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RECENT DEFORMATIONS OF THE EARTH'S CRUST IN UKRAINE BASED ON GNSS NETWORK DATA FROM GEOTERRACE AND SYSTEM.NET

The paper analyzes the recent trends of horizontal and vertical displacements of Ukraine's territory based on the GeoTerrace and System.Net GNSS network data. This includes the construction of relevant movement maps and the selection of deformation zones of the upper crust. The object of research is horizontal and vertical deformations of the upper crust. The goal is to identify and analyze deformation zones in Ukraine's territory. The source data includes the horizontal and vertical displacement rates of GNSS stations from the GeoTerrace network for 2018 to 2023 and the System.Net network for 2021 to 2023. This data is complemented by known tectonic map of the territory, sourced from the National Atlas of Ukraine, along with descriptive materials. The methodology includes comparison and analysis of recent deformations of the Earth's crust in the region with its known tectonic structure. New maps of recent horizontal displacement velocities of Ukraine's upper crust have been created, along with vertical displacement velocities of GNSS stations. These studies indicate that the recent horizontal movements within Ukraine are complex and closely linked to the known tectonic structure. Additionally, these movements were compared with regional model values derived from the ITRF-2020 model. Most GNSS stations have vertical subsidence trend, likely due to denudation processes. This study outlines the recent movements of the Earth's crust, however, a detailed interpretation should incorporate additional data from specialists in the Earth sciences. When observed over extended time intervals, the measured velocities of GNSS stations will help identify the spatial distribution characteristics of Earth's crust movement across Ukraine. This, in turn, will facilitate the development of regional geodynamic models for specific tectonic structures or regions, including Ukraine as a whole. Such models hold practical significance for advancing accurate navigation through precise positioning using networks of active GNSS stations.

Keywords: recent geodynamics, deformations of the Earth's crust, horizontal movements of the Earth's crust, vertical movements of the Earth's crust, displacement rates of GNSS stations, GNSS network, GNSS network GeoTerrace, GNSS network SystemNet, Ukraine, Ukrainian Shield, the Carpathians.

Introduction

Today, assessing recent geodynamic processes based on the data from the space-time series of GNSS stations is a common practice. This is facilitated by the constant growth of the number of permanent GNSS stations in the world, and in particular in Ukraine. On the website of GAO NAS of Ukraine [Ukrainian GNSS Network], the list of Ukrainian GNSS stations was last updated on November 10, 2020. The list includes 417 active and 108 dismantled Ukrainian permanent GNSS stations. As of the beginning of 2022, the number of permanent GNSS stations on the territory of Ukraine [Brusak et al., 2024] was estimated at more than 450 units. This number decreased after the full-scale Russian offensive, but as of 2024, the number of stations continues to increase.

GNSS stations of Ukraine are united in a network of state and privately owned stations. The following GNSS networks operate on the territory of Ukraine: the Main Astronomical Observatory of the National Academy of Sciences of Ukraine (GAO), the State Geocadastre of Ukraine (UPM GNSS), PJSC System Solutions (System.NET), Lviv Polytechnic National University (GeoTerrace), Navigation and Geodetic Center (NGC.net), Kyiv Institute of Land Relations (KyivPOS), Coordinate-Time System of Ukraine (NET.Spacecenter), TNT TPI company (RTKHUB Network), etc.

GeoTerrace and System.NET network data were used in this study, as they complement each other's geometry and provide coverage for the entire territory under Ukrainian control, excluding temporarily occupied areas.

The GeoTerrace network was established in 2007 in the Lviv region and now consists of 84 GNSS stations that create a cohesive network spanning 14 regions of Ukraine. Additionally, to enhance the network, we have included stations located in Poland near the Ukrainian border, which are part of the Polish networks ASG EUPOS (http://www.asgeupos.pl) and TPI NET pro (https://tpinet.pl). These stations facilitate data exchange between the networks [Siejka, 2017]. Most GNSS stations are equipped with Trimble and Leica receivers. Real-time data management of the GeoTerrace network is conducted using the Sino GNSS CDC.NET software suite in the laboratory of Lviv Polytechnic National University.

The System.NET network was established in 2012 and has grown to support approximately 300 stations. In 2019, this private network was designated as a special-purpose geodetic network [Novikova et al., 2020]. Most active GNSS stations within the System.NET network are equipped with receivers from Leica Geosystems. The network is managed in real-time using the comprehensive Leica Spider software.

The primary goal of the GeoTerrace and System.NET networks is to offer users real-time differential corrections for accurate positioning. This capability is essential for monitoring spatial displacements of the Earth's crust and assessing the stability of large engineering infrastructures, such as hydroelectric and nuclear power plants, as well as the deformation of the surrounding areas. Furthermore, these networks are fully integrated with the networks of EUPOS countries, including Poland, Slovakia, Hungary, Romania, and Moldova. The GeoTerrace and System.NET networks are operated by separate Control Centers that continuously perform GNSS measurements utilizing GPS, GALILEO, and BEIDOU satellites.

Preliminary studies on the geodynamics of Ukraine based on GNSS data

Extensive research has been conducted over the past decade on the horizontal and vertical displacement velocities of GNSS stations in Ukraine, as well as on the assessment of earth surface deformations. Initially, these studies focused on stations within Europe. For instance, [Ishchenko, 2016] evaluated the spatial movements of 12 Ukrainian stations from 1997 to 2006. [Vysotenko, 2010] determined the rate of change in coordinates for a total of 16 permanently operating stations and periodically operating UPM points in the GNSS network, based on observations from 1995 to 2007. Additionally, [Tretyak and Vovk, 2014] estimated the horizontal displacement rates of six Ukrainian stations from 2000 to 2010. As the number of GNSS stations increased, similar studies began to cover the entire territory of Ukraine, including specific regions.

The geodynamics of various regions of Ukraine have been studied in detail using GNSS data. [Marchenko et al., 2019] analyzed the horizontal deformations in western Ukraine by utilizing data from 26 GNSS stations in Ukraine, along with 11 nearby stations from European countries, from 2016 to 2019. In another study, [Doskich, 2021] examined data from 28 GNSS stations in the Carpathian region from 2013 to 2020, estimating the horizontal displacement rates. This study identified two active zones of extension: the Rakhiv–Verkhovyna zone and the Syanok – Ustryky – Dolishni zone, as well as a zone of compression in the Rakhiv – Khust – Mukachevo area. The study by [Tretyak and Brusak, 2021] investigated geodynamic anomalies in the GNSS stations of the GeoTerrace network to identify short-term vertical displacements caused by non-tidal atmospheric loading during 2019 [Brusak and Tretyak, 2020; 2021]. A more extensive regional analysis of the geodynamics of western Ukraine was investigated [Tretyak and Brusak, 2022] based on the data of 48 GNSS stations from 2018 to 2021 of the GeoTerrace networkThe horizontal and vertical deformations of the area have been analyzed alongside geophysical and tectonic data to enhance the understanding of these deformation processes. Specifically, a study by [Pelc-Mieczkowska, 2020] evaluated the effectiveness of GNSS stations in Ukraine for geodynamic research, utilizing results derived from the Precise Point Positioning (PPP) method. Additionally, the study by [Doskich et al., 2023] analyzed data from 30 GNSS stations that employed the PPP method between 2017 and 2020. The authors deemed this data suitable for addressing geodynamic issues, as the time series of the coordinates adhered to the normal distribution. Most of these stations are located in Podillia and the Kyiv region. Horizontal displacement rates, as well as compression and tension in the territory, were calculated based on this data.

Results from 120 GNSS stations observed over four years, from 2013 to 2016, were analyzed to assess the recent movements of GNSS stations in Ukraine. However, the network of GNSS stations is not continuous; there are virtually no stations suitable for geodynamic research in the southern regions of Ukraine, particularly in Odesa, Mykolaiv, and Kherson, as well as in the northern regions, specifically Chernihiv and Sumy. Although the study provides a comparison with the tectonic map, the lack of uniform data from GNSS stations hinders a comprehensive assessment of the geodynamics of the entire Ukraine`s territory.

An analysis of a network of 202 permanent GNSS stations conducted between 1997 and 2017 [Ishchenko, 2018] identified various deformations in the upper crust of Ukraine, including stretching, compression, rotation, and dilation. This comprehensive study included data from GNSS stations in

Moldova, Romania, and Poland. Some debated aspects of the study include using a time series of station coordinates with different durations and the uneven distribution of stations throughout Ukraine. Notably, the complex geodynamic region of the Ukrainian Carpathians is represented by only four GNSS stations. The results reveal the compression and tension in different portions of the Earth’s crust, as well as their rotational movements. These findings were compared to geomagnetic field studies that employed geophysical methods, the UKG2012 quasi-geoid, and recent maps illustrating Earth’s crust movements in Ukraine [Orlyuk and Ishchenko, 2019a; Orlyuk and Ishchenko, 2019b]. The authors identified four major modern morphostructures, or geoblocks, within Ukraine: North-Western (I) and North-Eastern (II), rotating clockwise; Southwestern (III) and Southeastern (IV) rotating counterclockwise. These geoblocks are characterized by lineament zones trending both northeast and northwest.

The work [Khoda, 2024] is the latest publication on the assessment of displacement rates of Ukrainian GNSS stations in the IGb08 reference system. This study has established 356 sets of coordinates and 256 sets of displacement velocities for 233 permanent GNSS stations. The coordinates and displacement speeds of these stations in the IGb08 reference system for the epoch of 2005.0 were evaluated. The average convergence of the station coordinates is 1.69 mm for the northern component, 1.40 mm for the eastern component, and 3.63 mm for the altitudinal component.

Recent research in Europe, particularly utilizing data from several dozen GNSS stations in Ukraine, focuses on establishing a three-dimensional model of displacement velocities across the continent [Piña-Valdés et al., 2022]. In a study by [Savchyn and Bilashuk, 2023], horizontal geodynamic deformations in the Carpathian Mountains, including the Ukrainian Carpathians, are analyzed based on GNSS station data. Additionally, research on high-altitude deformations of the upper crust in Poland [Kowalczyk et al., 2020] allows for comparisons with similar deformations in the border regions of Ukraine. A significant contribution is provided by [Naumowicz et al., 2024], which presents a model of absolute vertical movements of the Earth’s crust in Poland, developed using the PPP solution and incorporating geological, tectonic, hydrological, and mineral information. The authors suggest that analogous models should be created for the territory of Ukraine.

Numerous studies focusing on the movements of GNSS stations and Ukraine`s geodynamics highlight the importance of this research area. Many scientists concentrate on reporting the results related to station displacement velocities [Khoda, 2024; Savchuk and Doskich, 2017] or deformation parameters [Ishchenko, 2018; Marchenko et al., 2019; Doskich et al., 2023]. Additionally, some publications not only derive deformation parameters from GNSS data but also attempt to interpret them [Orlyuk and Ishchenko, 2019; Tretyak and Brusak, 2020; Savchyn et al., 2021; Tretyak and Brusak, 2022; Piña-Valdéset al., 2022; Naumowicz et al., 2024]. It is important to note that defining the current vector field of displacements across Ukraine’s Earth’s crust will enable a better understanding of recent geodynamic processes and facilitate temporal forecasting. This understanding is crucial for the development of the country’s primary GNSS networks.

This study aims to clarify the current geodynamics in the region by utilizing a regular network of GNSS stations, as much as feasible under the challenging conditions of military operations in areas controlled by Ukrainian authorities.

Initial data and their processing

As mentioned earlier, the results of GNSS stations of two GeoTerrace and System.NET networks were used for geodynamic studies. To compare the results, 30-second daily RINEX files were selected from all stations. The daily solutions for the GNSS stations were calculated in post-processing using the Bernese GNSS Software, following the methodology outlined by [Dach et al., 2015]. Consistent strategies and settings were employed throughout the entire process.

Data processing utilized the Double Difference method, with IGS network stations as reference points. The calculations were conducted solely based on GPS signal data and adhered to the latest IGS14 standards for phase center variation and other necessary corrections required for precise GNSS data calculations.

The data processing started with the preprocessing phase for each baseline, utilizing triplet difference techniques. The latest time products were used in the calculations [Maciuk et al., 2023]. Cycle shifts were eliminated by analyzing various linear combinations of L1 and L2 frequencies, and unreliable data points were either removed or recalibrated. A cutoff angle of 7 degrees was set. The GMF and DRY-GMF models with an update frequency every two hours were used to estimate tropospheric delays. Ionospheric effects were reduced using an ionospheric-free dual-frequency linear combination approach, improving resolved ambiguities accuracy.

The determination of solid Earth tides was conducted following the IERS 2010 Conventions. These conventions do not consider oceanic tidal loading but do account for the effects of atmospheric tidal loading. The satellite orbits and Earth orientation parameters were obtained using the most accurate IGS products, ensuring high precision in the calculated coordinates.

A weighted least squares algorithm was employed to estimate the station coordinates. Ionospheric corrections were obtained from reference stations to enhance accuracy, helping to resolve ambiguities for baselines ranging from very short (0−20 km) to several thousand kilometers. The calculated coordinates for the GNSS stations generally achieved a planned accuracy of 3−4 mm in both longitude and latitude. The accuracy for the height component is between 7–8 mm. Coordinate accuracy is reported at a 95 % confidence level, which varies according to the duration of the data, thereby ensuring a reliable and thorough data processing methodology.

The geocentric coordinates (X, Y, Z) of GNSS stations are defined within the ITRF-2020 system. The displacements of GNSS stations (ΔX, ΔY, ΔZ) are calculated by subtracting the coordinates of the station at the current epoch from the coordinates recorded at the first epoch.

The analysis was conducted using a method where a catalog of daily solutions from the Bernese GNSS Software was exported to custom-developed software. Vertical jumps in the time series were removed both manually and through a simple filter, excluding deviations greater than 1 cm from the overall trend. It is worth noting that only 0.1 % to 0.2 % of the extracted data from three years or more needed to be filtered. Overall, the quality of the data was good.

In this study, time series decomposition was not performed; instead, the trend was represented by the average value of the series. The definitions of seasonality, noise, and other components for this time series remain unclear. An example of a factor that could influence the GNSS time series in this region is the recorded impact of non-tidal atmospheric loading (NTAL) [Brusak and Tretyak, 2020; Tretyak et al., 2021a, 2021b]. It is recognized that the International Earth Rotation Service (IERS) recommends accounting for simulated deformations in software products caused by tidal loads when analyzing GNSS time series. However, there are no such recommendations for non-tidal models. Non-tidal adjustments have been shown to deform the upper crust, yet we do not account for this effect based on IERS guidelines. Due to this oversight and other potential deformation factors, we chose not to decompose the time series into components.

Based on the experience of processing GNSS measurements conducted by various researchers, the accuracy of determining vertical displacement velocities from measurements taken for more than 2.5 years at a GNSS station is typically within 0.3−0.6 mm/year [Desai et al., 2016]. This level of accuracy is satisfactory for determining linear velocities, which are indicative of movements within the Earth's crust. However, if the measurement duration is reduced to one or two years, the accuracy of the velocity determination declines to 1−2 mm/year or more [Esposito et al., 2015; Devoti et al., 2017].

Overall, 214 GNSS stations were established in Ukraine, operating effectively for at least three years from 2021 to 2023. The results from these stations and their time series graphs underwent further analysis:

1. Some of these stations were discarded and are unsuitable for geodynamic studies if they contain less than 200 annual solutions.

2. The accuracy of the solutions was evaluated separately, as military factors have noticeably affected data accuracy. For instance, jamming or distortion of the GNSS signal has been observed in certain regions of Ukraine [Brusak et al., 2024]. We rejected daily solutions with a low **mean squared error** of position (MSE), specifically those with planar accuracy below 10 mm and height accuracy below 30 mm.

3. In the final stage of the analysis, we considered the geometry of the GNSS network. In large cities, the distance between some GNSS stations could be as much as 10 kilometers. For further analysis, we selected the GNSS station with the smallest MSE of time series, which usually had a longer time series. For distances less than 10 kilometers, some stations were choosen if they were situated on different tectonic structures, as shown in comparison with the tectonic map from the National Atlas of Ukraine [2007] and, additionally, some stations were located across natural separations, i.e. on opposite banks of the Dnipro River.

Analyzing the time series, we considered the replacement of antennas for some GNSS stations. For example, Fig. 1 shows the spatial displacements of the SULP GNSS station along the geocentric axes X, Y, and Z in ITRF-2020 coordinate system. Shifts ΔZ along the Z axis have seasonal deviations [Davis et al., 2012; Gruszczynska et al., 2017] from the trend line. The longest series of observations is required to eliminate the influence of seasonal fluctuations. The trend line reflects the linear displacement velocity of the GNSS station along the corresponding axes, shown in Fig. 1.

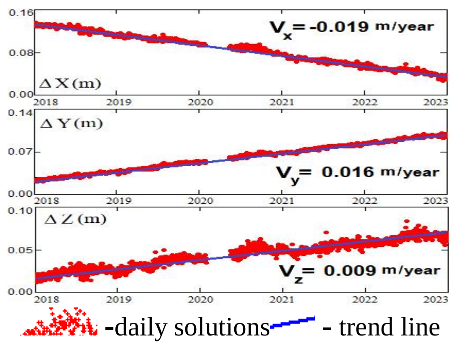

Fig. 1. Space-time series of GNSS displacements of the SULP station in ITRF-2020 coordinate system.

A network of 168 GNSS stations has been established for geodynamics studies in Ukraine, excluding the temporarily occupied territories. The average distance between neighboring GNSS stations in the combined network of GeoTerrace and System.NET is 50 to 70 kilometers. This spacing is effective for monitoring the recent geodynamics of the area covered by the network. Fig. 2 illustrates the locations of the GNSS stations.

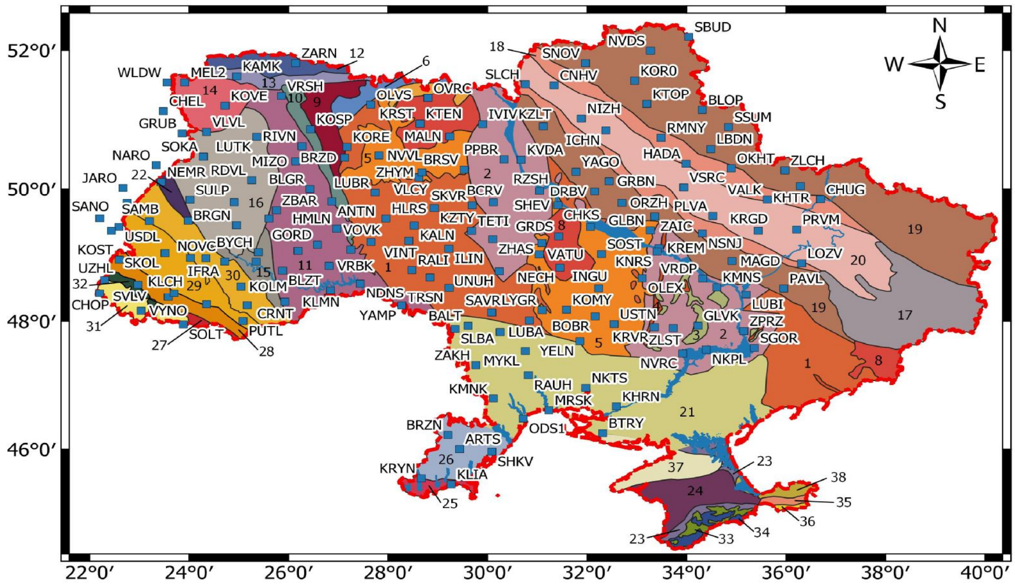

Fig. 2. Location of GNSS stations against the background of the tectonic map of Ukraine's territory (based on materials [National Atlas of Ukraine, 2007]).

Notations for Fig. 1:

ZOLH - GNSS stations,

Legend to the tectonic map:

UKRAINIAN SHIELD

Megablocks

Structural floors

1 - Granulite and granulite-diafluorite-granite pluto-metamorphic complex of the early Eogee (early Archaean);

2 - Amphibolite-granite pluto-metamorphic complexes of the Late Eogee (Middle Archaean);

3 - Greenstone metalvolcanic complex of the early Protogean (late Archaean);

4 - Iron-silica-shale (metachemogenic-terrigenous-volcanogenic) complexes of the late Protogean (late Archaean - early Proterozoic);

5 - Late Protogean gneiss-schist (meta carbonate-terrigenous) complexes;

Deflections, belts, and autonomous arrays

6 - The Volyn-Polish belt: the Osnytsk volcanic-plutonic complex at the end of the Late Protogean;

7 - The Ovruch depression and its satellites: the Ovruch volcano-sedimentary complex of the early Neogeon;

8 - Autonomous intrusive massifs of the final stages of cratonization;

COVER STRUCTURES

VOLYN-PODIL PLATE

Structures that were formed in the era:

a) Baikal-Caledonian

9 - Volyn-Podilsky depression (on the pre-Mesozoic section);

10 - Volyn trap cover (on the pre-Mesozoic section);

11 - Volyn-Podilskyi monocline;

b) Baikal-Hercynian

12 - Polissya saddlery;

13 - North Ukrainian horst zone;

c) Hercynian

14 - Kovel ledge;

15 - Boyanetsky depression (on the pre-Mesozoic section);

16 - Lviv Paleozoic trough;

17 - Donetsk Hercyna structure;

Dnipro-Donetsk depression

18 - Offshore areas;

19 - On-board areas;

20 - Central zone (graben);

d) alpine

21 - South Ukrainian monocline;

EPIOROGENIC ZONES ("YOUNG PLATFORMS")

a) Epicaledonian

22 - Rava-Ruska

b) Hercynian-Cimmerian

23 - Scythian;

24 - The Central Crimean Uprising;

25 - Nizhnyprutsky ledge;

26 - Pre-Dobrudzha depression;

ALPINE STORAGE ROOFS

OROGENEOUS STRUCTURES

Carpathians

27 - Marmaros massif;

28 - Internal flysch covers and areas of rocks;

29 - External flash coverings;

30 - Pre-Carpathian depression;

31 - Transcarpathian depression;

32 - Volcanic Carpathians;

Crimean mountains

33 - Tavriyskyi;

34 - Yail;

35 - Vladyslavskyi;

36 - Krasnopilskyi;

ALPINE DEFLECTIONS

37 - Karkinitskyi;

38 - Indo-Kuban;

Table 1 shows the calculated annual displacement rates of V_N (direction to the north), V_E (direction to the east), and V_H (direction to the height) of the selected GNSS stations and their accuracy assessment in the ETRF-2020 coordinate system.

Table 1

Components of vectors of linear annual displacement rates of GNSS stations and assessment of their accuracy (ETRF-2020)

GNSS station	Annual velocities, mm/year			MSE of annual velocities, mm			GNSS station	Annual velocities, mm/year			MSE of annual velocities, mm			GNSS station	Annual velocities, mm/year			MSE of annual velocities, mm		
	V_N	V_E	V_H	V_N	V_E	V_H		V_N	V_E	V_H	V_N	V_E	V_H		V_N	V_E	V_H	V_N	V_E	V_H
ANTN	–0.7	–0.9	–2.9	0.0	0.0	0.1	KRGD	–1.0	–0.9	–0.4	0.1	0.1	0.1	SAVR	–1.3	–1.3	–1.2	0.0	0.0	0.1
ARTS	0.1	–0.4	–0.0	0.1	0.1	0.1	KRST	0.8	–1.1	–2.4	0.2	0.2	0.4	SBUD	–1.2	–1.2	–3.7	0.1	0.1	0.2
BALT	–0.4	–0.5	0.8	0.1	0.1	0.1	KRVR	–1.3	–0.3	–2.5	0.1	0.1	0.1	SGOR	–0.3	1.1	0.8	0.1	0.1	0.2
BCRV	0.1	0.1	–3.2	0.1	0.1	0.2	KRYN	–1.0	–0.7	–2.7	0.1	0.1	0.1	SHEV	0.7	–1.0	–0.7	0.1	0.1	0.1
BLGR	0.1	–0.2	0.2	0.1	0.1	0.1	KTEN	–0.2	–0.1	–0.1	0.1	0.1	0.1	SHKV	–1.4	–1.2	–2.0	0.1	0.0	0.1
BLOP	–1.5	–1.8	–2.5	0.1	0.1	0.2	KTOP	–0.1	–0.1	–0.5	0.1	0.1	0.1	SHVC	–1.7	–1.9	–1.0	0.1	0.1	0.1
BLZT	–0.3	0.5	–3.8	0.0	0.0	0.1	KVDA	–0.1	–0.5	0.0	0.1	0.1	0.2	SKOL	0.1	–0.4	–0.7	0.0	0.0	0.1
BOBR	–0.5	–1.3	0.2	0.1	0.1	0.1	KZLT	0.0	–0.1	–0.7	0.1	0.1	0.1	SKVR	–0.1	0.0	–0.1	0.1	0.1	0.1
BRGN	0.2	–0.4	–1.4	0.0	0.0	0.1	KZTY	0.0	–0.6	–0.1	0.1	0.2	0.1	SLBA	–0.6	–0.7	–0.4	0.0	0.0	0.1
BRSV	–2.4	–1.6	–2.3	0.1	0.1	0.1	LBDN	–0.1	–1.4	–0.9	0.1	0.1	0.1	SLCH	–0.6	–0.8	2.0	0.1	0.1	0.2
BRZD	–2.2	–2.0	0.7	0.0	0.1	0.1	LOZV	–0.9	–0.9	–0.0	0.1	0.1	0.1	SNOV	0.2	0.6	–0.3	0.1	0.1	0.1
BRZN	–2.0	–1.0	–2.0	0.1	0.1	0.1	LUBA	–0.7	–0.8	0.8	0.1	0.1	0.1	SOKA	0.3	–0.1	–0.4	0.0	0.0	0.1
BTRY	0.6	–0.7	1.4	0.1	0.1	0.2	LUBI	–0.6	–0.8	0.0	0.1	0.1	0.1	SOLT	–0.3	–0.5	–0.5	0.0	0.0	0.1
BUCH	0.5	–1.3	–0.3	0.1	0.0	0.1	LUBR	–0.2	–0.8	–0.7	0.1	0.1	0.1	SOST	–0.7	–0.5	–1.0	0.1	0.1	0.1
BYCH	–1.5	–1.4	–2.7	0.0	0.0	0.1	LUTK	–0.4	–0.7	–2.1	0.1	0.0	0.1	SSUM	0.3	0.1	–0.3	0.1	0.1	0.1
CHEL	–0.8	–0.8	–1.7	0.0	0.0	0.1	LYGR	–1.2	–0.5	–1.1	0.1	0.1	0.1	SULP	0.2	–0.4	–1.3	0.0	0.0	0.1
CHKS	–0.7	0.9	–0.7	0.1	0.1	0.2	MAGD	–0.1	–0.3	–1.3	0.1	0.1	0.1	SVLV	–0.1	–0.5	–0.9	0.0	0.0	0.1
CHOP	–0.8	–0.6	–0.1	0.0	0.0	0.1	MALN	–0.9	–0.9	–0.8	0.1	0.1	0.1	TERE	–0.8	–0.9	–1.4	0.1	0.1	0.1
CHUG	0.4	–0.3	0.4	0.1	0.1	0.1	MEL2	–1.8	–1.1	–1.8	0.1	0.1	0.1	TETI	–0.3	–1.0	–1.1	0.1	0.1	0.1
CNHV	–1.3	–3.8	–1.1	0.1	0.2	0.2	MIZO	0.5	0.9	0.0	0.1	0.1	0.1	TRNO	0.3	–0.5	–0.7	0.1	0.1	0.2
CRNT	–0.1	–0.5	–0.6	0.0	0.0	0.1	MRSK	–0.7	–0.9	–1.2	0.1	0.1	0.1	TRSN	–1.6	–1.1	–1.3	0.1	0.1	0.1
DLNA	4.3	–1.2	0.7	0.1	0.1	0.2	MYKL	–1.9	–0.5	–1.0	0.1	0.1	0.1	TULC	0.0	–0.2	0.1	0.1	0.1	0.1
DRBV	0.5	0.1	1.4	0.1	0.1	0.1	MYKO	0.1	–0.9	–1.2	0.0	0.0	0.1	UNUH	–1.0	–1.9	1.6	0.1	0.1	0.1
GLBN	–0.3	–0.0	–1.1	0.1	0.1	0.1	NARO	–3.0	–2.3	0.0	0.1	0.0	0.1	USDL	–0.6	–0.6	–1.8	0.0	0.0	0.1
GLVK	–0.4	–0.8	–0.5	0.1	0.2	0.3	NDNS	–2.8	–2.6	–0.7	0.1	0.0	0.1	USTN	–2.5	1.3	0.8	0.1	0.1	0.1
GORD	–0.9	–0.3	–0.9	0.1	0.1	0.1	NECH	–0.7	–0.7	–0.3	0.1	0.1	0.1	UZHL	0.4	–1.8	0.9	0.1	0.1	0.1
GRBN	0.5	0.3	–1.2	0.1	0.1	0.2	NEMR	–1.1	–1.1	–2.9	0.1	0.0	0.1	VALK	0.8	0.3	1.9	0.1	0.1	0.2
GRDS	–2.4	–1.4	–1.8	0.1	0.1	0.1	NIZH	–0.3	–0.4	–1.1	0.1	0.1	0.1	VATU	0.0	0.2	0.9	0.1	0.1	0.1
GRUB	–1.6	–0.6	–1.1	0.1	0.1	0.1	NKPL	–0.9	–0.2	0.4	0.1	0.1	0.2	VINK	–0.6	–1.0	–0.3	0.1	0.1	0.1
GUSI	0.6	–0.2	0.1	0.0	0.0	0.1	NKTS	0.2	–0.2	0.6	0.1	0.1	0.1	VINT	0.1	–0.4	0.7	0.1	0.1	0.1
HADA	0.4	–0.1	1.0	0.1	0.1	0.1	NOVC	–1.3	–1.2	–4.0	0.1	0.0	0.1	VLCY	–0.3	–0.6	–1.0	0.1	0.1	0.1
HLRS	1.5	–1.3	0.5	0.1	0.1	0.4	NSNJ	–3.0	–3.1	–3.2	0.1	0.1	0.1	VLVL	0.2	–0.5	–1.4	0.0	0.0	0.0
HMLN	–0.3	–0.6	1.3	0.1	0.1	0.2	NVDS	–0.8	–0.4	–0.9	0.1	0.1	0.1	VOVK	–1.4	–1.7	–0.4	0.0	0.0	0.1
ICHN	–0.1	–0.2	–0.8	0.1	0.1	0.2	NVRC	–2.6	–2.3	–1.7	0.1	0.1	0.1	VRBK	–2.1	–2.6	–0.5	0.1	0.1	0.1
IFRA	1.4	–0.5	–0.7	0.0	0.0	0.1	NVVL	0.5	–0.5	–0.2	0.1	0.1	0.1	VRDP	–0.5	–0.5	–1.1	0.1	0.1	0.1
ILIN	–1.6	–0.6	–4.3	0.1	0.1	0.1	ODS1	–0.8	–1.0	1.6	0.1	0.1	0.1	VRSH	0.1	–0.0	–0.3	0.1	0.1	0.1
INGU	0.1	–0.7	0.1	0.1	0.1	0.1	OKHT	–0.2	0.1	–1.0	0.1	0.1	0.1	VSRC	1.1	0.2	–0.2	0.1	0.1	0.1
IVIV	–0.5	–0.5	–1.9	0.1	0.1	0.2	OLEX	–0.9	–1.1	2.0	0.1	0.1	0.2	VYNO	–1.1	–0.7	–1.2	0.0	0.0	0.1
JARO	–0.8	–1.1	1.0	0.1	0.1	0.1	OLVS	0.3	–0.3	–0.5	0.1	0.1	0.1	VYZN	0.4	–0.4	0.2	0.1	0.1	0.1
KALN	0.2	–0.3	–0.2	0.1	0.1	0.1	ORZH	–0.6	–1.4	–2.0	0.1	0.1	0.1	WLDW	–1.1	–1.2	–1.9	0.1	0.1	0.1
KAMK	–0.3	–0.5	–1.3	0.0	0.0	0.1	OVRC	–1.6	–1.1	1.1	0.1	0.1	0.2	YAGO	–0.0	0.2	–0.5	0.1	0.1	0.1
KHRN	–0.4	–0.6	0.8	0.1	0.1	0.1	PAVL	0.4	0.3	–0.8	0.1	0.1	0.2	YAMP	–0.8	–1.2	–1.2	0.1	0.1	0.1
KHTR	–0.2	–1.1	–1.5	0.1	0.1	0.1	PERV	0.0	–0.6	0.7	0.1	0.1	0.1	YASN	–1.1	–1.8	–0.2	0.1	0.1	0.1
KLCH	–0.5	–0.4	0.6	0.1	0.0	0.1	PLVA	0.1	0.4	–3.1	0.0	0.1	0.2	YELN	–2.2	–1.7	–1.8	0.1	0.1	0.1
KLIA	–0.4	–0.4	–0.5	0.1	0.1	0.1	POLN	–0.6	–1.6	0.1	0.1	0.1	0.1	ZAIC	–1.9	–1.8	–2.0	0.1	0.1	0.1
KLMN	–1.7	–1.8	–0.2	0.1	0.1	0.1	PPBR	–1.0	–2.5	–1.5	0.1	0.1	0.2	ZAKH	–2.5	–2.6	–0.9	0.1	0.1	0.1
KMNK	–2.8	–1.2	–3.2	0.1	0.1	0.1	PRVM	–2.0	–1.9	–1.2	0.1	0.1	0.2	ZARN	–2.3	–1.6	–0.9	0.1	0.1	0.1
KMNS	–3.4	–2.4	–4.7	0.1	0.1	0.2	PRZM	–0.3	–1.7	–1.0	0.1	0.1	0.1	ZBAR	–1.4	–1.2	–1.3	0.1	0.1	0.1
KNRS	–1.2	–1.5	1.0	0.1	0.2	0.2	PUTL	–1.5	–1.1	–1.6	0.1	0.0	0.1	ZHAS	–0.3	–0.9	0.9	0.1	0.1	0.1
KOLM	–2.0	–1.8	–1.8	0.1	0.1	0.1	RALI	–1.5	–1.4	0.4	0.1	0.1	0.1	ZHYM	0.5	–0.5	–0.4	0.1	0.1	0.1
KOMY	–0.7	–1.2	1.0	0.1	0.2	0.1	RAUH	–1.6	–1.8	–1.3	0.1	0.1	0.1	ZLCH	–0.2	0.3	–0.1	0.1	0.1	0.1
KOR0	–0.4	–1.5	1.3	0.1	0.1	0.1	RDVL	0.3	–0.4	–1.4	0.0	0.0	0.1	ZLST	–0.1	–0.2	0.9	0.2	0.1	0.2
KORE	–0.5	0.6	–0.9	0.2	0.3	0.4	RIVN	0.7	–0.2	–0.7	0.0	0.0	0.1	ZOLH	1.2	–1.5	–1.9	0.0	0.0	0.0
KOSP	–1.4	–0.9	0.7	0.1	0.1	0.1	RMNY	–1.0	–1.3	–0.5	0.1	0.1	0.1	ZPRZ	–0.1	–0.1	0.9	0.1	0.1	0.2
KOST	0.0	0.3	–0.5	0.1	0.1	0.1	RZSH	–0.7	–1.3	0.1	0.1	0.1	0.1	**max**	**4.3**	**1.3**	**2.0**	**0.2**	**0.3**	**0.4**
KOVE	–0.1	–0.4	–1.2	0.1	0.0	0.1	SAMB	–0.2	–0.3	–1.2	0.0	0.0	0.1	**min**	**–3.4**	**–3.8**	**–4.7**	**0.0**	**0.0**	**0.0**
KREM	0.2	0.1	–0.5	0.1	0.1	0.2	SANO	–0.9	–1.6	0.2	0.0	0.0	0.1	**Av.**	**–0.6**	**–0.8**	**–0.7**	**0.1**	**0.1**	**0.1**

Based on the values presented in Table 1, it is evident that, on average, the horizontal displacement velocities of the GNSS stations are mutually compensating. The maximum annual displacement rate toward the north is 4.3 mm/year for the ILIN station, while the maximum rate toward the south is 3.4 mm/year for the KMNS station. Additionally, the highest annual eastward displacement is 2.9 mm/year for the SHAZ station, whereas the maximum rate toward the west is 3.8 mm/year for the CNHV station.

Most GNSS stations in the studied region exhibit negative vertical displacement rates; however, a few individual stations show elevations. This aligns with the findings of [Khoda, 2024]. The subsidence rate across all GNSS stations is 0.7 mm per year. Based on the data in Table 1, maps depicting the current vertical and horizontal movements of the upper layer of the Earth’s crust in Ukraine have been created.

Recent vertical movements of the earth's crust on the territory of Ukraine

Fig. 3 illustrates the vertical displacement velocity vectors for the GNSS stations within the network. To better highlight general trends based on the vertical data, interpolation was performed using isolines of displacement rates, which are drawn every 1 mm/year. The velocity field representing the vertical movements of the Earth’s crust across Ukraine is heterogeneous, with values ranging from –3 mm to +2 mm per year. Additionally, the vector field is generally influenced by tectonic faults.

In western Ukraine, the land primarily subsides at a rate of 1 to 3 mm per year. However, anomalous uplift has been recorded in areas with tectonic faults, particularly in Prykarpattia and Transcarpathia, where the average uplift rate is 0.5 mm per year. The northern part of the Volyn-Podilsky monocline is also experiencing a rise, at a rate of 0.5 to 1 mm per year. In contrast, the southern part of this monocline is subsiding at a similar rate of 0.5 to 1 mm per year. These vertical dynamics are consistent with previous studies conducted in the western Ukraine region [Tretyak and Brusak, 2022].

In the southwestern part of the Ukrainian shield, the field of vertical displacement velocities exhibits distinct variations. In the northern region, subsidence occurs at a rate of 0.5 to 1 mm per year, while the southwestern area experiences uplift at the same rate. Along the southern edges of the Ukrainian shield, vertical movements of the Earth's crust are sharply differentiated: the northern section shows an uplift rate of 0.5 to 1 mm per year, whereas the southern section experiences a decline of 0.5 to 1 mm per year (known as the South Ukrainian monocline).

The Dnipro-Donetsk depression primarily displays negative vertical displacement rates ranging from 0.5 to 1 mm per year. However, positive vertical displacement rates of 0.5 to 1 mm per year can be observed in certain locations along the borders of faults, which may indicate geological activity or local geodynamic processes. In contrast, the Pre-Dobrudzha depression and the South Ukrainian monocline present a more uniform vector field with a subsidence rate of 1 to 2 mm per year.

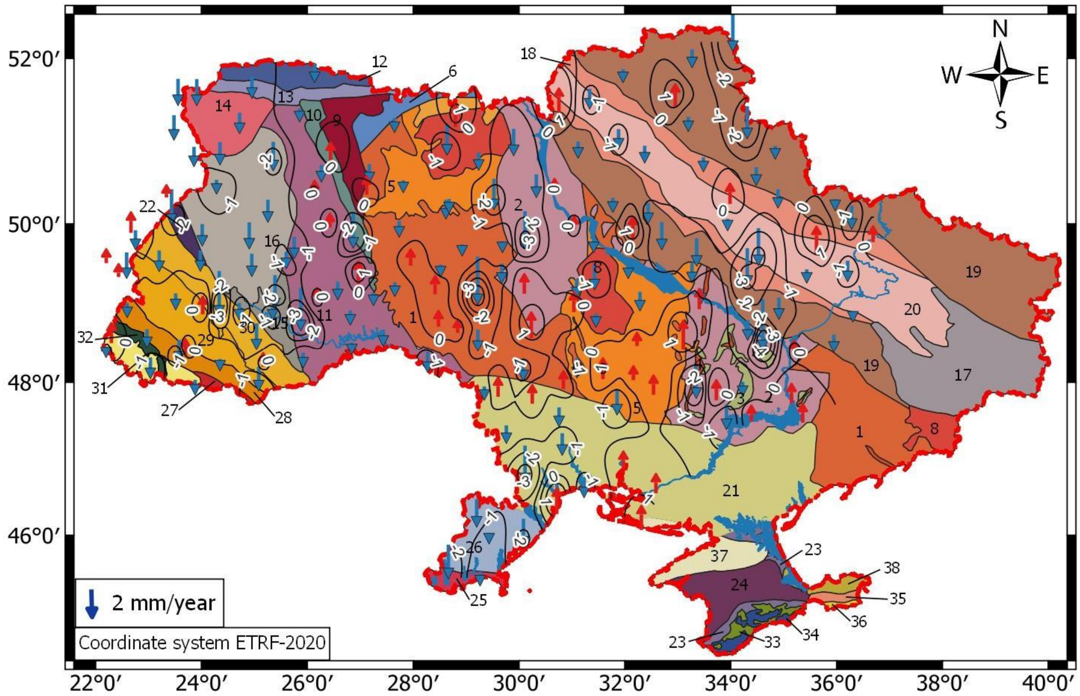

Fig. 3. Vertical displacement velocities of GNSS stations on the territory of Ukraine. The legend of the tectonic map is presented in Fig. 2.

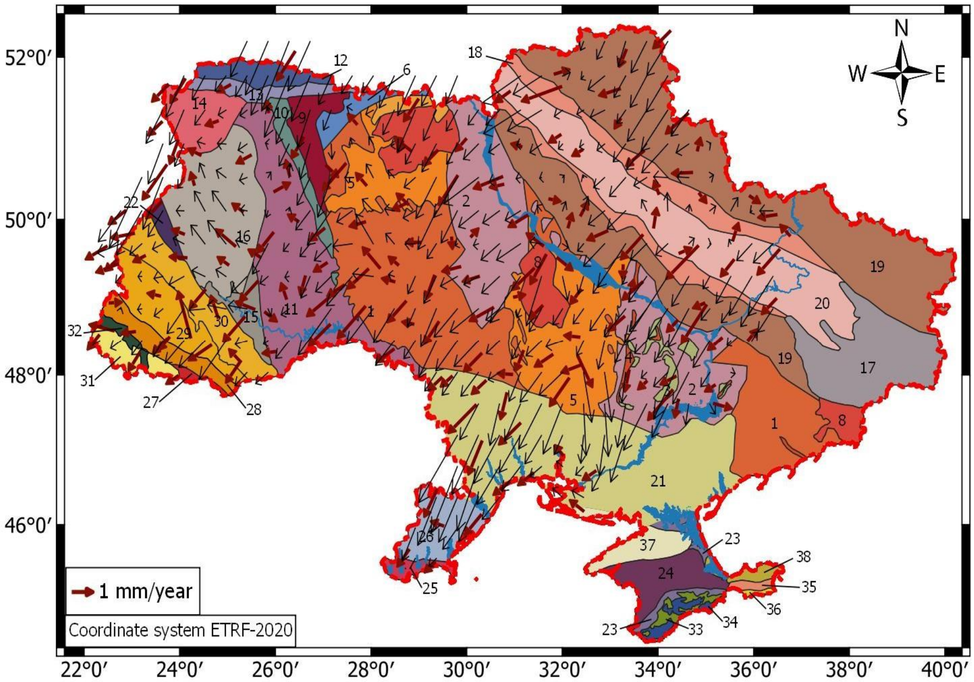

Fig. 4. Condensed vector model of horizontal displacement velocities of GNSS stations in the ETRF-2020 coordinate system on Ukraine's territory. T he legend of the tectonic map is presented in Fig. 2.

Recent horizontal movements of the Earth's crust on the territory of Ukraine

Fig. 4 depicts a condensed vector model of the horizontal displacements of the Earth's crust within the ETRF-2020 coordinate system for the territory of Ukraine, based on data from GNSS stations collected between 2018 and 2021year.

The overall trend indicates that the horizontal movements of the Earth's surface in Ukraine are primarily directed towards the southwest, with an average displacement speed of 1–2 mm per The Dnipro-Donetsk depression, located in the northern part of the region, exhibits a uniform displacement rate of 2 mm per year towards the southwest. At the boundary between the central and lateral zones, anomalous displacement rates of 0.5 mm per year are observed, showing a direction opposite to expected. In the central zone, the trend continues southwest with a displacement rate of 0.5 to 1 mm per year.

The gneiss-schist complexes, which include metacarbonate-terrigenous materials from the Late Protogean era, represent an anomalous zone. In this area, anomalous vector displacement rates of 0.5 mm per year are directed towards the north. Additionally, vertical deformations in this territory are also considered anomalous. In western Ukraine, the Lviv Paleozoic trough is another anomalous area, where displacement vectors are directed northeast with a rate of 1 mm per year.

The distribution of horizontal displacement rates is tied to the boundaries of the Ukrainian shield. On the northern edges of the borders, horizontal displacement rates decrease to 0.5–1 mm/year, and on the southern edges, they gradually increase in the southern direction to 2 mm/year.

On the territory of the Precarpathian and Transcarpathian depressions, the field of displacement velocity vectors is differentiated by geological structures and tied to the boundaries of tectonic faults. The Teisseyre-Tornquist deep fault zone has distinct characteristics. The northern edge displays displacement velocity vectors directed northwest, while the southern edge shows vectors directed southwest.

The final stage of the research compared calculated horizontal velocities with the residual model values of ITRF-2020. Displacement rates within the ITRF-2020 system were determined for 168 GNSS stations using the GAGE software [GACE]. The projections of the vectors pointed north range from 21 to 24 mm/year, and those directed east range from 11 to 14 mm/year. Since these values have a clear northeastern direction and are not suitable for direct comparison with the smaller calculated vectors in ETRF-2020, a transition to regional deformation values was performed. This transition involved a straightforward method where the maximum displacement speed from among the 168 stations was subtracted from the speeds of each GNSS station along both axes.

Table 2 shows the components of the vectors of linear annual displacement rates of GNSS stations based on the residual model values of ITRF-2020.

Table 2

Components of vectors of linear annual displacement rates of GNSS stations according to residual model values ITRF-2020

GNSS station	Annual velocity to the north, V_N, mm/year	Annual velocity to the east V_E, mm/year	GNSS station	Annual velocity to the north, V_N, mm/year	Annual velocity to the east V_E, mm/year	GNSS station	Annual velocity to the north, V_N, mm/year	Annual velocity to the east V_E, mm/year
ANTN	–1.8	–0.7	KRGD	–0.3	–2.3	SAVR	–0.9	–1.3
ARTS	–0.6	–1.2	KRST	–1.7	–1.0	SBUD	–1.1	–2.0
BALT	–0.9	–1.2	KRVR	–0.4	–1.9	SGOR	0.0	–2.3
BCRV	–1.2	–1.3	KRYN	–0.7	–1.0	SHEV	–1.0	–1.5
BLGR	–1.9	–0.7	KTEN	–1.7	–1.0	SHKV	–0.5	–1.3
BLOP	–0.8	–2.1	KTOP	–1.0	–1.9	SHVC	–0.9	–1.5
BLZT	–1.7	–0.6	KVDA	–1.3	–1.4	SKOL	–2.2	–0.2
BOBR	–0.6	–1.7	KZLT	–1.3	–1.5	SKVR	–1.3	–1.2
BRGN	–2.0	–0.4	KZTY	–1.4	–1.1	SLBA	–1.0	–1.2
BRSV	–1.4	–1.2	LBDN	–0.7	–2.1	SLCH	–1.5	–1.4
BRZD	–1.9	–0.8	LOZV	–0.1	–2.5	SNOV	–1.3	–1.6
BRZN	–0.7	–1.1	LUBA	–0.8	–1.3	SOKA	–2.4	–0.3
BTRY	–0.2	–1.7	LUBI	–0.2	–2.3	SOLT	–1.9	–0.3
BUCH	–1.9	–0.5	LUBR	–1.7	–0.9	SOST	–0.7	–1.7
BYCH	–1.9	–0.5	LUTK	–2.2	–0.5	SSUM	–0.7	–2.2
CHEL	–2.7	–0.2	LYGR	–0.8	–1.5	SULP	–2.3	–0.3
CHKS	–0.8	–1.7	MAGD	–0.3	–2.2	SVLV	–2.2	–0.1
CHOP	–2.3	0.0	MALN	–1.6	–1.2	TERE	–2.1	–0.2
CHUG	–0.2	–2.6	MEL2	–2.7	–0.3	TETI	–1.2	–1.2
CNHV	–1.4	–1.5	MIZO	–2.0	–0.6	TRNO	–2.0	–0.5
CRNT	–1.6	–0.6	MRSK	–0.5	–1.5	TRSN	–1.1	–1.1
DLNA	–2.1	–0.3	MYKL	–0.7	–1.4	TULC	–1.2	–1.1
DRBV	–0.9	–1.7	MYKO	–2.2	–0.3	UNUH	–1.0	–1.3
GLBN	–0.6	–1.9	NARO	–2.5	–0.2	USDL	–2.5	–0.1
GLVK	–0.2	–2.1	NDNS	–1.4	–0.8	USTN	–0.5	–1.8
GORD	–1.7	–0.7	NECH	–0.8	–1.5	UZHL	–2.4	–0.0
GRBN	–0.9	–1.7	NEMR	–2.5	–0.2	VALK	–0.3	–2.4
GRDS	–0.9	–1.5	NIZH	–1.2	–1.6	VATU	–0.9	–1.5
GRUB	–2.5	–0.3	NKPL	–0.1	–2.1	VINK	–1.6	–0.8
GUSI	–1.8	–0.6	NKTS	–0.4	–1.6	VINT	–1.4	–1.0
HADA	–0.7	–2.0	NOVC	–2.1	–0.3	VLCY	–1.6	–1.0
HLRS	–1.5	–0.9	NSNJ	–0.5	–2.1	VLVL	–2.4	–0.3
HMLN	–1.7	–0.8	NVDS	–1.1	–1.9	VOVK	–1.5	–0.9
ICHN	–1.1	–1.7	NVRC	–0.2	–2.0	VRBK	–1.6	–0.7
IFRA	–2.0	–0.4	NVVL	–1.8	–0.9	VRDP	–0.3	–2.1
ILIN	–1.2	–1.1	ODS1	–0.5	–1.4	VRSH	–2.3	–0.6
INGU	–0.6	–1.7	OKHT	–0.6	–2.2	VSRC	–0.6	–2.0
IVIV	–1.5	–1.3	OLEX	–0.5	–1.9	VYNO	–2.1	–0.1
JARO	–2.6	–0.1	OLVS	–1.9	–0.9	VYZN	–1.8	–0.5
KALN	–1.4	–1.0	ORZH	–0.8	–1.8	WLDW	–2.7	–0.2
KAMK	–2.5	–0.4	OVRC	–1.8	–1.1	YAGO	–1.0	–1.6
KHRN	–0.3	–1.8	PAVL	–0.1	–2.4	YAMP	–1.2	–1.0
KHTR	–0.3	–2.5	PERV	–0.8	–1.4	YASN	–1.9	–0.3
KLCH	–2.1	–0.2	PLVA	–0.5	–2.1	YELN	–0.6	–1.6
KLIA	–0.6	–1.2	POLN	–2.5	–0.0	ZAIC	–0.6	–1.9
KLMN	–1.5	–0.7	PPBR	–1.3	–1.3	ZAKH	–0.8	–1.2
KMNK	–0.7	–1.3	PRVM	–0.2	–2.5	ZARN	–2.3	–0.6
KMNS	–0.3	–2.2	PRZM	–2.5	–0.1	ZBAR	–2.0	–0.6
KNRS	–0.6	–1.9	PUTL	–1.7	–0.4	ZHAS	–1.1	–1.3
KOLM	–1.8	–0.4	RALI	–1.3	–1.0	ZHYM	–1.6	–1.1
KOMY	–0.7	–1.6	RAUH	–0.6	–1.4	ZLCH	–0.4	–2.4
KOR0	–1.1	–1.8	RDVL	–2.1	–0.5	ZLST	–0.3	–2.0
KORE	–1.9	–0.8	RIVN	–2.1	–0.6	ZOLH	–2.1	–0.4
KOSP	–2.1	–0.7	RMNY	–0.8	–1.9	ZPRZ	–0.1	–2.3
KOST	–2.4	–0.1	RZSH	–1.1	–1.5	**Max.**	**0.0**	**0.0**
KOVE	–2.5	–0.4	SAMB	–2.4	–0.2	**Min.**	**–2.7**	**–2.6**
KREM	–0.6	–1.9	SANO	–2.6	0.0	**Av.**	**–1.3**	**–1.2**

According to the values presented in Table 2, the largest annual displacement rate towards the south is 2.7 mm per year, observed at the MEL2 and CHEL stations. In the westward direction, the highest rate is 2.6 mm per year, recorded at the CHUG station. Based on the results from Table 2, we developed a condensed residual vector model for the territory of Ukraine.

Fig. 5 displays this condensed model of the residual field of horizontal displacement velocities of the Earth's surface, derived from the ITRF-2020 model (represented by black arrows).

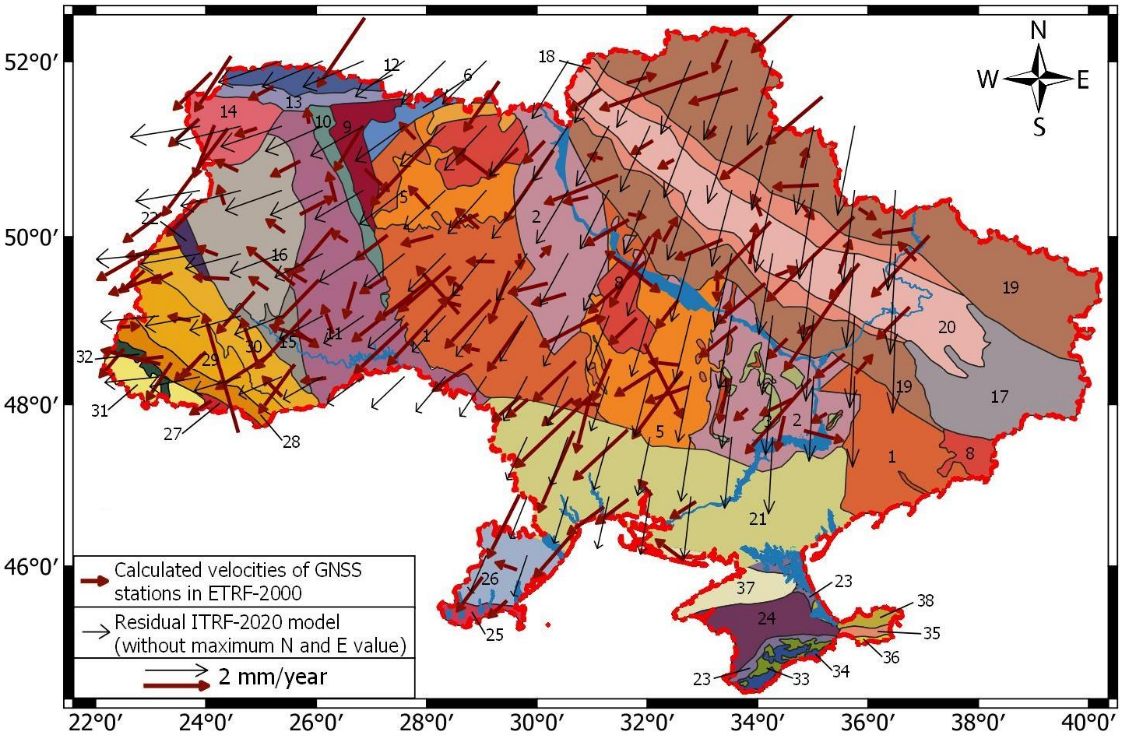

Fig. 5. Condensed vector residual model of ITRF-2020 and calculated horizontal displacement velocities of GNSS stations in ETRF-2020 on Ukraine's territory.
The legend of the tectonic map is presented in Fig. 2.

Fig. 5 shows the residual model values predominantly demonstrate a southwest direction with velocities ranging from 1.2 to 2.7 mm per year. The vector field, calculated in the ETRF-2020 system (represented by red arrows), reflects local geodynamic processes that are less pronounced in the ITRF-2020 residual model. Notably, the overall trends of the residual model vector field in ITRF-2020 and the vector field in ETRF-2020 exhibit similar kinematics. This similarity is clear in specific tectonic structures, including the Granulite and granulite-diafluorite-granite plutonic-metamorphic complex of the Early Eogee, the Amphibolite-granite plutonic-metamorphic complexes of the Late Eogee, the Pre-Dobrudzha depression, the Kovel ledge, and the Transcarpathian depression.

Regions showing unusual variations in displacement between the residual ITRF-2020 model and the calculated horizontal velocities of GNSS stations include the Dnipro-Donetsk depression, especially its onshore area, the Volyn trap cover, the region around the Terceira-Tornquist deep fault, and the Zakarpattia deep tectonic fault. These anomalies indicate the existence of local geodynamic processes at the boundaries of different tectonic structures.

Conclusions

1. The research establish and analyze recent vertical and horizontal movements in Ukraine using data from GNSS stations within the GeoTerrace networks from 2018 to 2023 and the System.NET from 2021 to 2023. The study focused on a time series of 168 GNSS stations. The spacing between neighboring stations in the network allows for relatively uniform coverage of the research area, with an average distance of 50 to 70 kilometers between stations.

2. The constructed map of isolines and vectors representing vertical displacements of GNSS stations indicates that most stations in Ukraine are experiencing subsidence, likely due to denudation processes. The velocity field of vertical movements in the Earth's crust across Ukraine is heterogeneous, with speeds ranging from −3 mm to +2 mm per year.

3. Maps showing the horizontal velocity displacements of GNSS stations indicate that tectonic faults significantly influence the overall vector field of displacement velocities. Generally, the trend of horizontal movements in the Earth's surface throughout Ukraine shows displacement velocity vectors directed toward the southwest, with an average speed of 1−2 mm per year. The abnormal velocity of vertical and horizontal movements at certain stations may indicate spatial instability in the GNSS station structure or could be the result of local near-surface hydrogeological processes.

4. The gneiss-schist complexes (metacarbonate-terrigenous) of the Late Protogean represent an anomalous zone. In comparison to the neighboring areas, this region is characterized by distinct horizontal and vertical displacement rates. Additionally, as noted in previous studies [Tretyak and Brusak, 2022], the Lviv Paleozoic depression exhibits anomalous deformation patterns in western Ukraine.

5. A comparison was made between the residual vector model of ITRF-2020 and the horizontal velocities of GNSS stations that we computed for ETRF-2020 in Ukraine. The residual model velocity vectors from ITRF-2020 indicate a southwest direction and vary between 1.2 to 2.7 mm/year. It is noteworthy that these displacement velocities exhibit a proportionality in magnitude and are closely aligned in direction to the values we calculated. Additionally, the vector field we computed in the ETRF-2020 system reflects local geodynamic processes, which are less pronounced in the residual model of ITRF-2020.

6. Research results show that the deformations of the territory of Ukraine are uneven. In the future, it is worth moving to more detailed maps based on additional geological and geophysical survey data to analyze the marked deformation zones.

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СУЧАСНІ ДЕФОРМАЦІЇ ЗЕМНОЇ КОРИ ТЕРИТОРІЇ УКРАЇНИ ЗА ДАНИМИ ГНСС-МЕРЕЖ GEOTERRACE ТА SYSTEM.NET

У роботі проаналізовано сучасні тенденції горизонтальних та вертикальних зміщень території України за даними ГНСС-мереж GeoTerrace та System.Net, із побудовою відповідних карт рухів та виділенням зон деформацій верхнього шару земної кори. Об'єктом дослідження є горизонтальні та вертикальні деформації верхнього шару земної кори. Мета – виявлення та аналіз деформаційних зон на території України. Вихідними даними є горизонтальні та вертикальні швидкості зміщень ГНСС-станцій за 2018–2023 рр. мережі GeoTerrace та за 2021–2023 рр. мережі System.Net, відомі тектонічні карти території з Національного атласу України та описові матеріали. Методика передбачає порівняння та аналіз сучасних деформацій земної кори регіону із його відомою тектонічною структурою. У результаті побудовано нові карти сучасних горизонтальних швидкостей зміщень верхнього шару земної кори України як єдиного регіону, а також вертикальних швидкостей зміщень ГНСС-станцій. Встановлено, що сучасні горизонтальні рухи території України є складними та співвідносяться з відомою тектонічною будовою. Їх також порівняно з регіональними модельними значеннями, обчисленими на основі моделі ITRF-2020. Більшість ГНСС-станцій зазнають висотних просідань, імовірно, через денудаційні процеси. Наведено описання сучасних рухів земної кори, але детальна інтерпретація повинна охоплювати додаткові дані спеціалістів із наук про Землю. Визначені швидкості зміщень ГНСС-станцій зі збільшенням часового інтервалу спостережень дадуть можливість встановити особливості просторового розподілу руху земної кори на території України та в майбутньому створити відповідні регіональні геодинамічні моделі кожної тектонічної структури чи окремих регіонів та України загалом, які будуть практично цінними для розвитку точної навігації з використанням точного позиціонування за мережами активних ГНСС-станцій.

Ключові слова: сучасна геодинаміка, деформації земної кори, горизонтальні рухи земної кори, вертикальні рухи земної кори, швидкості зміщень ГНСС-станцій, ГНСС-мережа, ГНСС-мережа GeoTerrace, ГНСС-мережа SystemNet, Україна, Український щит, Карпати.

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