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MONITORING OF CRUSTAL MOVEMENTS IN UKRAINE USING THE NETWORK OF REFERENCE GNSS-STATIONS

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The main goal of our research was to identify the features of the spatial distribution of crustal movements in Ukraine using GNSS-technology. **Methods.** As the initial date for investigation were the observations of 4 years (2013–2016) from over 120 reference stations in Ukraine. The cumulative solution was estimated by program GAMIT/GLOBK. For reference (real), we have taken solutions from EPN Analysis Combination Centre. By comparing the real coordinate and coordinate determined in our cumulative solution we compute RMS of the positioning. **Results.** The RMS analysis revealed that the received cumulative solution may be used for regional and local geodynamic studies, geophysical interpretation and for many practical applications in geodesy. Based on the estimated horizontal components of velocities, their vectors were constructed on the digital tectonic map of Ukraine. Horizontal rates (22–25 mm/yr) show a clear trend – a dextral character. Movement components are in the direction of Voronezh crystalline massifs. For the vertical component of the relative site velocities, accuracy will increase with an increase in the time interval of GNSS-observations. **Scientific novelty and practical significance**. For the first time the digital tectonic map of Ukraine was prepared with vectors of horizontal velocities of GNSS-stations. The values of the determined velocities are homogeneous and with the increase of the observation interval, it will be possible to determine the peculiarities of the movements of the earth crust on the territory of Ukraine and in the future to create a regional geodynamic model of Ukraine.

Key words: combined solution; reference stations; tectonic structures of Ukraine.

Introduction

The definition and maintenance of the global terrestrial reference frame are one of the main tasks of geodesy. The quality of the reference frame realization has important implications for ability to study both regional and global properties of the Earth, including post-glacial rebound, sea level change, plate tectonics, regional subsidence and loading, plate boundary deformation, and Earth orientation excitation [Altamimi et al., 2001; Seeber, 2003, Fastellini et al., 2009]. Nowadays the actual terrestrial reference frame is ITRF2014. This realization is available from 21 January 2016. By that time, realization ITRF2008 was used. The ITRF uses as input data time series of station positions and Earth Orientation Parameters (EOPs) provided by the Technique Centers of the four space geodetic techniques (VLBI, SLR, GNSS and DORIS). The GNSS, compared to the other techniques, has the advantage of being the most efficient one for the ITRF densification purpose (regional and local networks), given its ease use, low cost and the availability of the IGS products for all users [Altamimi, 2003]. Nowadays there has been a continued and growing interest of using GNSS for monitoring crustal deformation. Many experts around the world [Lim et al., 2010; Kutoglu, 2010; Kaloop and Li, 2009; Rutledge et al., 2001; Chen et al., 2000] are trying to detect the natural disasters event in advance by using GNSS technique. So regional and local networks of GNSS reference stations are elements of a great interest to the study of regional crustal deformations and seismic activity.

The Department of Geodesy and Astronomy of Lviv Polytechnic National University operate three private local reference GNSS networks in Ukraine. Until now, these networks have been mostly used for engineering purpose but they also have a strong potential for the monitoring of regional and local crustal deformation in Ukraine. This is important because Ukraine has the seismically active tectonic structure – Mediterranean zone.

Aim

The main goal of our research was to identify the features of the spatial distribution of crustal movements in Ukraine using GNSS-technology.

The main tasks of the research are:

1. Estimation of a combined solution (coordinates and velocities) for all available reference GNSS-stations.
2. Interpretation of the obtained results in relation to the main tectonic structures of Ukraine.

3. Creation of a digital tectonic map for the territory of Ukraine with the indicated vectors of the horizontal component of the reference GNSS-stations velocities and determination of the main spatial distribution of the earth crust.

Tectonic structures of Ukraine

Major tectonic structures within Ukraine are (Table 1): ancient (Precambrian) Eastern-European movable platform and the Mediterranean zone.

Table 1

Major tectonic structures within Ukraine

Eastern-European Platform	Ukrainian Shield
	Voronezh crystalline massifs
	Galicia-Volyn cavity
	Volyno-Podilska Plate
	Dniprovsko-Donetska Depressions
	Prychornomorska Depressions
	Donetsk folded structures
Scythian Platform	
Western-European Platform	
Mediterranean zone	Carpathian fold system
	Folded-brylova Building Mountain Crimea
	Black Sea depression

In the East-European platform distinguish the Ukrainian shield (one of the oldest the Earth's crust in Europe), Volyn-Podolska plate (on the western slope of the shield), Galicia-Volyn cavity, Dniprovsko-Donetska and Prychornomorska depressions and Voronezh crystalline massif. The main structures in the Mediterranean belt are moving Carpathian fold system and fold-brylova Building Mountain Crimea. In Ukraine there are long (hertsynska) Donetsk folded building and youth Scythian Western platform. The Mediterranean zone is moving area of modern seismic activity. All tectonic structures of Ukraine are shown in Fig. 1.

Fig. 1. Tectonic map of the Ukrainian

In order to obtain information on crustal deformations for different tectonic structures, a regional GNSS network of Ukraine was used.

Methods

Currently (as of July 2017) the Ukraine reference GNSS network consists of ~120 stations (Fig. 2). We considered data available between 2013 and 2016 years. Data from three private GNSS networks distributed throughout Ukraine (ZAKPOS, THT-TPI, System Solutions) was used. Additionally, we also use data from several stations of the neighbours GNSS networks such as ASG-EUPOS (Poland), ROMPOS (Romania), MOLDPOS (Moldavia), SKPOS (Slovakia).

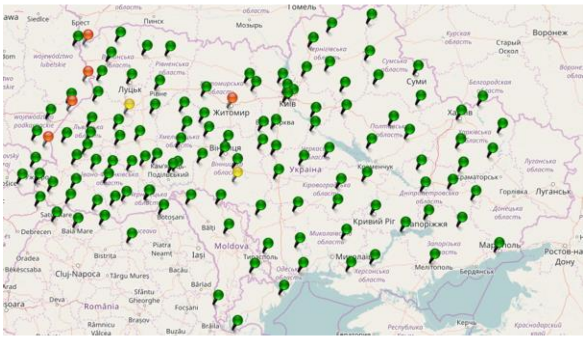

Fig. 2. Ukraine reference GNSS network

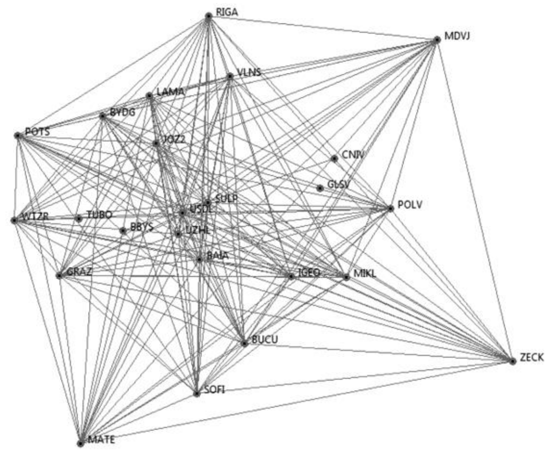

Fig. 3. Schemes of the fiducial stations networks

Dual-frequency phase and pseudo range data are recorded at sites at 30-s intervals in the internal memory of the receivers in 24-hour-long files. Data files are downloaded automatically on a daily basis via ftp-server in Department of Geodesy and Astronomy of Lviv Polytechnic National University. Then GNSS data were processed using the Gamit-Globk software (Herring et al., 2016) developed by MIT, Scripps Institution of Oceanography, and Harvard University with support from the National Science Foundation and using final GPS orbit products. In Gamit-Globk the orbits were fixed by choosing BASALINE experiment. Observable was the ionosphere-free linear combination (LC_AUTCLN). Using Gamit-Globk the input files were imported the main analysis by software package – Gamit. This program inverted the (constrained) correlation or covariance matrix to the unconstrained normal equation. Reference frame were realized by the EPN/IGS stations (Fig. 3) from Poland (BYDG, JOZ2, LAMA, USDL), Austria (GRAZ), Moldova (IGEO), Italy (MATE), Russian (MDVJ, ZECK), Germany (POTS, WTZR), Latvia (RIGA), Bulgaria (SOFI), Lithuania (VLNS) and Ukraine (CNIV, GLSV, MIKL, POLV, SULP, UZHL).

Seven components of Helmert translation related to ITRF08 were estimated by minimum constraint method. Following such a strategy allowed to eliminate the errors in network's geometry trigged by some errors in stations (used for reference frame realization) and also not make any significant changes in the reference frame [Araszkiewicz, 2009].

Results

When cumulative solution (1721–1929 GPS weeks) from GAMIT-GLOBK software was estimated, several stations have incorrect values of coordinates and velocities. We have investigated that these "bad" values have several reasons such as incorrectly indicated receiver's antenna, error during transmission of data to our Centre when the wrong antenna was automatically recorded and some stations have a small time span of observations. Figures 4 illustrate diagrams of the time interval for the problematic station during 4 years (1461 days) [Savchuk S., Doskich S., 2017].

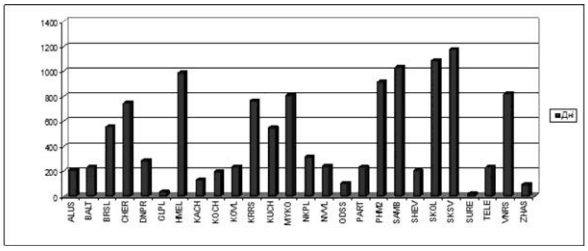

Fig. 4. The time interval of the stations observations

Such stations with incorrect values of coordinates and velocities ware excluded from the research.

To investigate accuracy and correctness of our cumulative solutions it was compared with EPN solutions by common station and coordinates differences was determined (Fig. 5). EPN solutions were taken from EPN_A_IGb08.SSC (http://www.epncb.oma.be/_productsservices/coordinates/). Coordinates have been calculated on the same epoch as in our solution.

Table 2 shows the statistical summary of the differences.

Table 2

Statistical result of the coordinate differences EPN-Ukraine solutions

Value	$X_{(мм)}$	$Y_{(мм)}$	$Z_{(мм)}$
St.dev	5.2	4.6	6.9

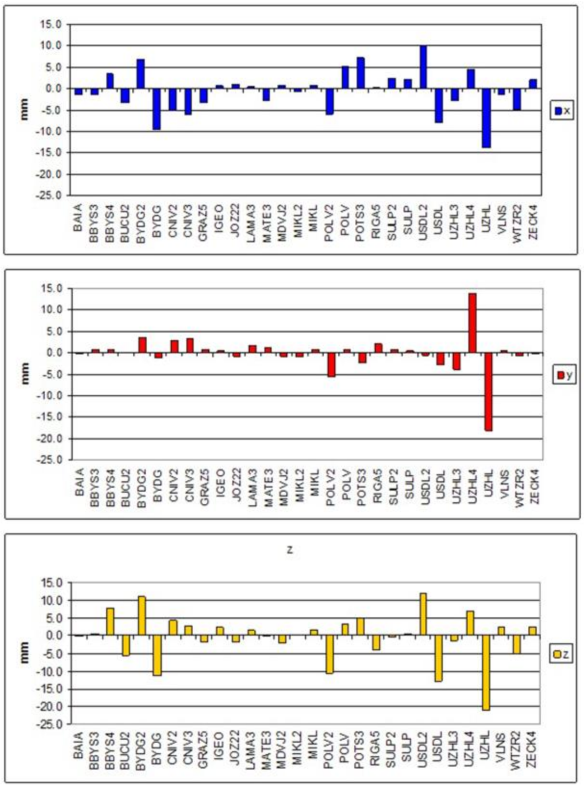

Fig. 5. Comparison of common sites coordinates from IGS/EPN and Ukraine solutions

The comparison made between coordinates obtained in national processing and official EPN solution gave good results since differences do not exceed 1 cm. So, the received cumulative solution may be used for regional and local geodynamic studies, geophysical interpretation and for many practical applications in geodesy.

Final processing of GNSS data from the Ukraine reference stations gives the station velocities in their north (N), east (E) and altitude (H) components. Annual stations movement velocities are determined from station time series, in units of mm/yr. To investigate the accuracy of estimated velocities it was compared with IGS/EPN solutions by the common station and velocities differences were determined (Fig. 6).

The standard deviation between velocities obtained in national processing and official IGS/EPN solution does not exceed 0.4 mm in the north (N) and east (E) and 1mm in altitude (H).

Most Ukrainian GNSS-stations are located on three tectonic structures: Carpathian fold system, Volyno-Podilska Plate and Ukrainian Shield, which makes it possible to do a statistical analysis which is represented in Table 4.

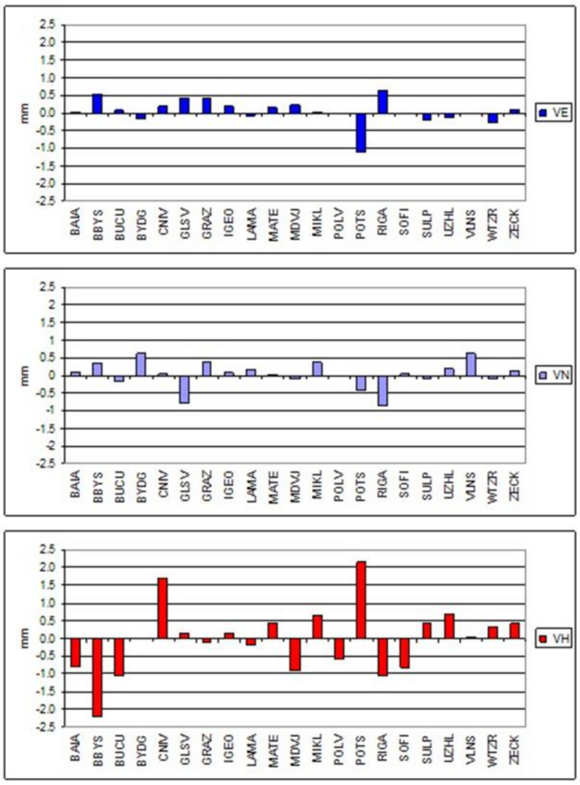

Fig. 6. Comparison of common sites velocities from IGS/EPN and Ukraine solutions

Table 3

Statistical result of the velocities differences between IGS/EPN-Ukraine solutions

Value	V_E (mm/yr)	V_N (mm/yr)	V_H (mm/yr)
max	0.6	0.6	2.2
min	-1.1	-0.9	-2.2
mean	0.1	0.0	0.0
St. dev	0.4	0.4	1.0

Table 4

Statistical result of the stations velocities on three main tectonic structures of Ukraine

Value	V_E (mm/yr)	V_N (mm/yr)	V_H (mm/yr)
	Carpathian fold system		
max	23.1	14.6	2.8
mean	22.0	13.8	0.3
St.dev	0.6	0.7	1.7
	Volyno-Podilska Plate		
max	23.9	14.7	4.0
mean	22.2	13.7	1.8
St.dev	1.2	0.8	1.7
	Ukrainian Shield		
max	25.3	14.9	3.6
mean	23.0	12.9	0.5
St.dev	1.1	0.9	1.6

The differences between mean values of velocities between three main tectonic structures in the east (E) are 1 mm, in the north (N) are 0.9 mm and in altitude (H) are 1.5 mm.

The analysis of detected movements in the Ukraine region was directed toward an evaluation of movement velocities of structures in the region. The size and direction of the horizontal component of the relative site velocities, determined from measurements on all GNSS-stations, are given in Fig. 7.

Fig. 7. Example of the geodynamic interpretation of GNSS data of the reference stations located in Ukraine

The movement components of all stations display a dextral character. Movement components in the direction of Voronezh crystalline massifs. These mobile trends described to correlate with the geological and geophysical materials in the investigated region (Somov and Rahimova, 1992).

The vertical component of the relative site velocities estimated in Gamit-Globk software was compared with geophysical materials by four stations: SRTY, KIRV, VNRS and SHPT (Table 5).

Table 5

Vertical component of the site velocities

Station	**Gamit-Globk**	**Geophysical**
	$V_{H(mm/yr)}$	$V_{H(mm/yr)}$
STRY	+2.8	+2.2
KIRV	+0.0	+1.0
VNRS	+3.2	+3.5
SHPT	+2.9	+3.5

The results show the closeness of vertical component values. Certainly, with an increase in the time interval of GNSS observations, accuracy will also increase.

The analysis of the movement trends completed for Ukraine displayed points toward the importance of geodynamic studies on the local scale. Subsequently, their mutual consecutive linkage will allow the creation of a regional geodynamic model of Ukraine to be compiled.

Scientific novelty and practical significance

Today, due to the active development and spreading of GNSS-technologies, networks of active reference stations have begun to be used for geodynamic purposes, specifically for the study of regional movements of the earth's crust and seismic activity. Such studies are actively conducted on the territory of the European Union, Japan and the United States. For the territory of Ukraine, where the number of such stations is about one hundred and twenty, such geodynamic studies have not yet been conducted. Although the tectonic structures of Ukraine include a seismically active zone – the Mediterranean belt, which is the subject of research not only for geodesists, but also for geophysicists.

Using GNSS observations, we determined the velocities of the reference stations that we take for the earth's crust movements in the area where these stations are located.

For the first time, an electronic tectonic map with a scale of 1:500,000 with velocity vectors was constructed and an interpretation of the results was performed.

In the future, with the increment of the time interval of such observations, it is planned to create a regional geodynamic model of Ukraine.

Conclusions

1. Cumulative solution (coordinates and velocities) for all available reference GNSS-stations (~120) for four years (2013–2016) in software GAMIT/GLOBK was estimated.

2. Horizontal rates show a clear trend – a dextral character. Movement components are in the direction of Voronezh crystalline massifs. Most of the measured absolute rates are about 22–25 mm/yr.

3. According to the results of satellite observations, we can not confidently detect the dependence of the obtained velocities on regional geotectonic. Even with an increasing the interval of observations for several times the preliminary conclusion is practically unchanged for the horizontal component of the relative site velocities. For the vertical component of the relative site velocities, accuracy will increase with an increase in the time interval of GNSS observations.

4. The analysis of the movement trends completed for Ukraine displayed points toward the importance of geodynamic studies on the local scale. Subsequently, their mutual consecutive linkage will allow the creation of a regional geodynamic model of Ukraine.

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МОНІТОРИНГ РУХУ ЗЕМНОЇ КОРИ В МЕЖАХ УКРАЇНИ З ВИКОРИСТАННЯМ МЕРЕЖІ GNSS-СТАНЦІЙ

Мета. Виявити особливості просторового розподілу руху земної кори на території України за допомогою GNSS-технології. **Методика.** Вихідними даними для дослідження послужили результати спостережень тривалістю чотири роки (2013–2016) на понад 120 референцних станціях України. З цих спостережень за допомогою наукового програмного забезпечення GAMIT/GLOBK обчислено об’єднаний у часі розв’язок (часові ряди координат та швидкості). За контрольні ми прийняли розв’язки із Комбінаційного центру EPN. З порівняння значень нашого та контрольного розв’язку отримано середні квадратичні помилки положень та швидкостей станцій. **Результати.** Аналіз отриманих значень середніх квадратичних помилок положення та швидкостей станцій показав, що створений регіональний об’єднаний розв’язок можна використати для регіональних та локальних геодинамічних досліджень, геофізичної інтерпретації та багатьох практичних застосувань у геодезії. За обчисленими горизонтальними складовими швидкостей побудовано вектори на цифровій тектонічні карті України. Вектори горизонтальних складових швидкостей (22–25 мм/рік) мають чітку тенденцію напряму до Воронезького кристалічного масиву. Для вертикальної складової швидкостей цей часовий інтервал спостережень (чотири роки) не є достатнім для проведення аналізу та отримання конкретних оцінок. Точність визначення вертикальних швидкостей збільшуватиметься зі збільшенням часового інтервалу GNSS-спостережень. **Наукова новизна та практична значущість**. Вперше підготовлено електронну тектонічну карту України з векторами горизонтальних складових швидкостей GNSS-станцій. Значення визначених швидкостей є однорідними і зі збільшенням часового інтервалу спостережень дадуть можливість встановити особливості просторового розподілу руху земної кори на території України та в майбутньому створити регіональну геодинамічну модель України.

Ключові слова: комбінований розв’язок; референцні станції; тектонічні структури України.

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МОНИТОРИНГ ДВИЖЕНИЯ ЗЕМНОЙ КОРЫ В ПРЕДЕЛАХ УКРАИНЫ С ИСПОЛЬЗОВАНИЕМ СЕТИ GNSS-СТАНЦИЙ

Цель. Выявить особенности пространственного распределения движения земной коры на территории Украины с помощью GNSS-технологии. **Методика.** Исходными данными для исследования послужили результаты наблюдений продолжительностью четыре года (2013–2016) на более чем 120 референсных станциях Украины. Из этих наблюдений с помощью научного программного обеспечения GAMIT/GLOBK вычислено объединенное во времени решение (временные ряды координат и скорости). За контрольные нами приняты решения с Комбинационного центра EPN. Из сравнения значений нашего и контрольного решения получены средние квадратические ошибки положений и скоростей станций. **Результаты.** Анализ полученных значений средних квадратических ошибок положения и скоростей станций показал, что созданное региональное объединенное решение может быть использовано для региональных и локальных геодинамических исследований, геофизической интерпретации и многих практических применений в геодезии. По вычисленным горизонтальным составляющим скоростей построены векторы на цифровой тектонические карте Украины. Векторы горизонтальных составляющих скоростей (22–25 мм/год) имеют четкую тенденцию напрямую к Воронежскому кристаллическому массиву. Для вертикальной составляющей скоростей данный временной интервал наблюдений (четыре года) не является достаточным для проведения анализа и получения конкретных оценок. Точность определения вертикальных скоростей будет увеличиваться с увеличением временного интервала GNSS-наблюдений. **Научная новизна и практическая значимость.** Впервые подготовлено электронную

тектоническую карту Украины с векторами горизонтальных составляющих скоростей GNSS-станций. Значение этих определенных скоростей являются однородными и с увеличением временного интервала наблюдений позволят установить особенности пространственного распределения движения земной коры на территории Украины и в будущем создать региональную геодинамическая модель Украины.

Ключевые слова: комбинированное решение; референсные станции; тектонические структуры Украины.

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