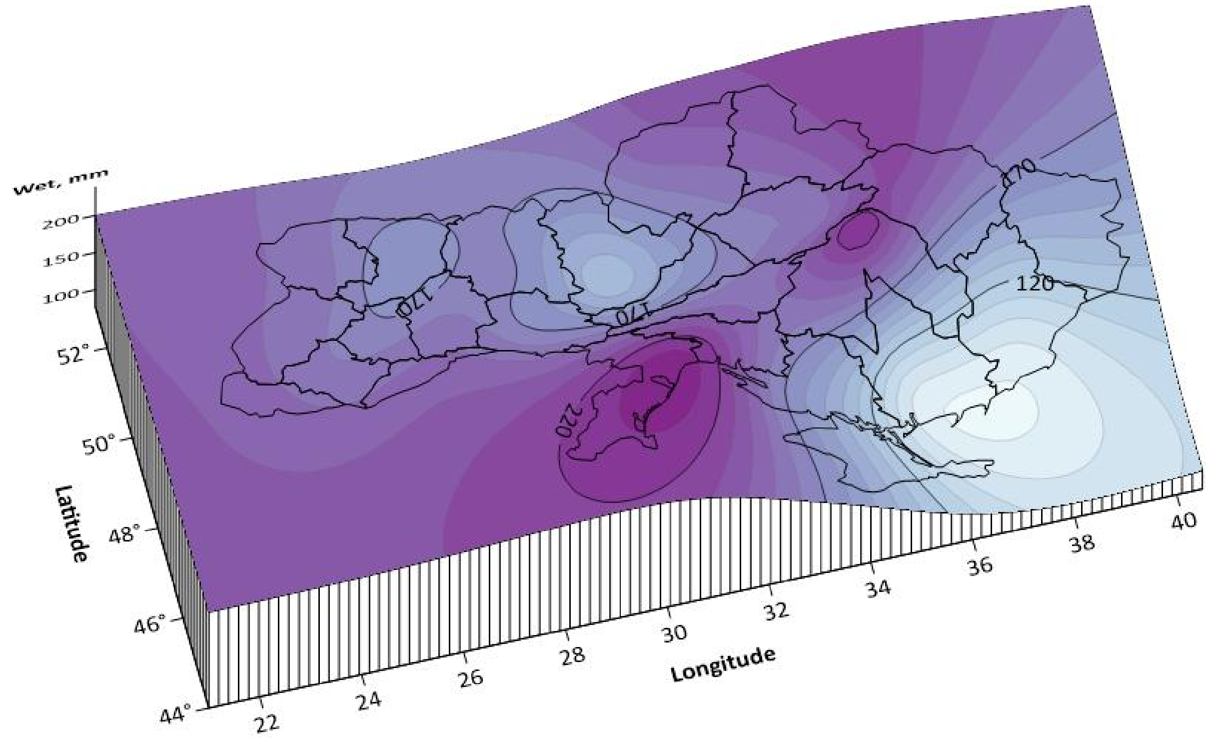


Fig. 21. 3D model of the wet component of the delay (mm) on the sparse model. Isolines are drawn through 10 mm

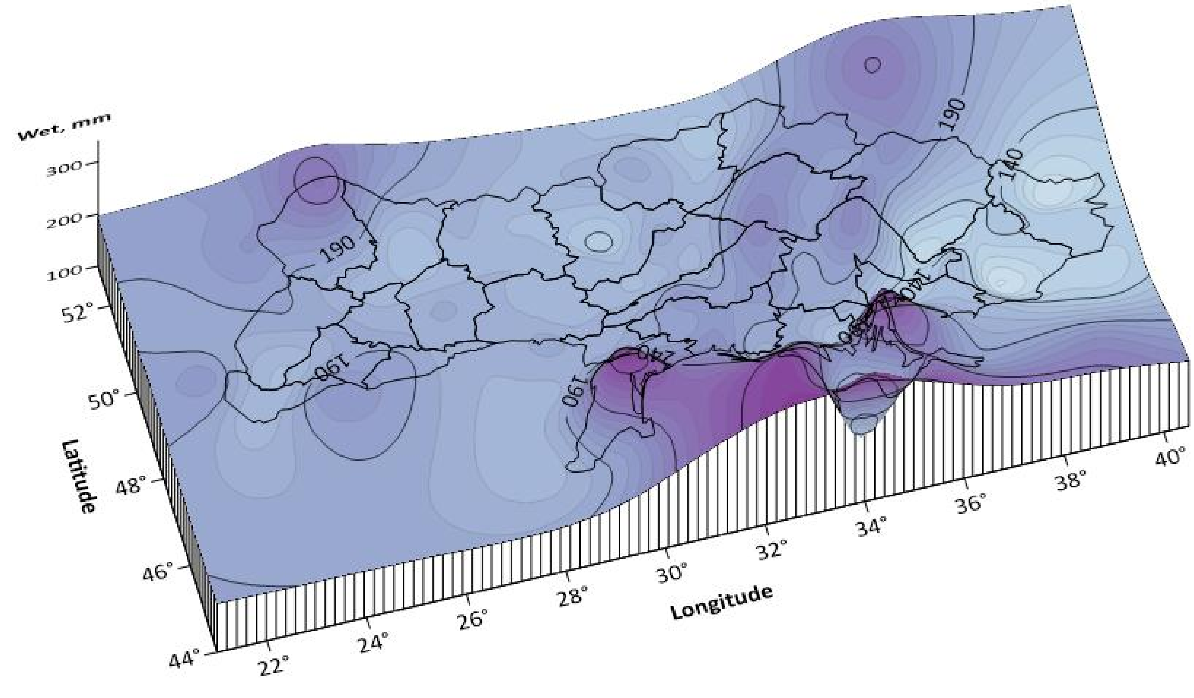


Fig. 22. 3D model of the wet component of the delay (mm) on the compacted model. Isolines are drawn through 10mm

Further compaction of the 3D model also did not lead to the expected increase in the accuracy of tropospheric delay determination, as the values of meteorological magnitudes at some points were not obtained from direct measurements but by interpolation.

Nevertheless, to obtain a more detailed model, it is necessary to evenly compact the model with points where reliable meteorological measurements will be performed and control the calculation of components by integrating according to aerological soundings conducted at individual points.

Scientific novelty and practical significance

The scientific novelty is to build 3D models of tropospheric delay components for the territory of Ukraine at a certain point in time.

The practical significance of the performed research is that they can be used as an initial step to build a Spatio-temporal model of tropospheric delay, reflecting the spatial changes of the delay in real-time for a particular area.

Conclusions

Considering the distribution of values of components of tropospheric delay in general on the territory of Ukraine, we can conclude that the dry component becomes more important in the southern and central territory of Ukraine, where observation points are lower in altitude and where the atmospheric pressure is higher.

The wet component is also higher in the southern part of Ukraine, but this is due to higher relative humidity. This component is much more difficult to predict because it depends on air temperature and humidity, which differently affect the component's value.

As a result of the compaction of the network to 100 points, more accurate models of component distribution were obtained, which allowed a more detailed assessment of the value of tropospheric delay for the territory of Ukraine.

Further compaction of the network for the territory of Ukraine did not lead to the expected increase in the accuracy of tropospheric delay, as the location of meteorological stations in the country is not uniform enough, and some values of meteorological values are obtained not by direct measurements but by interpolation. The compaction of models makes sense in considering the distribution of tropospheric delay components in small mountainous areas. There are significant differences in meteorological values. For example, the study of components in the Carpathian or Crimean mountains, where, considering significant differences in altitude, they will change dramatically or study the wet component in coastal areas, where its value is relatively large and changes significantly over short periods of weather conditions.

Nevertheless, to obtain detailed models, it is necessary to use the model of points evenly to carry out reliable meteorological measurements and control prefabricated integrations for this aerological sounding carried out at individual points.

REFERENCES

Ashraf, E. L., AbouAly, N., Sharaf, M., Zahra, H., & Darrag, M. (2016). Tropospheric wet delay estimation using GNSS: Case study of a permanent network in Egypt. *NRIAG Journal of Astronomy and Geophysics*, *5*(1), 76-86. https://doi.org/10.1016/j.nrjag.2016.01.002.

Aigong X., Zongqiu X., Maorong G., Xinchao X., Huizhong Z., & Xin S. (2013). Estimating Zenith Tropospheric Delays from BeiDou Navigation Satellite System Observations *Sensors*, *13*(4), 4514–4526; https://doi.org/10.3390/s130404514.

Abdel-Ghany M. S., A. Mahrous, E. A. Farid, Robaa S. M. & Abdel-Wahab M. M. (2019). Zenith Tropospheric Delay Corrections of GNSS Satellite Signal. *Current Science International*, 8, 230–235.

Bevis, M., Businger, S., Herring, T. A., Rocken, C., Anthes, R. A., & Ware, R. H. (1992). GPS meteorology: Remote sensing of atmospheric water vapor using the Global Positioning System. *Journal of Geophysical Research: Atmospheres*, *97*(D14), 15787–15801.

Junsheng D., & Junping, C. (2020). Assessment of Empirical Troposphere Model GPT3 Based on NGL's Global Troposphere Products. *Sensors*, *20*(13), 3631; https://doi.org/10.3390/s20133631.

Kablak, N. I. (2011). Monitoring of the besieged water vapor on the basis of the processing of GNSS data. *Space Science and Technology*. 17, 4, 65–73. https://doi.org/10.15407/knit2011.04.065.

Kablak, N., Reity, O., Ştefan, O., Rădulescu, A. T., & Rădulescu, C. (2016). The remote monitoring of Earth's atmosphere based on operative processing GNSS data in the UA-EUPOS/ZAKPOS network of active reference stations. *Sustainability*, *8*(4), 391. DOI:10.3390/su8040391.

Kladochnyi, B., & Palianytsia, B. (2018). The research of change in the components of zenith tropospheric delay. GeoTerrace. (in Ukrainian).

Mendes, V. B. (1999). Modeling the neutral-atmosphere propagation delay in radiometric space techniques. Ph.D. dissertation, Department of Geodesy and Geomatics Engineering Technical Report № 199, University of New Brunwick, Fredericton, New Brunswick, Canada, 353 p.

National Climatic Data Center, Asheville, North Carolina, USA. https://www.ncdc.noaa.gov/.

Paziak, M. (2019). Determination of precipitable water vapour, from the data of aerological ang GNSS measurements at europpean and tropical stations. *Geodesy, Cartography and Aerial Photography,* 89, 20–28.

Palianytsia, B. (2001). On determination of the tropospheric delay at calculation of GPS-measurements. *Modern achievements of geodetic science and production*. Lviv: Liga-Press, 48–52. (in Ukrainian).

Palianytsia, B., Oliynyk, V., & Boyko, V. (2016). The research of change of zenith troposperic dealay's components. *Geodesy, Cartography and Aerial Photography,* 83, 13–20.

Palianytsia, B. B., Kladochnyi, B. V., & Palianytsia, O. B. (2020a). Research of short-periodic changes in the components of zenith throposphere delay. *Geodesy, Cartography and Aerial Photography*, 91, 11–19.

Palianytsia, B. B., Kladochnyi, B. V., & Palianytsia, Kh. B. (2020b). Research of oscillations in the components of zenith tropospheric delay during the year in Ukraine. *Geodesy, Cartography and Aerial Photography*, 92, 5–14.

Raspisaniye Pogodi Ltd., St. Petersburg, Russia, https://rp5.ua/.

Saastamoinen, J. (1972). Atmospheric correction for the troposphere and stratosphere in radio ranging satellites. *The use of artificial satellites for geodesy*, *15*, 247–251.

Yang, Y. F., Chen, X. P., Yao, M. H., Zhou, C. L., & Liao, C. M. (2020). Research On Zenith Tropospheric Delay Modeling Of Regional Cors Network, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-3/W10, 1197–1200.

Zablotsky, F. D. (2000). On the choice of models for determining the components of zenith tropospheric delay in geodynamic research. *Geodynamics*. Lviv, 1 (3), 1–7.

Zablotsky, F., & Palyanytsya, B. (2004). Modified models for determining the dry component of zenith tropospheric delay in the South-Western region of Ukraine. *Geodesy, cartography and aerial photography*, 65, 51–56.

Zablotsky, F. D, Dovgan, N. R, & Palyanytsya, B. B. (2006). Peculiarities of tropospheric delay formation in Antarctica (according to McMurdo station. *Modern achievements of geodetic science and production.* Lviv: Liga-Press, 115–119. (in Ukrainian).

Zablotskyi, F., Gresko, Ju., & Palanytsa, B. (2017). Monitoring of water vapor content by radio sounding data at the Kyiv aerological station and by GNSS observation data at the GLSV station. *Geodesy, Cartography and Aerial Photography*, 85, 13–17.

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ПОБУДОВА 3D МОДЕЛЕЙ РОЗПОДІЛУ СКЛАДОВИХ ЗЕНІТНОЇ ТРОПОСФЕРНОЇ ЗАТРИМКИ ДЛЯ ТЕРИТОРІЇ УКРАЇНИ

Мета цієї роботи – побудувати 3D моделі складових зенітної тропосферної затримки (ZTD) за даними приземних вимірів метеорологічних величин, отриманих на 100 пунктах, що майже рівномірно розташовані на території України. Методика. Суха та волога складові зенітної тропосферної затримки обчислені за формулами Saastamoinen. За отриманими результатами складено поля сухої і вологої складових тропосферної затримки, побудовано поля їхньої зміни із використанням різної кількості досліджуваних пунктів. Також з допомогою графічного редактора побудовано 3D моделі одномоментного розподілу величини сухої та вологої складових зенітної тропосферної затримки для території України. Результати. Результатом роботи є побудовані 3D моделі складових ZTD; побудовані поля зенітної тропосферної затримки для території України; виконане порівняння розподілу складових затримки для вказаної території та її зміни протягом доби. Встановлено, що суха складова набуває більшого значення на південній та центральній території України, де пункти спостережень розташовані нижче за висотою, і де є більшим атмосферний тиск, який домінує при обчисленні цієї складової. Відповідно волога складова є більшою також у південній частині України, але це зумовлено вищою відносною вологістю. У результаті ущільнення мережі до 100 пунктів отримано точніші моделі розподілу складових, що дало змогу детальніше оцінити значення тропосферної затримки для території України. Подальше ущільнення мережі для території України не спричинило очікуваного підвищення точності визначення тропосферної затримки, оскільки недостатньо рівномірним є розташування метеостанцій на території країни, і деякі значення метеорологічних величин отримані не безпосередніми вимірюваннями, а методом інтерполяції. Для отримання детальнішої моделі необхідно рівномірно ущільнювати модель пунктами з надійними метеорологічними вимірюваннями, а для контролю використовувати обчислення складових інтегруванням за даними аерологічних зондувань, проведених на окремих пунктах. Наукова новизна полягає у побудові 3D моделей складових тропосферної затримки для території України на певний момент часу. Практична значущість виконаних досліджень у тому, що вони можуть використовуватися як початковий крок для побудови просторово-часової моделі тропосферної затримки, яка відображала б просторові зміни затримки у реальному часі для певної території.

Ключові слова: тропосферна затримка; вплив тропосфери на супутникові виміри; методи визначення тропосферної затримки; визначення складових тропосферної затримки; ГНСС-виміри.

Received 05.04.2021