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DETERMINATION OF HORIZONTAL DEFORMATION OF THE EARTH'S CRUST ON THE TERRITORY OF UKRAINE BASED ON GNSS MEASUREMENTS

The purpose of research is to identify horizontal deformation of the Earth`s crust on the Ukraine territory, using only proven and suitable for geodynamic interpretation GNSS stations. The initial data are observations from 30 GNSS stations for 2017 to 2020. Methodology. The methodology includes the analysis of modern Earth's crust deformations of Ukraine. As a result, for the first time the impact of the coordinates time series created by two different methods: Precise Point Positioning (PPP) and the classical differential method, on determining deformation processes was analysed. It was established that nowadays for the tasks of monitoring, including geodynamic, it is necessary to use the Precise Point Positioning (PPP) method, because the accuracy of determined velocities of the GNSS stations by this method was higher than in the classical differential method. Results. A map of horizontal Earth's crust deformations on the territory of Ukraine was created according to the coordinates time series of GNSS stations. The extension areas of Shepetivka-Starokostiantyniv Khmelnytsky region, Boryspil–Pryluky–Pereyaslav–Khmelnitsky Kyiv and Chernihiv region, as well as a compression area of the Earth's crust in Nizhyn–Stepovi Khutory–Kozelets of Chernihiv region was identified. Additionally, a map of horizontal displacements of the GNSS-stations was created, where the diverse of these displacements was observed, which is likely to be caused by the presence of modern subvertical and sub-horizontal faults and fault areas. For better interpretation of the obtained results, it is necessary to involve geological and geophysical data of tectonic activity of the Ukraine territory.

Key words: geodynamics; GNSS; PPP method; deformation of the Earth's crust, horizontal displacement

Introduction

Horizontal tectonic movements play a major role in the formation of the Earth's surface structure. In nature, there is a repeated transition of horizontal movements into vertical and vice versa. For example, stretching in horizontal terms leads to subsidence, and the squeezing of the layers into the folds and their uplift is caused by the horizontal compression in the vast majority [Mikhailov, 2002].

The causes of tectonic movements are gravitational convections in the Earth's mantle and high stresses in the lithosphere and the Earth's crust that arise from this. On the maps of tectonic zoning, 95 % of the territory of Ukraine is located on the Eastern-European platform (where the Ukrainian Shield, the Volyn–Podilska Plate, the Dniprovsko – Donetska and the Prychornomorska depressions are also distinguished), also there are a young Scythian platform in the south and four folded areas: Crimean mountains, which are a fold-block system of the Alpine geosynclinal zon; the folding system of the Ukrainian Carpathians; the Northern Dobrogea and the Donetsk folded structures (Fig. 1). The thickness of the Earth's crust is a range of 20 to 65 km. The thickness of crust reaches the maximum in the Carpathian region (65 km), decreases (up to 40–45 km) in the Volyn-Podilskyi region, increases again (up to 45–50 km) under the Ukrainian Shield, and in the south of Ukraine the thickness is within the limits 25–35 km. There are a number of layers in the structure of the Earth's surface, which differ in the composition of rocks and the speed of seismic waves distribution.

The main reason for the studies of tectonic movements of the Earth's crust is that they rise the stresses that causes shortening and thickening of rocks, which leads to deformation. This is especially relevant for areas where important engineering facilities such as hydroelectric power plants or nuclear power plants are located [Tretyak K. & Palianytsia B., 2021; Tretyak et al., 2022].

Nowadays, GNSS technology is widely used for estimation of tectonic movements movements [Savchuk et al., 2023]. The GNSS station time series allows to evaluate modern surface movements, as well as related deformations of the Earth's crust.

This work is devoted to the study of modern horizontal tectonic movements and deformations of the Earth's crust of Ukraine by using the GNSS-observations for assessment of the region`s natural hazards.

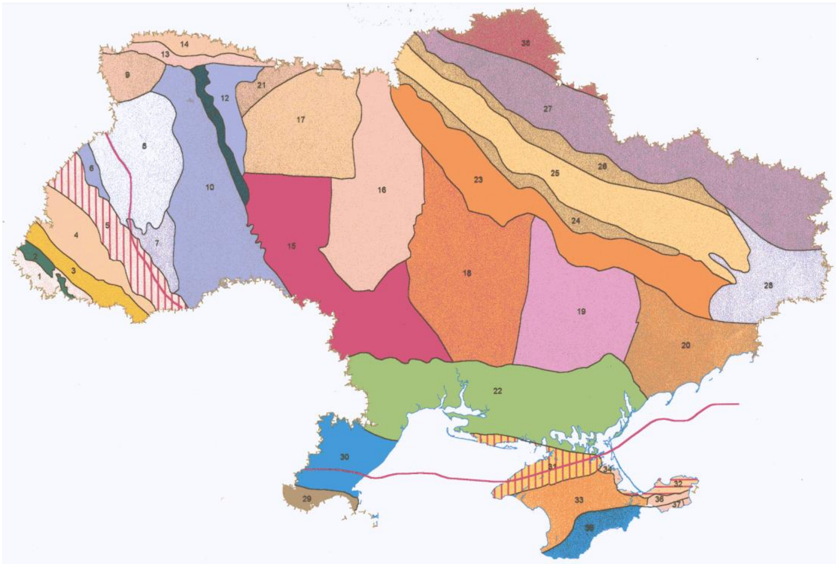

Fig. 1. Scheme of tectonic zoning of Ukraine [Kruhlov et al., 2007]:
Carpathian meganapnorium (1–5): 1 – Transcarpathian internal trough; 2 – Vyhorlat-Hutynska volcanogenic (zone) ridge; 3 – Marmara Massif, zone of rocks and internal flysch covers; 4 – Krosno zone and Skibovy cover; 5 – Precarpathian depression; Western European platform: 6 – Rava-Ruska epeirogenic zone; East European Platform (7–27): Volyn-Podilsky plate (7–14): 7 – Boyanetsky depression; 8 – Lvivskyi Paleozoic trough; 9 – Kovelskyi ledge; 10 – Volyno-Podilska monocline; 11 – Volynskyi traps; 12 – VolynoPoliska depression; 13 – the North Ukrainian handful zone; 14 – Polissya saddle; Ukrainian Shield (15–21): megablocks: 15 – Dniester-Buzky; 16 – Rosynsko-Tikytsky; 17 – Volynsky; 18 – Kirovohradsky; 19 – Serednyodniprovsky; 20 – Pryazovsky; 21 – Volyn'–Polissia volcanic-plutonic belt; 22 – South Ukrainian monocline; Dnipro-Donetsk depression (23–27): 23 – Southern side zone; 24 – Southern coastal zone; 25 – Central zone; 26 – Northern coastal zone; 27 – Northern side zone; Folded Donbass (28); Skyfska epiorogenic zone (29–34): 29 – Nyzhnoprutskyi ledge; 30 – Preddobrudzky deflection; 31 – North Crimean (Karkinitsky) depression; 32 – Indolsky deflection; 33 – Central Crimean uplift; 34 – Azov Upland; Crimean Meganapnorium (35–37): 35 – Tavriya and Yaylin tectonic covers 36 – Vladyslavivskyi tectonic cover; 37 – Krasnopilsky tectonic cover; Voronezh crystalline massif (38) — border of the East European platform.

The relevance and purpose of research

Geodynamic research of Ukraine territory on the basis of GNSS observations were conducted by a number of scientists [Savchuk & Doskich, 2017; Ishchenko, 2018; Orlyuk & Ishchenko, 2019, Marchenko et al., 2019; Ishchenko & Khoda, 2020; Doskich, 2021; Tretyak & Brusak, 2022]. However, the researches listed above have two quite significant disadvantages. The first disadvantage is that all available GNSS stations was use, for geodynamic studies, although not all of them are suitable for such tasks. According to [Dvulit, et al., 2021], the coordinate time series of most Ukrainian reference GNSS-stations is not conformed to the normal Gaussian distribution law. NETM (Non-classical error theory of measurement) accuracy diagnostics of high-precision GNSS measurements confirms the presence of weak, not removed from the processing systematic errors. The neglecting of such error creates the effect of the time coordinate series shifting, which, in turn, leads to subjective estimates of station velocity and their farther geodynamic interpretation. The second disadvantage is that the processing of the GNSS observations in all previous researches was carried out by the classic relative (differential) positioning method. So, a network solution was estimated, where baseline between stations were calculated and linked to the selected fiducial stations. In this case, the absolute values of various influences on a certain station are lost, and monitoring the phenomena that cause these influences in the study area is impossible.

Today, for monitoring tasks, including geodynamic, the Precise Point Positioning (PPP) method is used [Teunissen, et al., 2015; Zhang, et al., 2018; Łyszkowicz, et al., 2021]. The approach of this method uses un-differenced, dual-frequency and carrier-phase observations, along with precise satellite orbits and clocks, to obtain accuracy from a few centimetres to several millimetres with static positioning for one station [Khoptar, 2020]. The advantage of this method lies in the absence of the overall influence of the GNSS-station network, so the mistakes of one station’s solutions do not distort the solutions of other stations. Therefore, in this article coordinates time series was estimated, by using only verified and suitable for geodynamic interpretation GNSS stations, based on the PPP method, and comparison with time series formed by the differential method was made. The main purpose of this article was to determine the horizontal deformation of the Ukraine territory and to create the corresponding maps on the basis of estimated coordinates time series.

Methodology

More than 200 reference GNSS stations located in the territory of Ukraine for the period 2017–2020 were taken to calculate coordinated time series in the first stage. Further from these 200 stations, 72 were selected. The selection was based on the presence of continuous GNSS-observation data (the duration of observations was more than 1.5 years). According to research [Dvulit, et al., 2020], 72 selected stations were checked for residual systematic errors, using non-classical error theory. As a result, only 30 GNSS stations (with duration of observations more than 3 years) (Fig. 2) were left for further geodynamic interpretation.

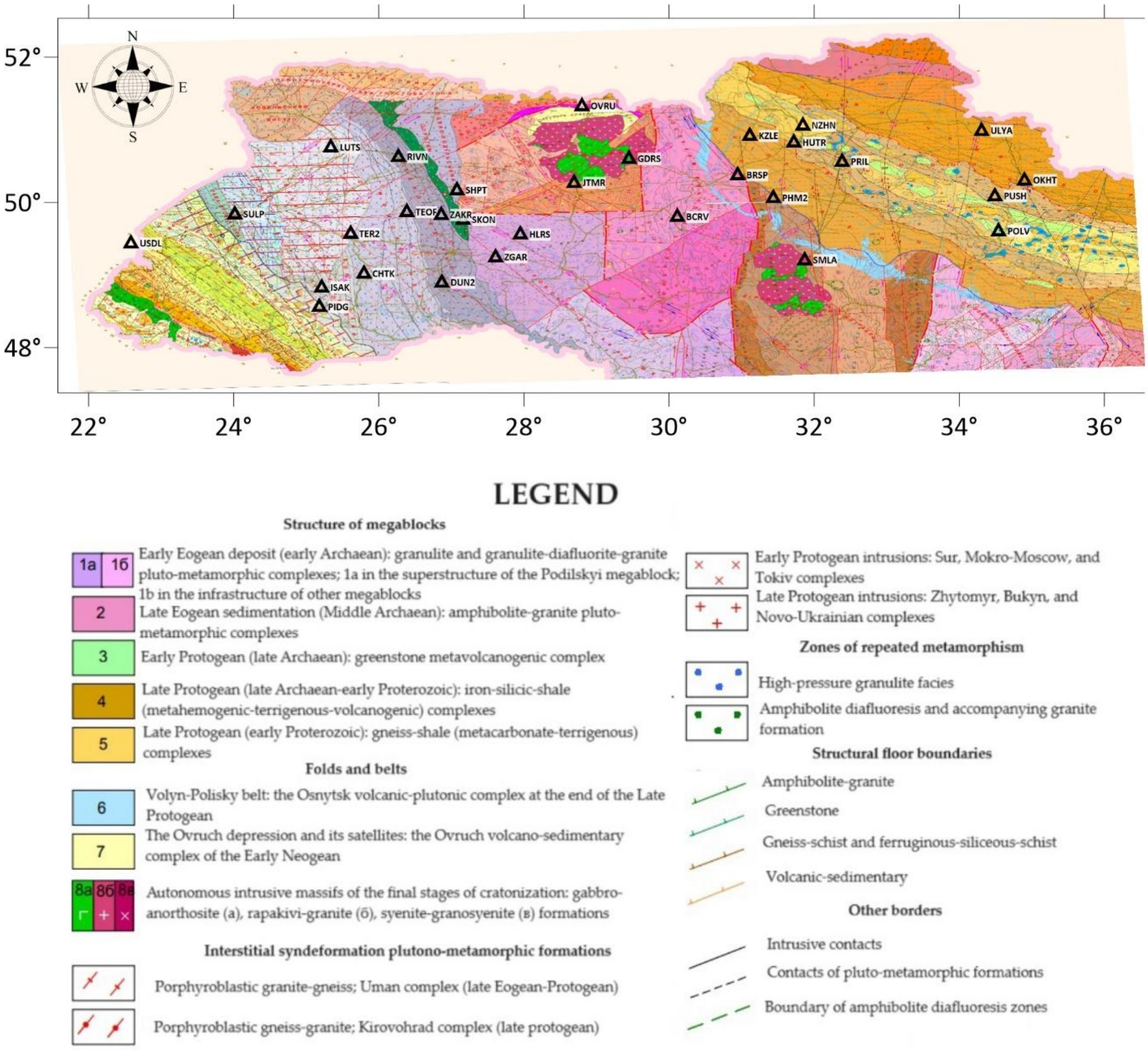

Fig. 2. Placement of GNSS-stations on a fragment of the Ukraine tectonic map [Kruhlov et al., 2007].

GNSS observation for 4 years were processed, and errors were estimated using two software Gamit/Globk developed by Massachusetts Institute of Technology [Herring, et al., 2018] and GIPSYX developed by Jet Propulsion Laboratory (JPL) [Gipsy X., 2023]. GAMIT/GLOBK software is based on the differential positioning method, and GIPSYX on the Precise Point Positioning (PPP) method. Reference frame ITRF14 were realized by the EPN/IGS stations from Ukraine (POLV, SULP) and Poland (JOZ2).

The solutions (coordinates and velocities) from the ITRF-2014 (XYZ) coordinate geocentric system were converted into a topocentric system (ENU).

Table 1 shows the estimated annual velocities V_E (east component), V_N (north component) and V_U (height component) of 30 selected GNSS stations from the GAMIT/GLOBK and GIPSYX software solutions.

To investigate the accuracy of the calculated solutions it was compared with the EPN solution by common stations (GDRS, POLV, SMLA, SULP, USDL) and the velocities differences was determined. Table 2 shows a statistical analysis of differences.

Table 1

Components of linear annual velocity vectors of GNSS stations (ITRF2014) from GAMIT/GLOBK and GIPSYX solutions

GNSS–station	Annual velocities, mm/yr. (GAMIT/GLOBK)			Annual velocities, mm/yr. (GIPSYX)		
	V_E	V_N	V_U	V_E	V_N	V_U
BCRV	24.5	13.0	3.1	24.7	12.4	4.0
BRSP	23.5	13.9	0.3	22.4	12.3	–0.1
CHTK	23.2	14.2	–0.3	24.3	14.8	0.5
DUN2	21.7	13.0	–0.9	22.5	12.9	–3.8
GDRS	21.6	13.2	1.8	21.6	12.6	2.5
HLRS	22.7	13.4	1.5	23.3	12.7	5.4
HUTR	22.5	17.7	–4.6	23.3	16.5	–4.2
ISAK	21.8	14.1	–0.5	24.0	13.9	–0.6
JTMR	23.0	14.0	1.5	22.2	12.8	–0.2
KZLE	25.6	13.5	–0.1	23.4	12.1	0.0
LUTS	20.5	14.1	0.7	21.8	13.5	2.1
NZHN	24.0	13.6	0.4	23.9	12.8	1.8
OKHT	25.2	11.1	2.6	23.9	10.4	4.2
OVRU	21.8	13.7	0.8	22.2	13.3	3.9
PHM2	25.0	13.6	–0.3	23.3	11.8	–2.8
PIDG	21.5	13.1	0.8	23.2	13.9	0.7
POLV	23.9	12.2	0.4	22.3	11.7	2.1
PRIL	24.8	12.3	–0.1	24.7	12.0	0.4
PUSH	24.5	12.3	1.3	24.3	12.6	–3.2
RIVN	21.2	13.7	0.4	21.9	13.4	4.8
SHPT	22.3	16.1	4.2	21.9	15.1	4.7
SKON	21.6	13.2	0.0	22.0	13.1	1.4
SMLA	23.5	12.6	1.4	22.7	12.7	1.9
SULP	20.2	13.6	0.4	21.5	13.6	1.6
TEOF	21.5	13.6	0.8	23.4	12.9	0.9
TER2	20.4	13.0	–0.7	21.4	13.3	2.5
ULYA	25.0	11.7	1.1	24.5	11.1	3.2
USDL	21.0	14.3	1.7	22.4	14.4	1.4
ZAKR	22.1	13.1	0.5	22.2	12.5	–1.4
ZGAR	22.2	12.1	2.0	23.1	12.2	3.4
St.dev.	0.03	0.04	0.16	0.02	0.02	0.07

Table 2

Statistical result of the velocities differences from EPN and GAMIT-GLOBK / GipsyX solutions

Value	GAMIT/GLOBK, mm/yr.			GIPSYX, mm/yr.		
	ΔV_E	ΔV_N	ΔV_U	ΔV_E	ΔV_N	ΔV_U
Max.	1.5	0.1	2.2	0.4	0.2	2.8
Min.	–1.4	–0.8	0.4	–0.7	–0.8	1.5
Aver.	–0.2	–0.3	1.3	–0.1	–0.4	2.1
St.dev.	1.2	0.4	0.8	0.4	0.4	0.5

From Table 2, we see that the standard deviation of the annual velocities in the north direction for two GAMIT/GLOBK and GIPSYX solutions are similar and up to 0.4 and 0.4 mm/year, and in the vertical 0.8

and 0.5 mm/year. However, the standard deviation of the annual velocities in the east direction from GAMIT/GLOBK solution is 1.2 mm/year, while from GIPSYX solution is 0.4 mm/year. This is a significant difference and it can further radically affect geodynamic interpretation. Therefore, for a more reliable demonstration of the geodynamic situation, the data obtained from the GIPSYX solution are offered for use in the future.

Fig. 3 shows the map of horizontal velocities vector of the GNSS-stations in the Ukraine territory, which was taken from the GIPSYX solution.

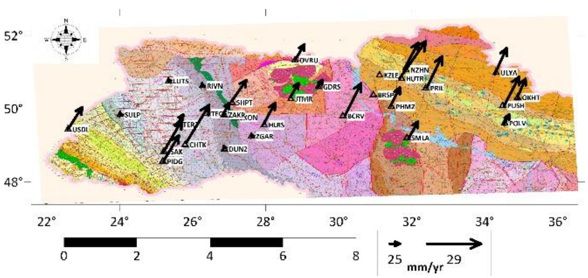

Fig. 3. Map of horizontal velocities vector of the GNSS-stations (ITRF2014).

In the future, these horizontal velocities will be used to calculate the deformation of the Earth crust. The arrows in the Fig. 3 show the direction of velocity vectors, and the values of speeds are characterized by the length of the arrows according to the scale.

Results

Tectonic processes inside the Earth's crust are reflected in modern movements that can be observed on the Earth's surface. Each point of the Earth's crust is corresponded the deformation tensor at that moment of time, if considered deformation of the Earth's crust as a change in the shape and volume of the body [Doskich, 2021]. To analyses the horizontal components of modern Earth's surface movements (deformation), horizontal components of the GNSS stations velocities were used. To determine the field of horizontal deformations velocities of the Ukraine territory, the Delone triangulation method, where the vertices of triangles are GNSS-stations, were used [Kowalczyk & Rapinski, 2017]. For each triangle, the corresponding calculations are made: displacement vector, rotation angle and curvature ellipse (maximum shear strain and area strain). To determine the impact of the accuracy of the estimated GNSS stations velocities on the deformation, their parameters were calculated according to data from two solutions: GIPSYX and GAMIT/GLOBK. The obtained results are presented in Table 3.

Table 3

The calculations results of the Earth's crust deformation

Triangle	GAMIT/GLOBK				GIPSYX			
	Displacement vector velocity, mm/yr.	Rotation (nano–rad/yr) (c – clockwise a –anti–clockwise)	Max shear strain (nano–strain)	Area strain (nano–strain)	Displacement vector velocity, mm/yr.	Rotation (nano–rad/yr) (c – clockwise a –anti–clockwise)	Max shear strain (nano–strain)	Area strain (nano–strain)
1	2	3	4	5	6	7	8	9
PIDG-USDL-ISAK	25.5	–1,2386(c)	33.2	41.5	27.1	–12.8086(c)	25.4	17.3
PIDG-CHTK-ISAK	26.1	–12,2679(c)	9.8	64.2	27.7	–1.92639(c)	45.4	–3.7
PIDG-CHTK-DUN2	25.9	–27,5864(c)	55.1	18.9	27.2	–27.0744(c)	55.1	18.5
CHTK-DUN2-TER2	25.6	16,5873(a)	71.4	–51.8	26.6	12.182 (a)	82.5	–62.3
CHTK-ISAK-TER2	25.8	22,9178(a)	72.4	32.3	27.1	35.2536(a)	47.1	9.3
USDL-ISAK-TER2	25.2	6,0855(a)	24.6	–13.1	26.5	12.7872(a)	34.6	–6.9
DUN2-ZGAR-TER2	24.9	–2,6678(c)	26.3	–0.2	25.8	–4.41932(c)	19.3	6.1
USDL-SULP-TER2	24.7	3,5739(a)	19.0	–4.2	25.8	3.90188(a)	16.7	–11.5
LUTS-SULP-TER2	24.5	–2,0765(c)	6.4	9.2	25.5	–2.54353(c)	1.2	1.1
LUTS-TEOF-TER2	24.8	1,6235(a)	13.4	27.2	25.9	–7.0981(c)	30.0	30.6
LUTS-TEOF-RIVN	25.2	–1,0957(c)	12.4	11.5	26	8.94116(a)	20.3	2.1
SHPT-TEOF-RIVN	26.1	24,3664(a)	46.0	22.1	26.3	28.7710(a)	31.8	–6.8

Continuation of Table 3

1	2	3	4	5	6	7	8	9
SHPT-TEOF-ZAKR	26.2	–0,2047(c)	63.6	98.7	26.3	–4.96868(c)	104.9	38.9
SHPT-SKON-ZAKR	26.2	6,2792(a)	97.2	48.1	25.9	24.2187(a)	73.9	42.5
TER2-ZGAR-TEOF	24.9	–5,3527(c)	11.0	36.2	26	–17.377(c)	26.7	18.8
HLRS-ZGAR-TEOF	25.7	0,6151(a)	24.8	44.7	26.5	–0.99049(c)	13.5	12.6
HLRS-JTMR-TEOF	26.2	0,9168(a)	2.4	17.5	26.3	4.39660(a)	12.8	–2.0
OVRU-JTMR-GDRS	26.0	–2,4681(c)	30.4	–22.4	25.5	–3.77963(c)	18.6	–8.9
OVRU-KZLE-GDRS	26.7	–9,6753(c)	29.0	35.1	25.7	–10.2491(c)	10.7	15.9
JTMR-BCRV-GDRS	26.7	11,4819(a)	47.1	–6.9	26.1	13.2166(a)	35.3	8.7
KZLE-BRSP-GDRS	27.2	–13,4125(a)	49.0	16.0	25.6	–9.55776(c)	18.9	7.2
BCRV-BRSP-GDRS	26.8	17,4201(a)	19.0	19.4	26	16.5226(a)	37.5	1.0
BCRV-BRSP-PHM2	27.8	16,6538(a)	28.0	25.9	26.4	11.8266(a)	42.0	1.1
BCRV-SMLA-PHM2	27.6	–6,2966(c)	21.3	11.7	26.6	–2.9083(c)	5.0	–24.8
BRSP-HUTR-PHM2	28.0	32,2066(a)	28.9	51.3	26.7	19.6281(a)	37.5	69.1
BRSP-HUTR-KZLE	28.2	20,1451(a)	144.4	–88.1	26.8	39.6932(a)	117.6	–22.8
NZHN-HUTR-KZLE	28.3	–12,1341(c)	173.6	–225.2	27.3	20.3514(a)	184.4	–160.5
NZHN-PRIL-KZLE	28.1	13,1644(a)	56.1	–1.7	27	7.63495(a)	6.8	28.8
ULYA-PRIL-OKHT	27.6	–2,2743(c)	7.8	5.5	26.8	–7.00101(c)	9.5	1.0
PUSH-PRIL-OKHT	27.5	–16,3306(c)	41.0	–30.0	27	–4.56691(c)	65.4	–71.6
PHM2-PRIL-HUTR	28.1	–17,8930(c)	116.2	93.7	27.3	–22.9816(c)	72.3	94.8
PHM2-PUSH-SMLA	28.1	11,4498(a)	62.9	47.9	26.5	–2.22872(c)	16.7	–3.4
PHM2-PUSH-PRIL	27.9	–2,6373(c)	15.5	–18.9	27	–8.80738(c)	24.9	3.7
SMLA-PUSH-POLV	27.0	–6,6722(c)	8.2	1.6	26.2	–22.2118(c)	37.3	5.3
OKHT-PUSH-POLV	27.3	–26,6305(c)	33.0	11.5	26.2	–58.4915(c)	73.6	–35.2
HLRS-JTMR-BCRV	27.0	–0,5005(c)	8.5	23.5	26.6	9.43537(a)	25.9	16.0
JTMR-SKON-SHPT	26.6	–20,4391(c)	57.9	66.9	26	–11.4849(c)	47.4	45.0
JTMR-OVRU-SHPT	26.7	–3,7820(c)	30.2	6.3	26.1	–10.2401(c)	21.2	7.6
RIVN-OVRU-SHPT	26.2	12,5462(a)	39.5	–22.7	26.1	4.39184(a)	26.8	–21.3
RIVN-OVRU-LUTS	25.3	4,2425(a)	14.9	15.9	25.7	–1.62771(c)	0.8	2.0
KZLE-OVRU-NZHN	27.4	44,9645(a)	90.0	7.0	26.4	–1.00807(c)	23.7	39.3
ULYA-PRIL-NZHN	27.6	0,5468(a)	25.2	22.1	27.1	2.39016(a)	23.2	9.8

Table 3 show that the values of deformations calculated from GIPSYX and GAMIT/GLOBK solutions in certain areas are similar, and in some triangles such as PIDG–CHTK–ISAK, SHPT–TEOF–ZAKR, BRSP–HUTR–KZLE the differences are ~ 68 nano-strain, which can dramatically change the geodynamic picture. Therefore, in the future, we will only analyse the results from GIPSYX solution.

The value of maximum shear strain is an indicator of geodynamic changes in the Earth's crust in the triangle area. It is noticeable that from all triangles the most active are (SHPT-SKON-ZAKR, SHPT-TEOF-ZAKR), Shepetivka – Starokostiantyniv – Zakrynychchia – Novostavtsi of Khmelnitsky region; (BRSP – HUTR – KZLE, NZHN – HUTR – KZLE) Boryspil – Nizhyn – Stepovi Khutory – Kozelets of Chernihiv region and (PHM2 – PRIL – HUTR) Pereyaslav-Khmelnitsky – Pryluky – Stepovi Khutory of Kyiv and Chernihiv region. Regarding the magnitude of area strain, the positive value indicates an extension of the Earth's crust areas, and the negative indicates a compression. On the basis of the obtained results (area strain from Table 3), we built a map of extension and compression of the Earth's crust areas (some data were excluded due to the small number of stations) according to the GNSS-stations observations from 2017 to 2020 (Fig. 4).

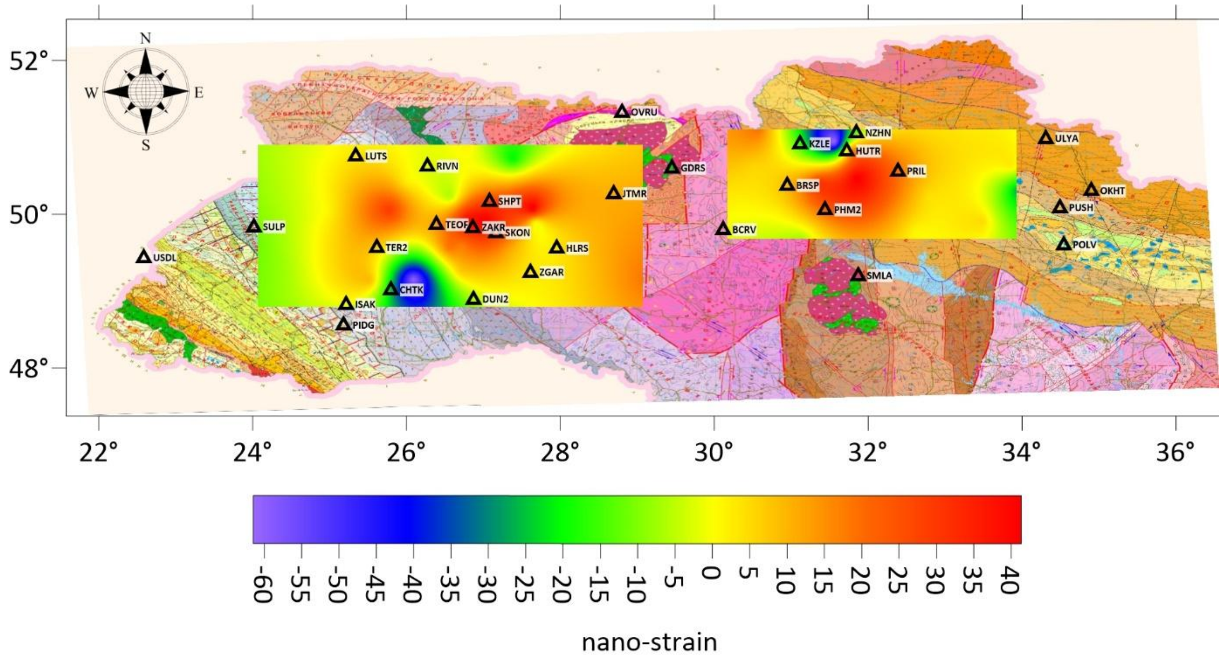

Fig. 4. Map of extension and compression of the Earth's crust areas.

Fig. 4. show the areas of the Earth's crust extension in the regions of Shepetivka – Starokostiantyniv, Khmelnytsky region, Boryspil – Pryluky – Pereyaslav-Khmelnitsky Kyiv and Chernihiv region, as well as a compression area of the Earth's crust in Nizhyn – Stepovi Khutory – Kozelets of Chernihiv region and Chernivtsi – Dunaivtsi on the border of Chernivtsi and Khmelnytskyi regions.

The next additional stage of our research was to estimate the Earth's crust deformations with the removal of the Eurasian tectonic plate motion components. For this purpose, the velocities from the GIPSYX solution in the geocentric system (ITRF-2014) was transformed into the ETRF-2014 system and converted into a topocentric coordinate system (ENU). Table. 4 shows the calculated annual velocities of V_N, V_E and V_U for selected GNSS stations.

Table 4

Components of linear annual velocity vectors of GNSS stations (ETRF2014) from GIPSYX solution

GNSS–station	Annual velocities, mm/yr.		
	V_E	V_N	V_U
1	2	3	4
BCRV	–0.4	1.3	3.9
BRSP	–0.3	–1.0	–0.1
CHTK	1.2	1.5	0.4
DUN2	–0.5	–0.5	–3.8
GDRS	–0.4	–1.5	2.4
HLRS	0.0	–0.5	0.2
HUTR	3.9	–0.1	–5.3
ISAK	0.2	1.3	–0.7
JTMR	–0.3	–0.9	–0.2
KZLE	–0.6	0.1	–0.1
LUTS	–0.1	–0.6	2.0
NZHN	0.2	0.4	1.8
OKHT	–1.6	–0.2	4.2
OVRU	0.1	–0.6	3.9
PHM2	–0.8	–0.3	–2.9
PIDG	0.1	0.5	0.7
POLV	–0.3	–1.8	2.1
PRIL	–0.4	1.1	0.3
PUSH	0.6	0.3	–3.2
RIVN	–0.1	–0.7	4.8

Continuation of Table 4

1	2	3	4
SHPT	1.7	–0.8	5.7
SKON	–0.3	–0.8	1.4
SMLA	0.1	–1.2	1.9
SULP	–0.3	–0.8	1.5
TEOF	–0.6	0.6	0.8
TER2	–0.3	–1.2	2.4
ULYA	–0.9	0.6	3.2
USDL	0.3	0.3	1.3
ZAKR	–1.0	–0.6	–1.4
ZGAR	–1.1	0.0	3.4
St.dev.	***0.02***	***0.02***	***0.05***
Max.	***3.9***	***1.5***	***5.7***
Min.	***–1.6***	***–1.8***	***–5.3***
Aver.	***–0.1***	***–0.2***	***1.0***

From Table 4, we observe that on average horizontal and vertical stations velocities are mutually compensated and up to –0.1 mm/year in the east direction, –0.2 mm/year in the north direction and 1 mm/year in height. The maximum annual velocity in the eastern direction is 3.9 mm/year for HUTR station, in the western direction – 1.6 mm/year for OKHT station, in the north direction – 1.5 mm/year for CHTK station, in the south direction – 1.8 mm/ year for POLV station. The maximum subsidence is observed at HUTR station up to 5.3 mm/year, and lifting at the SHPT station up to 5.7 mm/year.

According to the data from table 4 a model of horizontal displacements of the earth's crust in the ETRF-2014 coordinate system for the Ukraine territory by Kriging interpolation was created. Fig. 5 shows the map of these horizontal displacements.

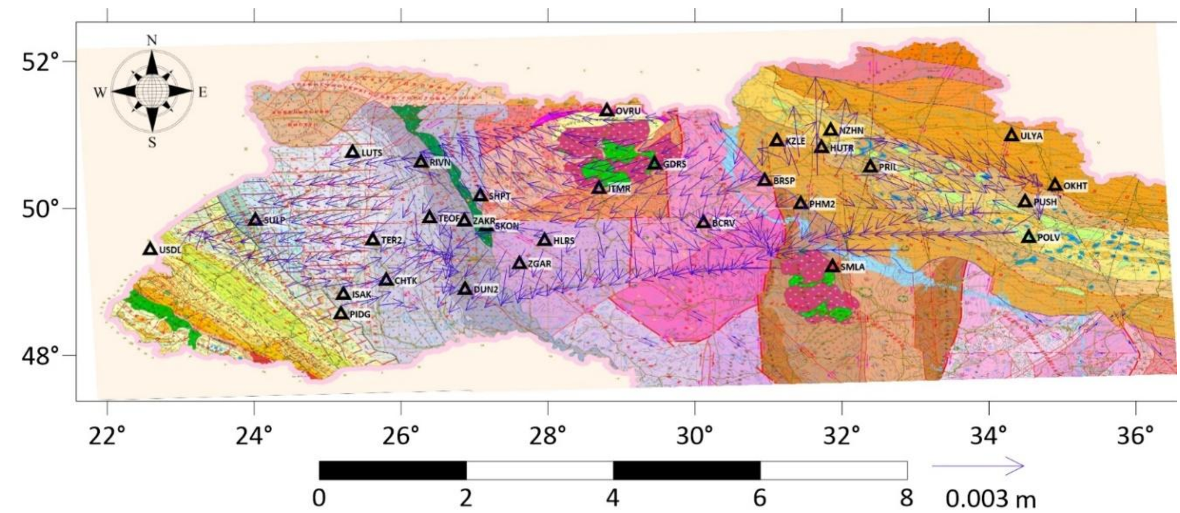

Fig. 5. Map of horizontal displacements of the earth's crust in the ETRF-2014 coordinate system for the Ukraine territory.

The obtained horizontal displacements in the territory of Ukraine are diverse. This is primarily due to the presence of modern subvertical and sub-horizontal faults and fault areas. In the future, geophysical and geological data should be used for better interpretation of the results.

Conclusions

For geodynamic research of Ukraine territory, the observation of reference GNSS-stations from 2017 to 2020 was estimated by two software, which are based on two different methods: classical differential (GAMIT/GLOBK) and Precise Point Positioning PPP (GIPSYX). From 72 stations only 30 was selected for further geodynamic interpretation after being checked, by non-classical error theory (the criterion was the absence of residual systematic errors). For further research only the coordinates time series from Precise Point Positioning (GIPSYX) solution will be used, since the accuracy of calculated velocities compared to the EPN solution is higher than in the differential method.

Another advantage of the PPP method is that its solution does not have the overall impact of the GNSS-station network, so the mistakes of one station's solutions do not distort the solutions of other stations.

The map of horizontal deformations of the Earth's crust in Ukraine was created according to the coordinates time series. The areas of the Earth's crust extension in the regions of Shepetivka – Starokostiantyniv, Khmelnytsky region, Boryspil–Pryluky–Pereyaslav–Khmelnitsky Kyiv and Chernihiv region, as well as a compression area of the Earth's crust in Nizhyn – Stepovi Khutory – Kozelets of Chernihiv region was determined.

Also, the map of horizontal displacements of the Earth's crust in the ETRF-2014 coordinate system by Kriging interpolation was created. The obtained horizontal displacements are diverse, which is most likely caused by the presence of modern subvertical and sub-horizontal faults and fault areas. To further interpretation of the results, we propose to use geophysical and geological data.

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ВИЗНАЧЕННЯ ГОРИЗОНТАЛЬНИХ ДЕФОРМАЦІЙ ЗЕМНОЇ ПОВЕРХНІ ТЕРИТОРІЇ УКРАЇНИ ЗА ДАНИМИ ГНСС ВИМІРІВ

Метою досліджень є виявлення горизонтальних деформацій території України, із використанням тільки перевірених і придатних для геодинамічної інтерпретації ГНСС станцій. Вхідними даними є спостереження з 30 ГНСС станцій за 2017–2020 рр. Методика. Методика передбачає аналіз сучасних деформацій земної кори території України. У результаті вперше проаналізовано вплив часових серій координат, створених двома різними методами: точного позиціонування PPP і класичним диференційним методом, для визначення деформаційних процесів. Встановлено, що сьогодні для задач моніторингу, зокрема геодинамічного, варто використовувати метод точного позиціонування PPP, точність визначення швидкостей ГНСС станцій якого в результаті перевірки виявилась вищою, ніж в класичному диференційному методі. Результати. Побудовано карту горизонтальних деформацій земної кори на території України за даними часових рядів координат ГНСС станцій. Визначено ділянки розтягу земної кори в районах Шепетівка – Старокостянтинів Хмельницької області, Бориспіль – Прилуки – Переяслав-Хмельницький Київської і Чернігівської області, а також ділянку стискання земної кори в Ніжин – Степові Хутори – Козелець Чернігівської області. Додатково побудовано карту горизонтальних зміщень ГНСС-станцій, де спостерігаємо різнонаправленість цих зміщень, що, швидше за все, спричинено наявністю сучасних субвертикальних і субгоризонтальних розломів та розломних зон. Для кращої інтерпретації отриманих результатів необхідно залучити геолого-геофізичні дані тектонічної активності території України.

Ключові слова: геодинаміка; ГНСС; метод PPP; деформації земної кори, горизонтальні зміщення.

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