UDC 551.24, 528.22

Kornyliy TRETYAK[1], Ivan BRUSAK[2]

Department of High Geodesy and Astronomy, Lviv Polytechnic National University, 12, S. Bandery Str., Lviv, 79013, Ukraine, [1] https://orcid.org/0000-0001-5231-3517, [2] https://orcid.org/0000-0001-5434-4931

MODERN DEFORMATIONS OF EARTH CRUST OF TERRITORY OF WESTERN UKRAINE BASED ON "GEOTERRACE" GNSS NETWORK DATA

https://doi.org/10.23939/jgd2022.02.016

The work analyzes the current horizontal and vertical displacement territory of western Ukraine according to GNSS data, including the creation of special maps of modern displacements and the allocation of deformation zones of the upper crust. The object of study is the horizontal and vertical deformations of the upper crust. The aim is to identify and analyze deformation zones in Western Ukraine. The initial data are horizontal and vertical velocities of 48 continuous GNSS stations from 2018 to 2021 of Geoterrace network, known tectonic maps of the territory and descriptive materials. The methods include comparison and analysis of modern Earth crust deformations of the region with its known tectonic structure. As a result, for the first time it was possible to create the maps of horizontal velocities of continuous GNSS stations and deformations as well as vertical velocities of GNSS stations of the upper crust of Western Ukraine as a whole region. It is established that the deformations of the territory of Western Ukraine are complex and only partially correlate with the known tectonic structure in the region. Most continuous GNSS stations subside in vertical components, possible due to denudation processes. The Galicia–Volyn depression, however, practically does not subside. On the slopes of the Ukrainian Shield there is a noticeable correlation of vertical displacements and the depth of the surface of crystalline rocks. Zones of compression are identified in Zakarpattia, which corresponds to the Zakarpathian (Transcarpathian) deep fault, and in the north-west of the region. It is necessary to mark the zone around the city of Khmelnytskyi, where abnormal vertical and horizontal displacements are observed. Geodynamic interpretation of anomalous deformation zones is given. Determined velocities of continuous GNSS stations with the increasing observation time interval will make it possible to establish the features of the spatial distribution of Western Ukraine crustal movement as well as create an appropriate regional geodynamic model in the future.

Key words: modern geodynamics; deformations of the Earth crust; GNSS data; Western Ukraine.

Introduction

Today, the researchers widely use the estimation of modern geodynamic processes on the basis of time series of continuous GNSS stations. Modern geodynamics of the Western Ukrainian territory as an object has not been studied so far using GNSS data. This territory is limited from the western administrative border of Ukraine to the surface of the structures of the Ukrainian Crystal Shield in the east. This area includes (from east to west) the Ukrainian Carpathians, Galicia-Volyn depression, Volyn-Podilia plate, which is shown as a frame of the Ukrainian shield, i.e. the depth reduction of the crystalline rock surface on the slopes of the Ukrainian shield (Fig. 1) [Kruglov et al., 1985; Chebanenko et al., 1990; Palienko, 1992].

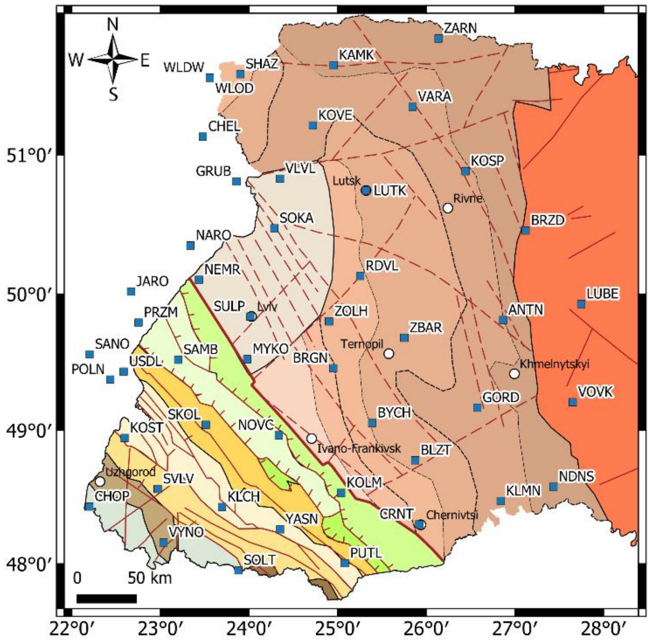
There are three major structural units of the Ukrainian Carpathians based on the schemes of tectonic zoning. They include Folded Carpathians and adjacent Pre-Carpathian advanced and Transcarpathian inland depressions [Kruglov et al., 1985; Starostenko, 2005; Tretyak et al., 2015].

From the tectonic point of view Folded region of the Carpathians consists of Protrusion of Paleozoic folded base (Rakhiv massif), Outer Anticlinal zone, Central Syncline zone, Internal Anticlinal zone, and Volcanic Carpathians. The Galicia–Volyn depression is represented by structures of the sedimentary cover formed in Hercynian. The depth of the crystalline rock surface on the slopes of the Ukrainian Shield varies from 4,000 m to its appearance on the surface in the west-east direction.

Preliminary studies of the region geodynamics based on the GNSS data

This region is partially researched within Europe [Tretyak & Vovk, 2014; Ishchenko, 2016], Carpathian-Balkan region [Tretyak & Brusak, 2020], and as a whole part within the territory of Ukraine [Marchenko et al., 2011, 2019; Savchuk & Doskich, 2017; Ishchenko, 2018; Orlyuk & Ishchenko, 2019; Ishchenko & Khoda, 2020]. However, the studies listed above present a small number of GNSS stations in the territory of Western Ukraine. Taking into account the complex geological and tectonic structure of the region [Kruglov et al., 1985; Palienko, 1992], this does not allow full reflection of the Earth crust movements within these structures. Thus, six GNSS stations were used in [Marchenko et al., 2011]; in [Ishchenko, 2018] – twenty two GNSS stations; [Savchuk & Doskich, 2017] – twenty five GNSS stations.

On the one hand, the positive side of these studies is the use of long time series (up to 10 years) for some continuous GNSS stations, which allows us to reliably estimate the components of velocity vectors. On the other hand, low density at distances between neighboring stations about 150-250 km significantly smoothes the deformation field and does not permit detection of local spatial deformations within individual tectonic structures.



Legend:

ZOLH – continuous GNSS stations,

Lviv – settlements; – tectonic faults

Legend to the tectonic map::

Folded region of the Carpathians:

– Protrusion of Paleozoic folded base (Rakhiv massif);

– Outer Anticlinal zone;

– Central Syncline zone;

– Internal Anticlinal zone;

– Volcanic Carpathians;

Boundary deflections and depressions:

– Zakarpattia depression;

– Pre-Carpathian depression. Outer zone;

– Pre-Carpathian depression. Internal zone;

– Pre-Carpathian depression. Bukovyna-Pokuttya uplift of the internal zone;

The structure of the sedimentary cover formed in Hercynian:

– Galicia–Volyn depression;

The depth of crystalline rocks surface on the slopes of the Ukrainian Shield:

– < 400 m; – 400–1000 m;

– 1000–2000 m; – 2000–3000 m;

– 3000–4000 m; – > 4000 m;

– surface

Fig. 1. Continuous GNSS stations on tectonic map of the Western Ukraine territory according to the materials [Kruglov et al., 1985; Chebanenko et al., 1990; Palienko, 1992].

In recent years, new continuous GNSS stations have been installed. Thus the amount of data is increasing, which allows to clarify the study of modern geodynamics in the region.

Spatial dynamics of some tectonic structures within the territory of Western Ukraine are well studied. A rather detailed assessment of the modern geodynamics of the Ukrainian Carpathians and adjacent territories is carried out by GNSS methods [Tretyak, et al., 2015, Doskich, 2021]. Doskich [2021] identifies active zones of tension (Rakhiv-Verkhovyna and Sanok–Oysters–Dolishni) and compression (Rakhiv–Khust–Mukachevo).

The geodynamics of large engineering objects, such as the Dnister Hydropower Cascade [Savchyn & Pronyshyn, 2020, Tretyak et al., 2021] is studied in order to investigate the geodynamic impact of local objects on regional deformations of territories.

The aim of the article is to show in detail the vertical and horizontal deformations of the Western Ukraine Region, using a fairly dense network of GNSS stations.

Geoterrace GNSS network

The study used the GNSS data from Geoterrace stations (https://geoterrace.lpnu.ua/) and stations located in Poland along the border with Ukraine. These continuous GNSS stations are part of the Polish networks ASG EUPOS (http://www.asgeupos.pl) and TPI NET pro (https://tpinet.pl), with which data exchange is established (see Fig. 1) [Siejka, 2017].

The creation of the Geoterrace network began in 2007 in the Lviv region. For today 72 continuous GNSS stations form a uniform network that almost completely covers 12 regions of Ukraine.

The purpose of the Geoterrace network is to provide users with real-time differential corrections for precise location determination. It also monitors spatial displacements of the Earth crust and stability of large engineering facilities (hydroelectric power plants, storage power plants, nuclear power plants), as well as deformations of adjusting territories. Geoterrace network management in Real-time Kinematic mode is performed using the comprehensive software Sino GNSS CDC.NET. For geodynamic studies, the calculation of daily GNSS solutions of stations in post processing is performed using Bernese GNSS Software [Dach et al., 2015].

The distance between the neighboring GNSS stations of the Geoterrace network is on average 70 km, which is effective for the differentiation of modern geodynamics of the areas covered by the network.

The research is based on the experience of GNSS measurements, which lasted more than 2.5 years. The accuracy of determining vertical velocities is in the range of 0.3–0.6 mm/year. [Desai et al., 2016]. This is quite a satisfactory result for determining the linear velocity, which is obviously a manifestation of the Earth crust movements. However, reducing the duration of measurements to one or two years impairs the accuracy of determining the rate to 1–2 mm/year or more [Cenni et al., 2013; Esposito et al., 2015; Devoti et al., 2017].

In addition, the stability and continuity of daily solutions, i.e. the absence of abrupt displacements and gaps in the time series, are important for the accuracy and reliability of determining the crustal movement velocities. For these reasons, we selected only 48 stations from 72 GNSS stations to perform the research, as the time series of the remaining stations have a duration of less than 2.5 years.

The calculation of the daily coordinates of GNSS stations was performed in the Bernese GNSS Software [Dach et al., 2015]. IGS stations around the territory of Western Ukraine are selected as GNSS reference stations. The result of the calculations is a network solution based on the strategy of double differences. Geocentric coordinates X, Y, Z of continuous GNSS stations are defined in the ITRF-2014 system. The GNSS displacements of the stations ΔX, ΔY, ΔZ are determined by subtracting the coordinates of the station for the current epoch from the coordinates for the first epoch.

The data computation was made according to the following method. The data from Bernese GNSS Software (catalog of daily solutions) was exported to MathCAD. Specifically developed code was used for the data analysis. The vertical jumps in the time series were removed manually and with the use of a simple filter (divergences from the general trend more than 1 cm). It should be mentioned that the removed data for the 3 years-period was only 0.1–0.2 %. In general, the data had good quality. The time series decomposition was not done. In this research, the trend is the average from the series. It is not clear how to identify seasonality, noise and other components for this time series. One example could be the recorded impact caused by non-tidal atmospheric loading (NTAL) on the GNSS time series in this region [Tretyak et al., 2021]. It is known that International Earth Rotation Service (IERS) conventions recommend taking into account the modeled deformations in software products caused by tidal loadings to GNSS time series. At the same time, there are no such recommendations for non-tidal models. The recorded NTAL deforms the upper Earth crust but we do not remove this impact based on IERS recommendations. Due to this and other possible deformation factors we did not perform time series decomposition.

Analysis of GNSS time series

The analysis of time series first of all takes into account the replacement of the antenna. We correct the offset for the following stations: KOST, SOKA, SHAZ. Data gaps were identified in some continuous GNSS stations due to technical problems with equipment or communications. Such stations in the territory of Western Ukraine are the following: BRZD, KLMN, NEMR, SAMB, SHAZ, SULP, YASN. For example, Fig. 2 shows the spatial displacement of the GNSS station SULP on the geocentric axes X, Y, Z coordinate system ITRF-2014.

Displacements of ΔZ along the Z axis have seasonal deviations [Tretyak, K. et al., 2012; Davis et al., 2012; Gruszczynska et al., 2017] from the trend line. In fact, a long series of observations is required to eliminate the effect of seasonal fluctuations. The trend line reflects the linear rate of displacement of the GNSS station along the respective axes, which is shown in Fig. 2.

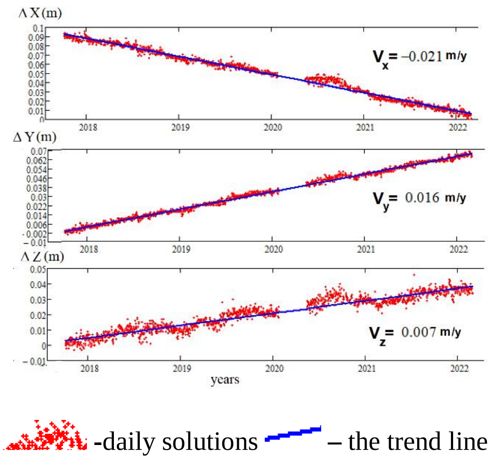


Fig. 2. Time series of continuous GNSS station SULP in the ITRF-2014 coordinate system.

Figure 3 presents the histogram of the integrity of the GNSS data by stations.

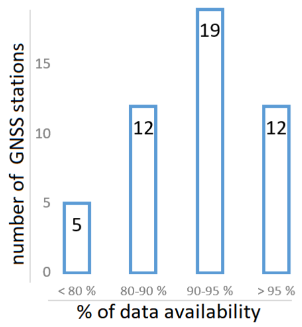


Fig. 3. The integrity of continuous GNSS station data from 2018 to 2021 in percent.

Fig. 3 shows that most continuous GNSS stations have a percentage of data integrity in the range of 90–95 %, which corresponds to ≈ 1,000 daily solutions. Only 5 GNSS stations have a percentage of data integrity less than 80 %, which corresponds to ≈ 850–900 daily interchanges. On average, the availability of daily solutions for 48 GNSS stations is 90 %, which is a high and at the same time sufficient indicator for the analysis of geodynamic displacements of the territory of Western Ukraine.

To determine the relative velocity vectors with the extracted components of the Eurasian tectonic plate motion, the displacements ΔX, ΔY, ΔZ in the geocentric system (ITRF-2014) are recalculated in the ETRF-2000 system and transformed into the topocentric coordinate system.

Table 2 shows the calculated annual velocities V_N (north component), V_E (east component) and V_H (altitude component) of the selected continuous GNSS stations and estimate their accuracy.

Table 1

Components of linear annual velocity vectors of continuous GNSS stations and accuracy estimation (ETRF-2000)

GNSS station	Annual speeds, mm/year			Accuracy, mm/yr		
	V_N	V_E	V_H	V_N	V_E	V_H
ANTN	-2.1	-2.2	-4.9	0.2	0.1	0.2
BLZT	0.1	0.4	-7.8	0.1	0.1	0.2
BRGN	-0.1	-0.5	-0.7	0.1	0.0	0.1
BRZD	-2.4	-1.7	-15.1	0.5	0.2	0.6
BYCH	0.1	0.3	-7.2	0.2	0.1	0.2
CHEL	-0.4	-0.6	-0.4	0.1	0.0	0.1
CHOP	-0.5	0.8	-2.2	0.2	0.1	0.2
CRNT	0.3	0.4	-7.2	0.1	0.1	0.2
GORD	0.7	0.3	-4.5	0.2	0.1	0.2
GRUB	-0.1	-0.2	-2.0	0.1	0.1	0.1
JARO	0.1	-0.1	-2.9	0.1	0.1	0.1
KAMK	-0.2	-1.0	-4.6	0.1	0.1	0.1
KLCH	0.1	-0.1	-6.3	0.1	0.1	0.1
KLMN	-0.4	0.6	-6.2	0.2	0.1	0.2
KOLM	0.6	0.7	-3.3	0.1	0.1	0.2
KOSP	0.7	0.6	-5.1	0.2	0.1	0.2
KOST	1.1	0.6	1.0	0.2	0.1	0.2
KOVE	0.2	-0.1	-5.7	0.1	0.1	0.1
LUBE	2.3	1.7	-16.5	0.5	0.4	0.5
LUTK	0.1	0.3	-5.6	0.1	0.1	0.2
MYKO	-0.2	-0.9	-1.4	0.1	0.0	0.1
NARO	-0.4	-0.3	-2.3	0.1	0.1	0.1
NDNS	0.2	1.3	-6.7	0.6	0.4	0.7
NEMR	0.4	-	-1.2	0.1	0.1	0.1
NOVC	-0.1	0.2	-2.8	0.2	0.1	0.2
POLN	-0.7	-0.6	-1.4	0.2	0.1	0.2
PRZM	0.9	1.8	1.1	0.1	0.1	0.1
PUTL	0.7	-0.3	-7.1	0.2	0.1	0.2
RDVL	0.2	-0.1	-1.3	0.1	0.1	0.1
SAMB	0.1	-0.1	-1.6	0.1	0.0	0.1
SANO	0.3	0.4	-7.5	0.2	0.1	0.2
SHAZ	-1.3	2.9	8.4	0.1	0.1	0.1
SKOL	-0.1	-0.0	-1.1	0.1	0.0	0.1
SOKA	0.2	-0.2	-0.7	0.1	0.1	0.1
SOLT	-0.4	0.6	-5.1	0.1	0.1	0.2
SULP	0.2	-0.4	-1.2	0.1	0.0	0.1
SVLV	-0.7	-0.3	-5.6	0.1	0.1	0.1
USDL	0.4	0.3	-2.3	0.1	0.1	0.1
VARA	0.6	-0.3	-6.4	0.1	0.1	0.2
VLVL	0.0	-0.6	-1.3	0.1	0.0	0.1
VOVK	0.2	1.4	-4.3	0.4	0.3	0.4
VYNO	0.3	0.1	-6.3	0.1	0.1	0.1
WLDW	0.1	-0.3	-1.2	0.1	0.0	0.1
WLOD	-0.1	0.2	-2.1	0.1	0.1	0.1
YASN	0.6	-0.1	-5.3	0.2	0.1	0.2
ZARN	-0.1	0.7	-6.8	0.2	0.1	0.2
ZBAR	0.7	-0.2	-7.0	0.1	0.1	0.2
ZOLH	-0.8	-0.2	-1.8	0.1	0.0	0.1
Max	2.3	2.9	8.4	0.6	0.4	0.7
Min	-2.4	-2.2	-16.5	0.1	0.0	0.1
Aver.	0.1	0.0	-5.2	0.1	0.1	0.2

In general, the average horizontal speeds of stations in the region are mutually compensated. The maximum annual speed to the north is 2.3 mm/year for LUBE station and to the south is 2.4 mm/year for BRZD station. The maximum annual speed to the east is 2.9 mm/year for the SHAZ station, and to the west – 2.2 mm/year for the ANTN station.

Vertical velocities in the region are negative, with an average subsidence rate of 5.2 mm/year for all GNSS stations. Maximum subsidence is typical for LUBE (16.5 mm/year), BRZD (15.1 mm/year) GNSS stations.

Maps of modern vertical and horizontal movements of the upper crust in western Ukraine are constructed according to Table 2.

Modern vertical displacements of territory of Western Ukraine

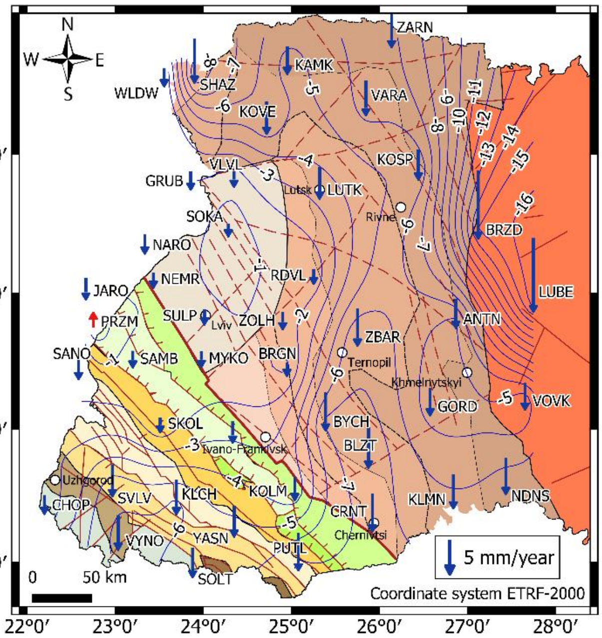
Fig. 4 shows the vertical velocity vectors of the continuous GNSS stations of the Geoterrace network. In order to highlight the general trends based on vertical velocities, they are interpolated in the form of velocity isolines.

Fig. 4 shows that the field of vertical velocities has negative values in the range of -1 to -16 mm/year and the whole area experiences subsidence over time. On average, for all GNSS stations, the subsidence rate is -5 mm/year, which may be explained by the manifestations of denudation processes in the region. Only one PRZM station rises at a low speed (+1 mm/year), which may be due to the peculiarities of its geological location or installation, as in general for this region of Poland there are subsidence to -3 mm/year [Kowalczyk, 2005, Kowalczyk & Rapiński, 2017].

Subsidence of the territory of Western Ukraine is not uniform, but can be regionally differentiated into zones: eastern (Ukrainian Crystalline Shield), southern (Zakarpattia), northern (Volyn) and the Galicia–Volyn depression.

The Galicia–Volyn depression (-1 mm/year), formed during the Hercynian fold, is experiencing the smallest subsidence. It should be noted that on the one hand the Lviv regional magnetic anomaly is distinguished in this region [Orlyuk & Romenets, 2005, Nechaeva et al., 2002; Tretyak et al., 2015; Anikeev et al., 2019], the source of which may be a magnetized block of the Earth crust at a depth of 40–55 km [Orlyuk, 1999]. A probable mechanism for the interpretation of tectonomagnetic anomaly is the piezomagnetic effect, i.e. the reaction of magnetic inhomogeneities to variations in tectonic stresses in the Earth crust [Tretyak et al., 2015]. On the other hand, the abnormally low values of subsidence in the Galicia–Volyn depression can probably be explained by the presence of a thermal anomaly (Rava-Rusko–Krekhivska, thermal anomaly where the geothermal gradient reaches 2.25 °C/100 m) [Krupskyi et al., 2014]. The high geothermal gradient is associated with deep faults that are part of the Teisseyre-Tornquist Zone.

To the east and north of the Galicia–Volyn basin, the intensity of annual subsidence is increasing. This is especially noticeable in the west-east direction from -1 mm/year in the Galicia-Volyn basin to -16 mm/year on the surface of the Ukrainian Shield. In general, these displacements correlate with a decrease in the depth of the surface of crystalline rocks on the slopes of the Ukrainian Shield. In this regard, the region around the city of Khmelnytskyi is anomalous, which coincides with the anomalous negative regional component of the anomalous magnetic field in the West of Ukraine [Nechaeva et al., 2002; Orlyuk & Romenets, 2005].



Legend:

BRGN – annual velocity of GNSS stations,
– isolines of annual velocities
Lviv – settlements; – tectonic faults

Legend to the tectonic map::

Folded region of the Carpathians:

– Protrusion of Paleozoic folded base (Rakhiv massif);
– Outer Anticlinal zone;
– Central Syncline zone;
– Internal Anticlinal zone;
– Volcanic Carpathians;

Boundary deflections and depressions:

– Zakarpattia depression;
– Pre-Carpathian depression. Outer zone;
– Pre-Carpathian depression. Internal zone;
– Pre-Carpathian depression. Bukovyna-Pokuttya uplift of the internal zone;

The structure of the sedimentary cover formed in Hercynian:

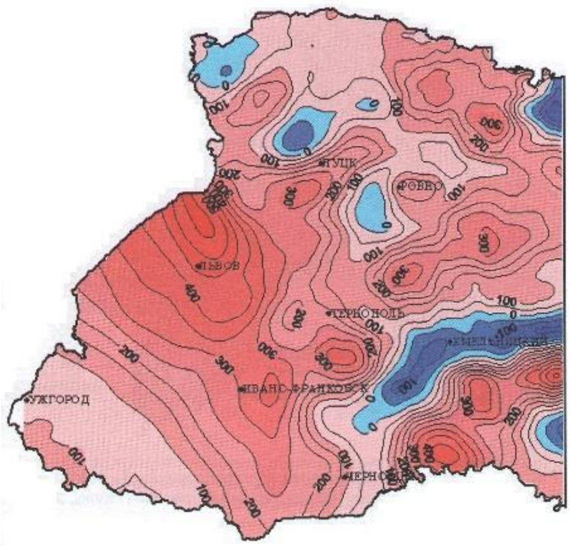
– Galicia–Volyn depression;

The depth of crystalline rocks surface on the slopes of the Ukrainian Shield:

– < 400 m; – 400–1000 m;
– 1000–2000 m; – 2000–3000 m;
– 3000–4000 m; – > 4000 m;
– surface

Fig. 4. Vertical displacements of territory of Western Ukraine based on GNSS data from 2018 to 2021.

Fig. 5 shows the regional component of the anomalous magnetic field in nanoteslas of territory of Western Ukraine.



-100 – isolines of the regional component of the anomalous magnetic field in nanoteslas

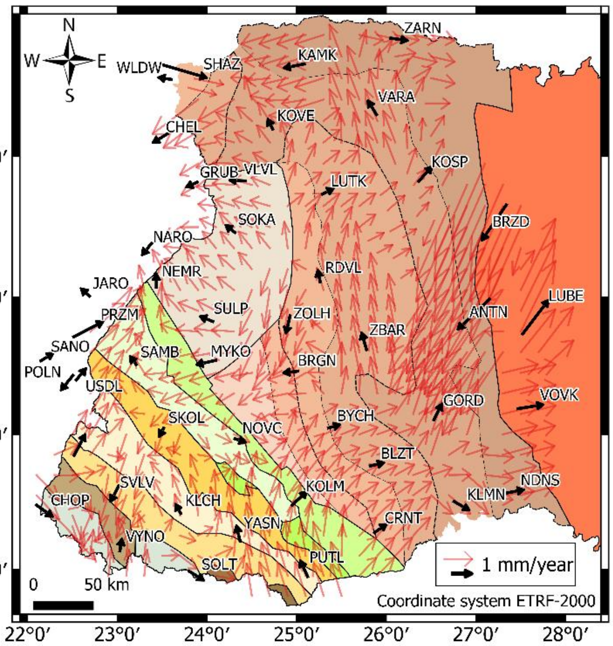
Fig. 5. Regional component of anomalous magnetic field of Western Ukraine territory [Orlyuk & Romenets, 2005].

Modern horizontal displacements and deformations of the territory of Western Ukraine

Figure 6 shows a dense vector model of horizontal displacements of the Earth crust in the ETRF-2000 coordinate system of the territory of Western Ukraine according to GNSS data from 2018 to 2021.

The value of horizontal velocities of GNSS stations reaches a maximum of 30 mm/year. Horizontal displacements of the territory of Western Ukraine are multidirectional. This is primarily due to the presence of numerous ancient faults and lineaments in the upper part of the Earth crust. Such rupture faults, as well as the complex tectonic structure of the region transform the single direction of horizontal movements in different directions.

Fig. 6 shows that the overall vector field of motion is differentiated into individual blocks. The dynamics of joint movement of PYTL, YASN, KOLM, BYCH, BLZT stations is distinguished. They form vortex horizontal movement despite the transverse extension of the Carpathian structures. It should be noted that the GNSS stations GORD, BLZT, BYCH are moving towards the stations ANTN, BRZD (up to 30 mm/year). This may be a manifestation of the thrust. Smaller sliding movements (up to 15 mm / year) are also notasible in Zakarpattia, in Zakarpathian (Transcarpathian) fault zone (between SVLV and VYNO stations).



Legend:

BLZT – annual velocity of GNSS stations,

- vector of densed model,

– tectonic faults

Legend to the tectonic map::

Folded region of the Carpathians:

– Protrusion of Paleozoic folded base (Rakhiv massif);

– Outer Anticlinal zone;

– Central Syncline zone;

– Internal Anticlinal zone;

– Volcanic Carpathians;

Boundary deflections and depressions:

– Zakarpattia depression;

– Pre-Carpathian depression. Outer zone;

– Pre-Carpathian depression. Internal zone;

– Pre-Carpathian depression. Bukovyna-Pokuttya uplift of the internal zone;

The structure of the sedimentary cover formed in Hercynian:

– Galicia–Volyn depression;

The depth of crystalline rocks surface on the slopes of the Ukrainian Shield:

– < 400 m; – 400–1000 m;

– 1000–2000 m; – 2000–3000 m;

– 3000–4000 m; – > 4000 m;

– surface

Fig. 6. Densed vector model of horizontal displacements of the Earth crust of the territory of Western Ukraine based on GNSS data in coordinate system ETRF-2000 from 2018 to 2021.

To generalize the deformations, the territory of Western Ukraine is divided into separate triangles by Delaunay triangulation. The vertices of adjacent triangles are GNSS stations. The parameters of deformation of the Earth crust such as dilatation Δ, maximum compression or tension along the main axes E1 E2 and Θ – azimuth of the main axis of deformation for each center of triangle are found. Then the parameters are interpolated to a regular grid.

Fig. 7 shows a map of the dilatation distribution of Western Ukraine territory based on GNSS data from 2018 to 2021.

The total dilatation from 2018 to 2021 is in the range from -10^{-9}/year to $+8{\cdot}10^{-8}$/year. Analyzing Fig. 7, we can identify several anomalous zones of the Earth crust deformation.

Figure 8 shows the compression and extension of the Earth crust of Western Ukraine territory according to GNSS data from 2018 to 2021.

The largest compression zone is observed in the north-west of the region near the SHAZ station. Less compression is also present in the area of the Galicia–Volyn depression and the regional deflections of the Ukrainian Carpathians. This trend is confirmed in studies of neighboring regions of Poland [Araszkiewicz, et al., 2016; Kowalczyk, 2020].

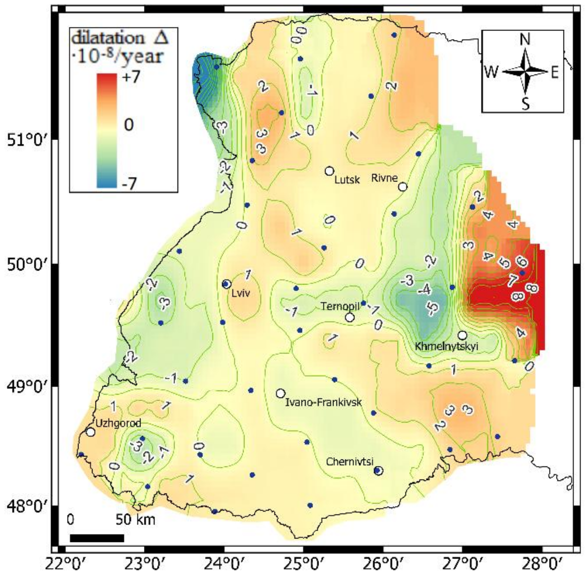
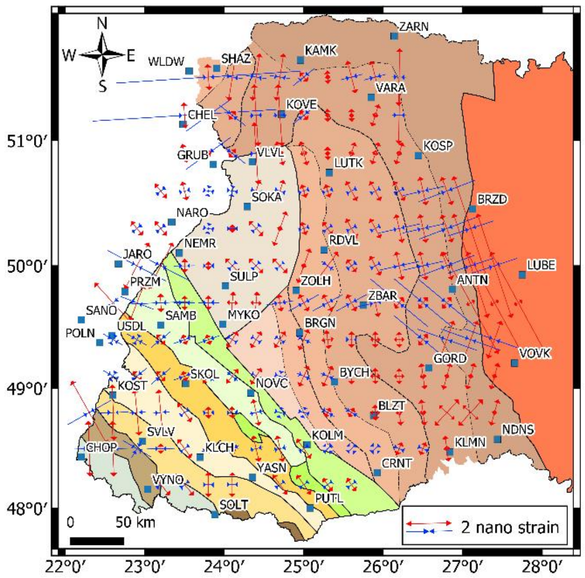


Fig. 7. Dilatation field of the territory of Western Ukraine based on GNSS data from 2018 to 2021.



- extension – compression

Fig. 8. The compression and extension of the Earth crust of territory of Western Ukraine according to GNSS data from 2018 to 2021.

The compression zone in Zakarpattia region corresponds to the area between SVLV and VYNO stations (see Figs. 7, 8). This region coincides with the Zakarpathian (Transcarpathian) fault zone of high seismicity, and is also characterized by increased heat flux density of the Carpathian region (100 mW/m^2) [Maksymchuk et al., 2018; Kutas, 2021].

The deformations of the region around the city of Khmelnytskyi are noticeable. Compression and tension are visible in the region where the GNSS stations GORD, BLZT, BYCH move towards the stations ANTN, BRZD (see Fig. 6). Figure 7 shows that this zone corresponds to compression, the value of dilatation is up to $\Delta = -5\cdot10^{-8}$ and the corresponding tension is east to $\Delta = 8\cdot10^{-8}$. The distribution of horizontal displacements suggests the presence of thrust elements. We also noted earlier that the region has anomalous altitude dynamics. In this region, scientists [Nechaeva et al., 2002; Orlyuk & Romenets, 2005] identify a negative regional component of the anomalous magnetic field of the territory of Western Ukraine. The reason for this may be the ancient faults of the north-south extension in the region [Palienko, 1992], which separate the zones of compression and tension.

The purpose of this article is not a thorough analysis of the causes of the Earth crust deformations. Its purpose is to show the details of the vertical and horizontal deformations of the region of the Western Ukraine territory, using a fairly dense network of GNSS stations. This research shows that the geodynamics of the region is much more complex than in [Ishchenko, 2018; Doskich 2021]. In the future, for the analysis of the marked deformation zones, it is necessary to use more detailed maps with additional data from geological and geophysical materials.

Conclusions

1. Modern vertical and horizontal deformations of territory of western Ukraine are established and analyzed according to the data from continuous GNSS stations from 2018 to 2021. The time series of 48 continuous GNSS stations are taken for the study. This guarantees conditionally uniform coverage of the study area with an average distance between stations near 70 km. It is established that the geodynamics of the region is complex, as well as that modern displacements cannot be explained by local movements of tectonic units in the region.

2. The created map of isolines and vectors of vertical displacements allows us to note that most GNSS stations subside, probably due to denudation processes but the Galicia–Volyn depression is stable. This territory conditionally coincides with the Lviv regional magnetic anomaly [Orlyuk & Romenets, 2005; Nechaeva et al., 2002; Tretyak et al., 2015]. A probable mechanism for the interpretation of a tectonomagnetic anomaly is the piezomagnetic effect, i.e. the reaction of magnetic inhomogeneities to variations in tectonic stresses in the Earth crust [Tretyak et al., 2015]. Therefore, we can assume that the reflection of this mechanism in the vertical geodynamics of the region is possible.

It was found that in the west-east direction, starting from the structures of the Galicia–Volyn depression to the surface of the Ukrainian Shield, the magnitude of negative vertical displacements of GNSS stations increases from -1 mm/year to -16 mm/year). In general, these displacements correlate with a decrease in the depth of occurrence of the crystalline rock surface (from a depth of 4,000 m to the appearance on the surface) on the slopes of the Ukrainian Shield.

3. There are two compression zones on the created maps of horizontal deformations and displacements of the Earth crust and the distribution of deformation parameters of territory of Western Ukraine. The zones include the one in Zakarpattia, corresponding to the Zakarpathian (Transcarpathian) deep fault, and the other in the north-west of the region near the SHAZ station.

4. At the junction of the Galicia–Volyn depression and the edge deflections of the Ukrainian Carpathians, horizontal compression ($\Delta = -3 \cdot 10^{-8}$) and subsidence of the territory up to -2 mm/year are noticeable. This correlates with the similar dynamics of Poland's neighboring regions [Kowalczyk, 2005, 2020; Araszkiewicz, 2016].

5. Anomalous vertical and horizontal displacements are observed in the region around the city of Khmelnytskyi. Compression is established in the region where the GNSS stations GORD, BLZT, BYCH move towards the stations ANTN, BRZD, and the tension is established to the east of this zone. In general, this zone corresponds to compression, the value of dilatation is up to $\Delta = -5 \cdot 10^{-8}$ and the corresponding tension is up to $\Delta = +8 \cdot 10^{-8}$. This region is identified with a negative regional component of the anomalous magnetic field of territory of Western Ukraine [Nechaeva et al., 2002; Orlyuk & Romenets, 2005]. The ancient north-south faults [Palienko, 1992] in the region which separate the zones of compression and tension could be a possible reason for these deformations.

6. The results of research show that the deformations of the territory of Western Ukraine are complex. In the future, for the analysis of the marked deformation zones, it is necessary to use more detailed maps with additional geological and geophysical materials.

References

Anikeev, S., Maksymchuk, V., Pylypyak M. (2019) Gravimagnetic model of the Kolomyia paleodolina along the Nadvirna-Otyniya-Ivano-Frankivsk geotraverse. *Geophysical Journal*, 73–92. (In Ukrainian).

Araszkiewicz, A., Figurski, M. & Jarosiński, M. (2016). Erroneous GNSS Strain Rate Patterns and their Application to Investigate the Tectonic Credibility of GNSS Velocities. *Acta Geophys.* 64, 1412–1429. https://doi.org/10.1515/acgeo-2016-0057

Cenni, N., Baldi, P., Loddo, F., Casula, G. et al. (2013). Present-Day vertical kinematic pattern in the central and northern Italy from permanent GPS stations. Conference: Atti del 32° Convegno Nazionale del Gruppo Nazionale di Geofisica della Terra Solida, *18–21 Novembre 2013, Trieste, vol. 2.*

Chebanenko, I., Vishnyakov, I., & Vlasov, B. (Eds.) (1990) Geotectonics of Volyn-Podillya. *Naukova dumka* (in Russian).

Dach, R., Lutz, S., Walser, P., & Fridez, P. (2015). Bernese GNSS software version 5.2.

Davis, J. L., Wernicke, B. P., & Tamisiea, M. E. (2012). On seasonal signals in geodetic time series. *Journal of Geophysical Research: Solid Earth*, 117(B1).

Desai, S., Bertiger, W., Gross J. et al. (2016). Introduction to JPL's GPS time series. California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Devoti, R., D'Agostino, N., Serpelloni, E., Pietrantonio, G. et al. (2017). A combined velocity field of the Mediterranean region. *Ann. Geophys.*, 60, 2, 2–17. DOI: 10.4401/ag-7059

Doskich, S. (2021). Deformations of the land crust of the Carpathian region according to the data of GNSS observation. Geodesy, *Cartography, and Aerial Photography*, 93(1), 35–41. https://doi.org/10.23939/istcgcap2021.93.035

Esposito, A., Pietrantonio, G., Bruno, V., Anzidei, M., Bonforte, A., Guglielmino, F., ... & Serpelloni, E. (2015). Eighteen years of GPS surveys in the Aeolian Islands (southern Italy): open data archive and velocity field. *Ann. Geophys,* 58(4), S0439. https://doi.org/10.4401/ag-6823

Gruszczynska, M., Klos, A., Rosat, S. and Bogusz, J. (2017). Deriving common seasonal signals in GPS position time series by using Multichannel Singular Spectrum Analysis. *Acta Geodyn. Geomater.,* 14, 3 (187), 273–284. https://doi.org/10.13168/ AGG.2017.0010

Ishchenko, M. (2016). Determination of velocities of East European stations from GNSS observations at the GNSS data analysis center of the main astronomical observatory, national academy of sciences of Ukraine. *Kinematics and Physics of Celestial Bodies,* 32(1), 48–53. https://doi.org/10.3103/s0884591316010049

Ishchenko, M. (2018). Investigation of deformations of the earth crust on the territory of Ukraine using a GNSS observations. *Artificial Satellites,* 53(3), 117–126. https://doi.org/10.2478/arsa-2018-0009

Ishchenko, M., & Khoda, O. (2020, December). On GNSS Activity at the Main Astronomical Observatory NASU. *In International Conference of Young Professionals «GeoTerrace-2020» (Vol. 2020, No. 1, 1–5).* European Association of Geoscientists & Engineers.

Kowalczyk, K. (2005, May). Determination of land uplift in the area of Poland. In the *6th International Conference Environment, al Engineering* (Vol. 1, 903–907)

Kowalczyk, K., Kowalczyk, A. M., & Chojka, A. (2020). Modeling of the vertical movements of the earth's crust in Poland with the co-kriging method based on various sources of data. *Applied Sciences*, 10 (9), 3004.

Kowalczyk K. & Rapiński J. (2017) Robust network adjustment of vertical movements with GNSS data https://doi.org/10.15233/gfz.2017.34.3

Kruglov, S., Smirnov, S., Spitkovskaya, S., Filshtinsky L., Khizhnyakov A. (1985). Geodynamics of the Carpathians. *Naukova Dumka* (In Russian).

Krupskyi, Yu., Kurovets, I., Senkovsky, Yu., Mikhailov V., Chepil, P., Drygant, D., ... & Bodlak, V. (2014). Unconventional sources of hydrocarbons in Ukraine (In Ukrainian).

Kutas, R. I. (2021). Deep degasion and oil-and-gas containment of the Eastern (Ukrainian) Carpathians: geodynamic and geothermal aspects. *Geofizicheskiy Zhurnal*, 43(6), 23–41.

Maksymchuk, V., Klymkovych, T., Nakalov, Y., Chobotok, I., Tymoschyk, V. (2018). Informativity of tectonomagnetic monitoring in the Transcarpathians active seismic zone. XII *International Scientific Conference "Monitoring of Geological Processes and Ecological Condition of the Environment"*, Kyiv, Ukraine. DOI: 10.3997/2214-4609.201803170

Marchenko, O., Tretyak, K., Serant, O., & Vysotenko, R. (2011). Estimation of the Earth crust strain rate tensor from GPS observations data in the Eastern Europe. *Geodynamics* 1(10), 5–16. (In Ukrainian) https://doi.org/10.23939/jgd2011.01.005

Marchenko, A., Perii, S., Lompas, O., Golubinka, Y., Marchenko, D., Kramarenko, S. & Salawu, A., (2019). Determination of the horizontal strain rates tensor in Western Ukraine. *Geodynamics,* 2 (27), 5–15. https://doi.org/10.23939/jgd2019.02.005

Nechaeva, T., Garkavko, V., Shymkiv, L., & Yentin V. (2002). Map of the anomalous magnetic field of Ukraine: Northern State Regional Geological Enterprise "Pivnichukrheolohiya" (In Ukrainian)

Orlyuk, M. (1999). Magnetic model of the Earth crust in the southwest of the East European platform. *Institute of Geophysics of the National Academy of Sciences of Ukraine.* (In Russian).

Orlyuk, M., & Ishchenko, M. (2019) Comparative analysis of modern deformation and the newest motions of the Earth surface in the territory of Ukraine. *Geofizicheskiy zhurnal,* 4 (41), 161–181. (In Russian) https://doi.org/10.24028/gzh.0203-3100.v41i4.2019.177381.

Orlyuk, M. & Romenets, A. (2005). A new criterion for evaluating the space-time disturbance of the Earth magnetic field and some aspects of its use. *Geofizicheskiy Zhurnal*, 27(6), 1012–1023. (In Russian)

Palienko, V. (1992). The newest geodynamics and its reflection on Ukraine's relief. Naukova Dumka (In Russian).

Savchuk, S., & Doskich, S. (2017). Monitoring of crustal movements in Ukraine using the network of reference GNSS-stations. *Geodynamics,* 2(23), 7–13.

Savchyn, I., & Pronyshyn, R. (2020). Differentiation of recent local geodynamic and seismic processes of technogenic-loaded territories based on the example of Dnister Hydro Power Complex (Ukraine). *Geodesy and Geodynamics*, 11(5), 391–400

Siejka, Z. (2017). Evaluation of integration degree of the ASG-EUPOS polish reference networks with Ukrainian GeoTerrace network stations in the border area. *Artificial Satellites*, 52(3), 71. https://doi.org/10.1515/arsa-2017-0007

Starostenko, V. (Ed.). (2005). Research of modern geodynamics of the Ukrainian Carpathians. *Naukova dumka.* (In Ukrainian)

Tretyak, K., Smirnova, O., Bredeleva, T. (2012). Study of periodic changes of the world satellite permanent stations altitudes. *Geodynamics*, 12 (1), 11–29. (In Ukrainian) https://doi.org/10.23939/jgd2012.01.011

Tretyak, K. & Vovk, A. (2014). Results of determination of horizontal deformation of the Earth crust of Europe according to the data of GNSS observations and their relation with the tectonics structure. *Geodynamics*, 1(16), 21-33, (in Ukrainian). https://doi.org/10.23939/jgd2014.01.021

Tretyak, K., Maksimchuk, V., Kutas, R., Rokityansky, I., Gnilko, A., Kendzera, A., & Tereshin, A. (2015). Modern geodynamics and geophysical fields of the Carpathians and adjacent territories. Lviv: Publishing House of Lviv Polytechnic (in Ukrainian).

Tretyak, K., & Brusak, I. (2020). The research of interrelation between seismic activity and modern horisontal movements of the Carpathian-Balkan region based on the data from permanent GNSS stations. *Geodynamics,* 1(28), 5–18. https://doi.org/10.23939/jgd2020.01.005

Tretyak, K., Brusak, I., Bubniak, I., & Zablotskyi, F. (2021). Impact of non-tidal atmospheric loading on civil engineering structures. *Geodynamics* 2(31), 16–28. https://doi.org/ 10.23939/jgd2021. 02.016

Корнилій ТРЕТЯК, Іван БРУСАК

Кафедра вищої геодезії та астрономії, Національний університет “Львівська політехніка”, вул. С. Бандери, 12, Львів, 79013, Україна

СУЧАСНІ ДЕФОРМАЦІЇ ЗЕМНОЇ КОРИ ТЕРИТОРІЇ ЗАХОДУ УКРАЇНИ ЗА ДАНИМИ ГНСС МЕРЕЖІ «GEOTERRACE»

У роботі проаналізовано сучасні тенденції горизонтальних та вертикальних зміщень території заходу України за ГНСС-даними, з побудовою відповідних карт рухів та з 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 Заході України. Вихідними даними є горизонтальні та вертикальні швидкості 48 ГНСС-станцій з 2018 до 2021 років мережі “Geoterrace” на Заході України, відомі тектонічні карти території та описові матеріали. Методика передбачає порівняння та аналіз сучасних деформацій земної кори регіону з його відомою тектонічною структурою. У результаті вперше побудовано карти горизонтальних швидкостей ГНСС-станцій та деформацій верхнього шару земної кори Заходу України як єдиного регіону і вертикальних швидкостей ГНСС-станцій. Встановлено, що деформації території Заходу України є складними і лише частково співвідносяться з відомою тектонічною будовою в регіоні. Більшість ГНСС-станцій зазнають висотних просідань, імовірно, в зв’язку з денудаційними процесами, але Галицько-Волинська западина практично не просідає. На схилах Українського щита помітна кореляція вертикальних зміщень та глибини залягання поверхні кристалічних порід. Зони стиску виділяються на Закарпатті, що відповідає території Закарпатського глибинного розлому, а інша – на північному-заході регіону. Окремо необхідно виділити регіон довкола міста Хмельницький, де спостерігаються аномальні вертикальні та горизонтальні зміщення. Подано геодинамічну інтерпретацію аномальних зон деформацій. Визначено швидкості ГНСС-станцій зі збільшенням часового інтервалу спостережень дадуть можливість встановити особливості просторового розподілу руху земної кори на території Заходу України та в майбутньому створити відповідну регіональну геодинамічну модель.

Ключові слова: сучасна геодинаміка; деформації земної кори; ГНСС-дані; Захід України.

Received 12.03.2022