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INVESTIGATION OF DEFORMATIONS OF THE EARTH CRUST ON THE TERRITORY OF UKRAINE USING A GNSS OBSERVATIONS

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ABSTRACT. A regional GNSS network consisting of 202 permanent GNSS stations established to study the recent crustal strain deformation in the Ukrainian territory. The GNSS observations (from December 7, 1997 to January 28, 2017) collected and processed using Bernese GNSS Software ver. 5.2 in accordance with the recommendations of the Central Bureau of the EUREF Permanent GNSS Network. Based on the above results the velocity vectors were estimated using Bernese GNSS Software ver. 5.2 for the future calculation of deformation. In particular, ellipses of distortion, rotation, maximum shear strain, and deformation area are obtained. Due to the differences in rate of the horizontal extension and rotation the area is divided in two main blocks. The first block shows compression that prevails in the North-East direction. Stretch in both directions is prevailing on second block. The obtained results can indicate the presence of some force which could effect on the study area.

Keywords: GNSS, geodynamics, crustal strain, strain ellipses.

1. INTRODUCTION

The National atlas of Ukraine gives such a geological characteristic: "The territory of Ukraine is characterized by the diversity of geological structures the composition of which is a reflection and consequence of the complex and long history of the geological development. Belonging to two major geostructural types of the continental earth crust, they correspond with platform and folded regions. Within the boundaries of the East European platform, such main structures are distinguished: the Ukrainian Crystalline Shield, the Volyn'-Podillia plate, the Dnipro-Donets' depression, the South Ukrainian monocline (the Black Sea coastal depression), and the southwestern slope of the Voronezh massif. Features of the modern tectonic stage are: migration between zones with different types of crustal movements (unidirectional, oscillatory); quasi-periodicity of movements of the earth's crust fixed in phases, stages, and substages that differ in the movement intensity, deformation style, etc.; manifestation of vertical and horizontal movements, as well as complication of the tectonic component of movements of the earth's crust through halogenic, glacioisostatic, and technogenic components." More details can be found on the Atlas website[1].

At the present stage of science progress in the world Global Navigation Satellite Systems (GNSS) are used for a wide range of scientific tasks, in particular, in geodesy, geodynamics, cartography, cadaster, meteorology, etc. This method does not depend on many external factors, such as weather conditions, and provides a high level accuracy of satellite observations at permanent GNSS stations. GNSS observations accumulated over a long period of time and the precise coordinates make possible to obtain high-precision coordinate time series. The velocity vectors for each GNSS stations can be determined using the homogeneous time series. Such results for a long period of time can be useful for geodynamic research.

The creation and subsequent development of local GNSS networks on the territory of Ukraine made possible to study the crustal strain. At the GNSS Data Analysis Center Main Astronomical Observatory of National academy of sciences of Ukraine (MAO NASU) the crustal strain for the northern region of Ukraine was determined (Ishchenko, 2017). The results showed the investigation prospect of carrying out for the whole territory of Ukraine. It should be noted to how a variety of non-tectonic factors might affect the velocity values including groundwater and surface water, human activity, mass movement that might effect on the GNSS station, and so on.

2. INPUT DATA FOR GEODYNAMIC INVESTIGATION

To estimate the deformation of the earth's crust, the coordinates and the velocity vectors from permanent GNSS stations located in Ukraine territory were used. GNSS observations of state, academic, university and commercial networks of Ukrainian were used. First of all coordinates from GNSS stations based on reprocessing and regular processing were obtained. It was done in accordance with the recommendations of the Central Bureau of the EUREF Permanent GNSS Network (Guidelines for EPN Analysis Centres, 2013). The a priori coordinates and velocities of stations were taken from the IGb08 (Rebischung et al., 2012) catalogue[2] with a reference to the epoch 2005.0. To define the coordinate system, the minimum constrain condition No-Net-Translation on the coordinates of stations RIGA, MDVJ, BOR1, JOZE, GLSV, POLV, UZHL, WTZR, GRAZ, BUCU, SOFI, MATE, ISTA, CRAO, ANKR, ZECK and NICO was applied, ("stars" on Fig. 1). The *Bernese GNSS Software ver. 5.2* (Dach et al., 2015) developed at the Astronomical Institute of the University of Bern (Switzerland) was used to obtain solutions.

As the results, the consistent coordinate time series of coordinates for the entire processed period (December 7, 1997 – January 28, 2017) were obtained in the IGb08 reference frame[3] for 233 GNSS stations, Fig. 1.

[1] http://wdc.org.ua/atlas/en/4030100.html , accessed 21/06/2018.
[2] http://ftp.aiub.unibe.ch/BSWUSER52/STA/, accessed 21/06/2018.
[3] http://acc.igs.org/igs-frames.html, http://acc.igs.org/igs-frames.html

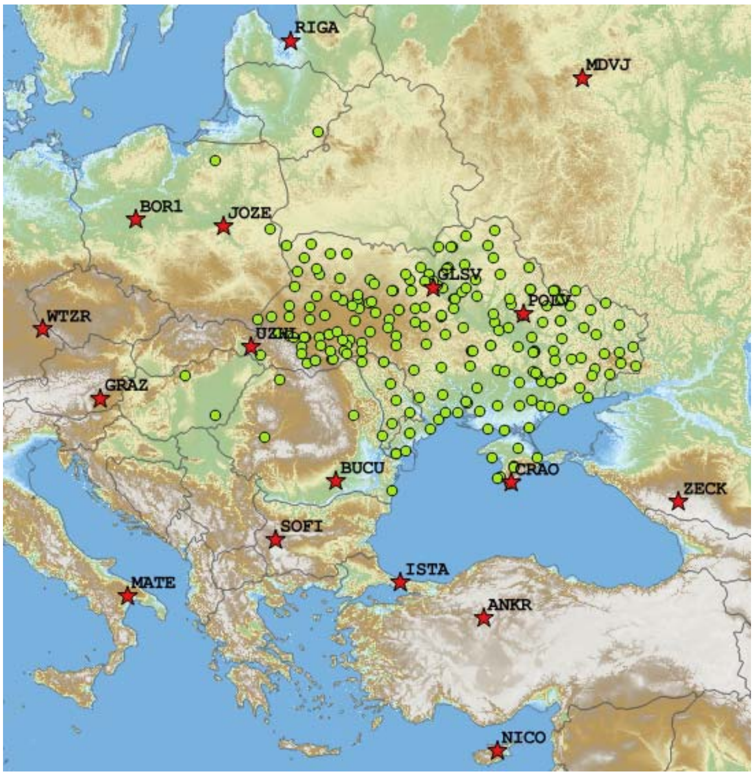

Fig. 1. Configuration of GNSS network (stars – reference stations, dots – other stations)

The obtained files in SINEX format are freely available on the ftp server[4] of the MAO NAS of Ukraine.

To estimate the velocity vectors the equalization of the files of normal equations for all 233 GNSS stations was carried out (Dach et al., 2017). However, not all GNSS stations, whose velocities were estimated, can be used in further studies related to the deformation of the earth's crust. This is due to the geographic location of the permanent stations and some features of the assessment of velocity determination. First of all, stations located far away from considered area and stations that had observations in less than three years were rejected (DeMets et al., 1994). After that, from 233 remain 108 GNSS stations, which can be used for future investigation of crustal strain. The GNSS stations and velocity vectors in Fig. 2 were shown.

[4] ftp://ftp.mao.kiev.ua/pub/gnss/products/IGb08/, accessed 21/06/2018.

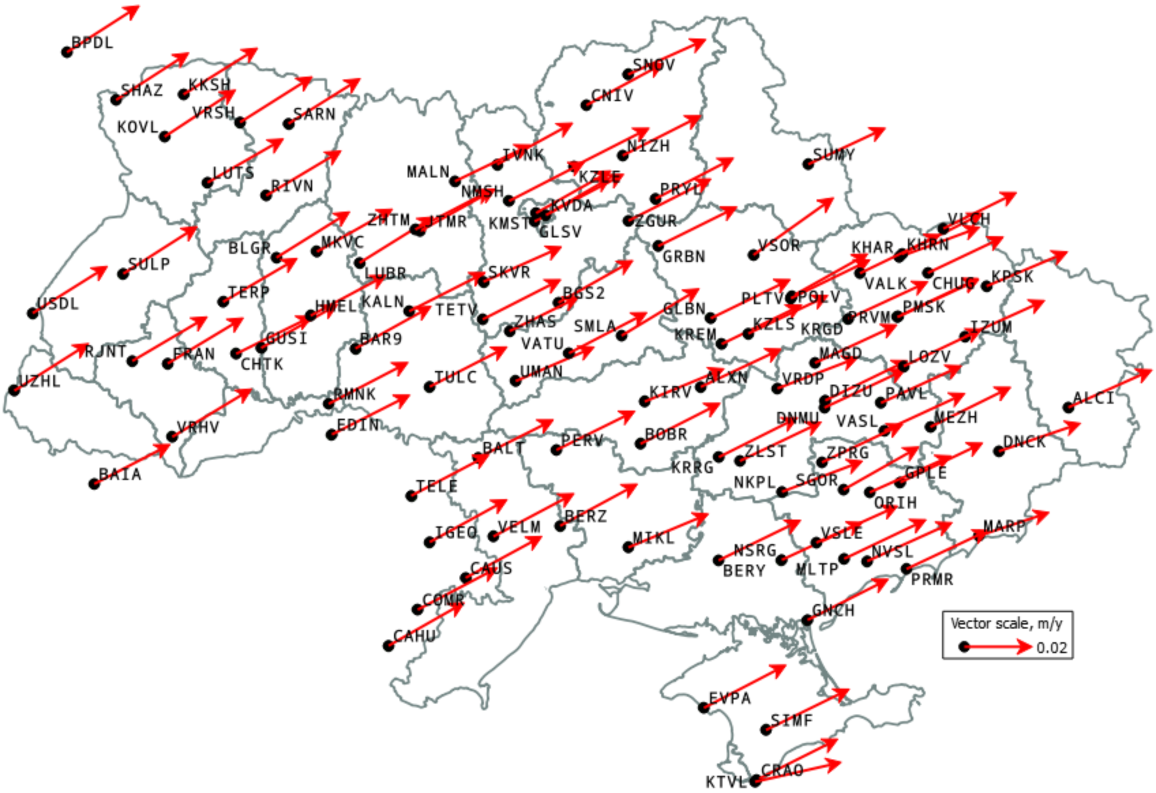

Fig. 2. Field of velocity vectors for GNSS stations (only horizontal component, m/y)

In Table 1 the velocity vectors for North and East components provide by *ADDNEQ2* that is a part of *Bernese GNSS Software ver. 5.2* are shown.

Table 1 (part one). Velocity values for North and East component, mm per year.

Station	VN, mm/y	VE, mm/y	Station	VN, mm/y	VE, mm/y
ALCI	11.05	24.62	MALN	10.71	22.22
ALXN	11.14	23.68	MARP	6.86	20.65
BAIA	11.60	22.30	MEZH	11.67	23.60
BALT	11.12	22.14	MIKL	9.85	23.55
BAR9	12.40	22.26	MKVC	12.52	22.21
BERY	11.77	24.12	MLTP	11.50	24.09
BERZ	12.29	22.72	NIZH	11.70	23.02
BGS2	12.40	21.91	NKPL	9.03	23.72
BLGR	13.46	21.54	NMSH	11.39	22.11
BOBR	11.94	23.44	NSRG	11.07	23.78
BPDL	13.66	21.25	NVSL	11.34	24.98
CAHU	12.67	22.26	ORIH	10.71	23.95
CAUS	12.20	22.44	PAVL	10.93	23.67
CHTK	11.05	22.38	PERV	11.41	23.07
CHUG	10.55	22.21	PLTV	11.27	23.25
CNIV	12.28	22.60	PMSK	11.17	23.59
COMR	12.34	23.48	POLV	12.56	22.43
CRAO	12.03	23.94	PRMR	11.39	24.12
DIZU	11.74	24.14	PRVM	11.05	23.95
DNCK	8.21	24.05	PRYL	11.94	22.97
DNMU	11.19	23.74	RIVN	13.13	21.98

Table 1 (part two). Velocity values for North and East component, mm per year.

Station	VN, mm/y	VE, mm/y	Station	VN, mm/y	VE, mm/y
EDIN	11.59	22.90	RJNT	12.99	22.04
EVPA	12.58	24.14	RMNK	12.15	23.34
FRAN	13.41	22.24	SARN	13.23	21.11
GLBN	11.39	23.37	SGOR	12.58	22.19
GLSV	12.90	22.35	SHAZ	13.83	21.33
GNCH	12.00	23.74	SIMF	12.03	24.50
GPLE	11.56	24.20	SKVR	10.26	22.99
GRBN	11.51	23.18	SMLA	13.81	22.81
GUSI	12.76	22.46	SNOV	10.28	22.90
HMEL	11.92	22.20	SULP	13.87	21.72
IGEO	12.47	22.74	SUMY	10.62	22.67
IVNK	12.21	22.24	TELE	12.03	22.86
IZUM	10.61	23.43	TERP	12.79	21.80
JTMR	12.37	22.15	TETV	11.69	22.93
KALN	11.37	22.37	TULC	11.70	22.75
KHAR	8.74	23.70	UMAN	10.02	23.08
KHRN	12.06	23.87	USDL	13.77	21.97
KIRV	9.66	23.36	UZHL	13.87	21.88
KKSH	13.62	21.80	VALK	11.39	23.57
KMST	12.41	21.98	VASL	10.95	23.73
KOVL	13.75	20.87	VATU	11.95	22.92
KPSK	10.07	23.82	VELM	12.64	23.74
KREM	11.46	23.56	VLCH	10.61	21.55
KRGD	10.88	23.37	VRDP	9.07	23.59
KRRG	11.60	23.17	VRHV	14.10	23.32
KTVL	5.72	25.37	VRSH	13.39	21.21
KVDA	12.00	22.87	VSLE	10.78	23.92
KZLE	11.26	22.11	VSOR	16.83	23.57
KZLS	11.19	23.43	ZGUR	12.29	24.29
LOZV	10.94	22.98	ZHAS	10.03	20.26
LUBR	13.52	21.71	ZHTM	11.63	22.39
LUTS	12.85	22.29	ZLST	11.43	23.94
MAGD	11.19	24.11	ZPRG	11.25	23.76

3. CRUSTAL STRAIN RATE

The main idea of the method of determination the deformation of the earth's surface using geodetic measurements is based on tectonic movements which are considered as a superposition of three general types of motion. This is a parallel translation, rotation, as absolutely solids body, and distortion of the earth's surface.

Additionally, the Finite Element Method (FEM, Reddy, 2006) was applied for geodetic data, because this algorithm makes sense for the small size of the study area. This method is appropriate to use when parameters of several points are known, and there is a need for approximation to the entire area. For a more precise approximation the territory is divided into smaller dimensions (usually triangles) and the problem of approximation is solved within each of them. It is assumed that the deformation inside the triangle is homogeneous. GNSS stations with known coordinates and velocity vectors are used as nodes of the triangle.

The calculation of the crustal deformation for the territory of Ukraine was performed using the *GeoStrain software* (Goudarzi et al., 2015), which is freely available[5] under the BSD license. GeoStrain is written in the MATLAB programming language using a graphical user interface (GUI). As input file two sets of data for each GNSS station used:

- file with coordinates defined in local geodetic Cartesian coordinate system and
- file with values of velocity vectors for North, East and Up components.

Before the start of calculations of the crustal deformation a set of data were applied the Covariance function of Gaussian. This made possible to check the effect of noise level on the estimated results. The interpolation for points of interest can be done when coefficients of the covariance function were computed. It is useful to note that interpolation can be done separately for horizontal and vertical velocity values. More details can be found at Goudarzi et al. (2015).

The result of the calculations is given for four components of strain deformation: strain ellipses, rotation, maximum shear strain and area strain. The algorithm of the calculation diagram that using in *GeoStrain software* is shown in Fig. 3.

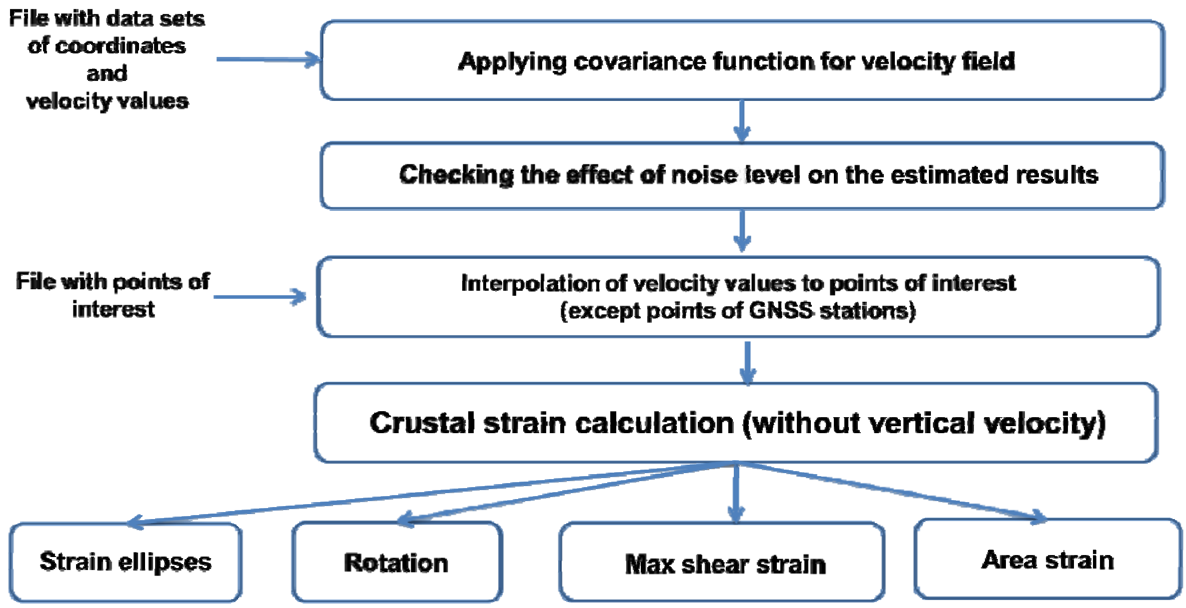

Fig. 3. The algorithm calculation diagram in *GeoStrain Software* (Goudarzi et al., 2015)

4. RESULTS

Maximum and minimum horizontal extension

According to the theory of deformation, any part of the surface can be characterized by two mutually perpendicular directions, one of which deformation will have a maximum extension and on the other maximum compression (Cronin and Resor, 2017). Values of extension and compression are represented by semi-major and semi-minor axes of the strain ellipse, respectively. Extension is a dimensionless number but it seemed add to express strain rate as some number "per year". The unit using GNSS data are expected in nano-strain per year. In Fig. 4 red arrows indicate extension while blue arrows – compression of the area of study.

[5] https://sourceforge.net/projects/geostrain/, accessed 21/06/2018.

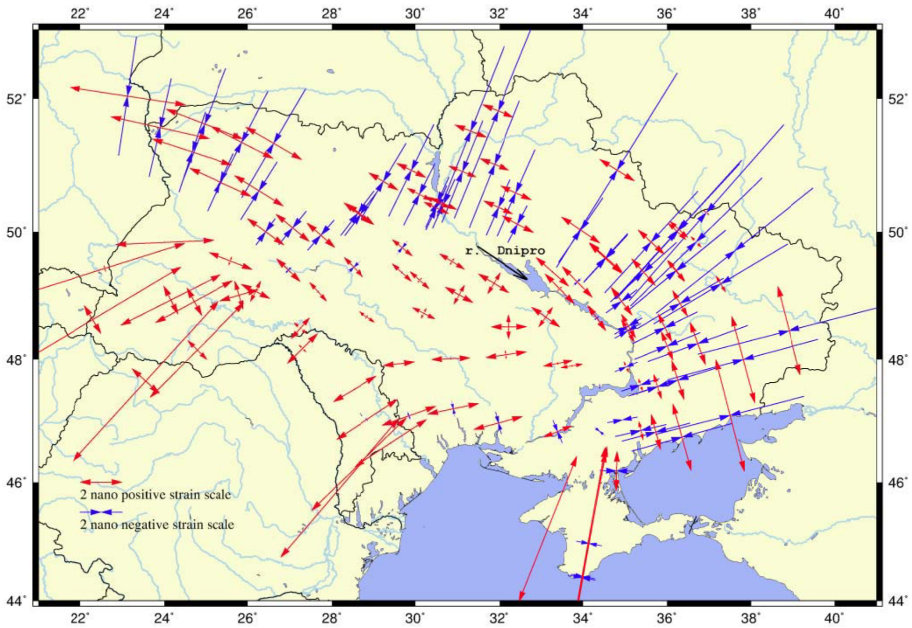

Fig. 4. Strain ellipses (red arrows denotes extension, blue – compression)

In Fig. 4 two areas of deformations can be clearly identified. The compression of area located on the left bank of the Dnipro River and on the northern part of the country prevails in the North-East direction. It shows what the deep processes of compression of the earth's surface are dominating there (Sollogub, 1986, Gintov et al., 2011). On the other part of the investigated area a tension in both directions are prevailing.

Rotation

This type of deformation characterizes the rotation of rigid triangular piece of crust in a year. The rotation is determined by the angular shift of the orientation of the major axe of the ellipse, Fig. 5.

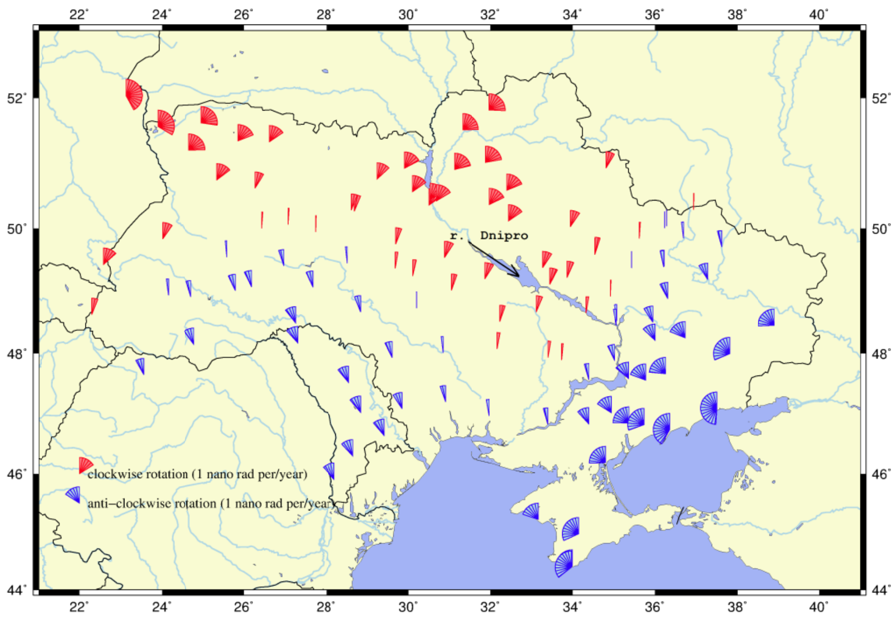

Fig. 5. Rotation (red marks denotes clockwise, blue – anti-clockwise rotation)

Two identical blocks with some geological processes (blue marks, anti-clockwise), separated by the block with the opposite rotation (red marks, clockwise) can be clearly identifying, Fig. 5.

Maximum shear strain and area strain

Maximum shear strain characterizes the maximum change the shape of a triangle, the degree of its deformation corresponding to the initial deformation (Hackl et al., 2009). The value is always positive, and the larger it is, the larger deformations occur in this area (Fig. 6). Area strain describes change of the shape of triangle. The value of area strain can be either positive and negative or single type. The positive values indicate extension, while negative – compression of the part of the earth's surface (Fig. 7).

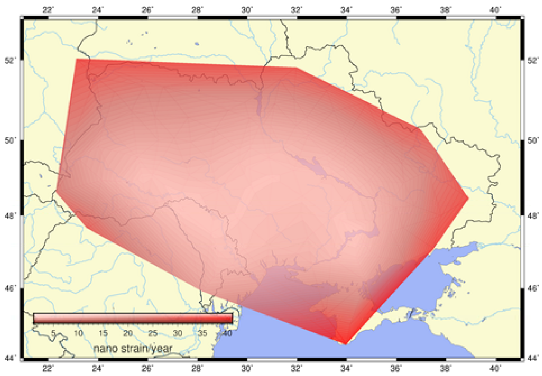

Fig. 6. Maximum shear strain

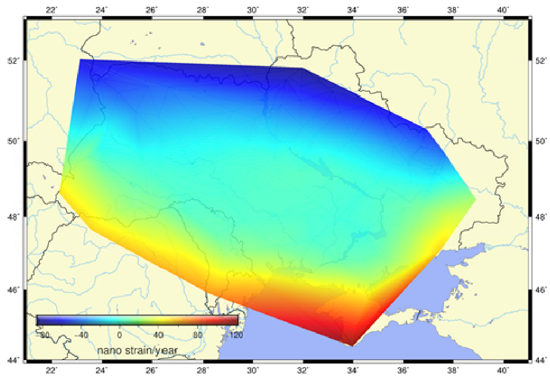

Fig. 7. Area strain

In Fig. 6 brighter color indicated level of active processes of deformation. In Fig. 7 a positive (> 0) value of area strain indicates that the area is extending, and a negative (< 0) indicates that area is compressing.

Analyzing Figs. 6 and 7 we can conclude that the less susceptible area to the deformation process is the Ukrainian crystalline shield. The shield is located on the central part of the Ukraine and value of maximum shear strain is about one nano strain/year. The most active positive deformation process was detected in the village of Katsiveli, located on the southern coast of the Crimea (Samoilenko et al., 2008). This area is rising, which is also confirmed by studies conducted on the geodynamic polygon. The most active compression occurs in the North-Eastern part of the country, near the Shatsky lakes (on the border of Ukraine and Poland).

5. CONCLUSIONS

The crustal strain deformation provides a description of geodynamic processes such as intensity of ground surface deformation, as well as fault strain accumulation. These parameters are important for study and monitoring of different geodynamic processes such as anthropogenic deformation, seismic hazard assessment, geological processes, etc.

Within this research the strain ellipse, rotation, maximum shear strain and area strain for Ukrainian territory were obtained. It was performed using GNSS observations from 108 GNSS permanent stations. This approach allows to evaluate kinematic situation without use of expansive geological equipment.

The results of strain analysis allowed detecting two main blocks with different strain activities: North-Eastern and South-Western blocks. The first is characterized by significant compression of territories on minor axes, another block – extension on both axes. Based on the strain analysis it can be concluded that there is a possibility of the existence of some geological processes that are contrary to each other in this area (Starostenko et al., 2011; Lazaruk et al., 2015). There is a need to continue monitoring of these processes in future with a more densified network of GNSS stations.

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