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DEFORMATIONS OF THE LAND CRUST OF THE CARPATHIAN REGION ACCORDING TO THE DATA OF GNSS OBSERVATION

The emergence of satellite observations was marked by their widespread use to determine the velocities and direction of horizontal motions of lithosphere plates (modern kinematics of lithosphere plates), which allowed to research the deformation processes at the global and regional levels. Today, permanent GNSS stations cover a large part of the land area. Since many of these stations have accumulated a large amount of daily observation over 20 years, it is possible to trace the deformation processes of certain areas. There is the problem of correct identification of observations of the true parameters of the deformation process. This issue requires the joint work of geophysicists and geodesists. But high-precision time series and values of GNSS station velocities are important and perspective data for the interpretation of geodynamic processes, which are much easier to obtain than geophysical or geological data, do not require special costs and should take into account their active development, the number of such stations is growing rapidly. Today, according to unofficial data, more than 300 reference stations operate in Ukraine. The aim of this work is to detect deformations of the Earth's crust in the Carpathian folded system using GNSS technology. The input data for the research were the observations over eight years (2013–2020) at reference stations in Ukraine (ZAKPOS network). From these observations, the combined solution (coordinates time series and velocities) was calculated using the scientific software GAMIT/GLOBK. According to the obtained data, the horizontal displacements vectors of GNSS stations were also constructed, and the deformations of the Earth's crust were calculated by the method of triangles, the vertices of which are GNSS stations, using the GPS Triangle Strain Calculator software. The calculated values of deformations showed a different geodynamic value, depending on the location of the triangles. In particular, the active zones of stretching (Rakhiv–Verkhovyna and Syanok–Ustryky-Dolishni) and compression (Rakhiv–Khust–Mukachevo) were identified. The research results make it possible to establish the features of the spatial distribution of crustal movement in the Carpathian region and in the future in a joint interpretation with geophysical data to create a regional geodynamic model of the Carpathian folded system.

Key words: GNSS, reference GNSS stations, crustal deformations, GAMIT/GLOBK.

Introduction

The territory of Ukraine is located on two main tectonic structures – the Eastern European Platform and the Mediterranean Mobile Belt. The main tectonic structures of the belt are the Carpathian fold system, the Folded-brylova Building Mountain Crimea and the Black Sea depression. The Carpathian fold system is part of the Alpine folded region. The system includes three large structural units: Folded Carpathians, Pre-Carpathian advanced and Transcarpathian internal depressions. Today Carpathian region is the largest zone of seismic activity in Ukraine. Earthquakes with a magnitude of 6–8 on a 12-point international scale are possible in the region. The most seismically active part of the region is Transcarpathia. Geodynamic and seismic forecasting researches using various geophysical methods (seismic, geoacoustic, magnetometric, geoelectric) in the Carpathian region of Ukraine have been conducted by Lviv geophysicists for over 40 years [Verbytsky, et al., 2011; Malytskyy, et al., 2000 Verbytsky, et al., 2002; Verbytsky, et al., 2005; Nazarevych et al., 2012]. Geodynamics of the Carpathian region is also studied by various geodetic methods, in particular, the staff of the Institute of Geodesy of the Lviv National Polytechnic University [Savchuk, et al., 2017; Tretyak, et al., 2016; Tretyak, et al., 2018] did a general regional profile re-levelling of 1st class through the Carpathians, Transcarpathia and Precarpathia, two subregional profiles levelling of 1st class in Transcarpathia, two local complex geodetic landfills were created on the southern slopes of the Carpathians (triangulation, trilateration, light-range and GNSS), and observations of reference GNSS stations located in the Carpathian region are being processed. GNSS data – observations allow to estimate modern surface movements and related deformations of the Earth's crust. Observations of movements (velocities at observation points) allow identifying (determine) zones of rapid accumulation of strain, which is likely to cause an earthquake in the future. This paper is dedicated to the study of the deformation of the Earth's crust in the Carpathian folded system according to GNSS observations, which is relevant for assessing the natural hazards of the region.

Method

Observations from the private network of reference GNSS stations – ZAKPOS for the period 2013–2020 were used for research. The ZAKPOS (Transcarpathian Position Determination System) network was established in 2008 by an initiative group for private funds in the Transcarpathian region with a computing centre in Mukachevo. [Official site of the ZAKPOS network]. During 2009–2011, the ZAKPOS network was developed in the neighbouring regions: Lviv, Volyn, Rivne, Chernivtsi, Ivano-Frankivsk, Ternopil and Khmelnytsky. In fact, ZAKPOS has acquired the status of a network of Western Ukraine. Through the cooperation agreement between the network and Lviv Polytechnic National University, the ZAKPOS analytical centre is located at the Department of Higher Geodesy and Astronomy. Currently, there are 28 reference GNSS stations in the Carpathian region.

GNSS-data for eight years were processed, and errors were estimated using GAMIT/GLOBK software of the Massachusetts Institute of Technology [Herring, et al., 2016; Krasuski, et al., 2020] using a two-step method. In the first stage, program GAMIT is used to determine inaccuracies (errors) depending on the coordinates of the stations, the parameters of the orbits, the orientation of the Earth and the atmospheric delays. In the second stage, the global Kalman filter (GLOBK) was used to estimate the sequential set of station coordinates and velocities, combining the daily free solutions obtained in the first stage and their covariance matrix. The ITRF08 in daily combined solutions were realized with the help of all available EPN/IGS stations from Ukraine (CNIV, GLSV, MIKL, POLV, SULP, UZHL) and neighbouring countries: Austria (GRAZ), Poland (BYDG, LAMA, JOZ2, USDL), Moldova (IGEO), Italy (MATE), Russia (MDVJ, ZECK), Germany (POTS, WTZR), Latvia (RIGA), Bulgaria (SOFI) and Lithuania (VLNS) [Savchuk, & Doskich, 2017]. To estimate the accuracy of the obtained combined solution, it was compared with the EPN solution at common stations and the differences in coordinates and velocities were calculated. Table 1 shows a statistical analysis of differences.

Table 1

Results of statistical analysis of differences between EPN and GAMIT/GLOBK solutions

Value	***X****(mm)*	***Y****(mm)*	***Z****(mm)*
St. dev	4.2	3.6	6.9
Value	VE (*mm*/yr)	VN (*mm*/yr)	VH (*mm*/yr)
St. dev	0.3	0.3	1.0

Table 2 presents the coordinates and velocities of horizontal displacements of GNSS stations of the Carpathian region and adjacent territories. By horizontal displacements, we mean the value of the velocities of GNSS stations.

Table 2

The coordinates and velocities of horizontal displacements of GNSS stations of the Carpathian region and adjacent territories

Station	**Longitude** (*degr.*)	**Latitude** (*degr.*)	V_E, *mm*/yr	V_N, *mm*/yr	**Station**	**Longitude** (*degr.*)	**Latitude** (*degr.*)	V_E, *mm*/yr	V_N, *mm*/yr
1	2	3	4	5	6	7	8	9	10
BAIA	23.5577	47.6518	22.3	13.6	RAHI	24.2012	48.0534	21.5	12.1
BBYS	19.1510	48.7518	21.2	14.9	RDVL	25.2555	50.1301	21.2	13.6
CHTK	25.7927	49.0147	21.3	13.0	RJNT	24.1556	48.9403	21.9	13.6
CRNI	25.9341	48.2764	22.6	13.9	RMNK	27.2509	48.4953	22.9	13.3
DORO	26.3944	47.9513	22.8	10.4	SANO	22.2008	49.5598	21.7	13.4
EDIN	27.3010	48.1737	22.7	13.0	SATU	22.8693	47.7904	22.2	13.8
FRA2	24.7141	48.9143	21.2	13.6	SHAZ	23.9019	51.5701	21.1	14.0
FRA3	24.7103	48.9180	21.2	13.6	SPAS	25.0198	48.4708	22.1	14.1
FRAN	24.7141	48.9143	21.2	13.6	STRY	23.8719	49.2748	22.0	13.6

Continuation of the Table 2

1	2	3	4	5	6	7	8	9	10
GRD2	25.4441	48.6528	21.1	14.1	SULP	24.0145	49.8356	21.7	13.7
GRDN	25.4471	48.6579	21.1	14.1	TER2	25.6102	49.5646	20.8	13.6
HUS1	23.3153	48.1926	21.9	13.6	TERN	25.5558	49.5498	23.8	14.2
HUST	23.2940	48.1762	22.3	13.7	TOML	23.3378	50.3502	20.9	15.2
ISAK	25.2128	48.8268	22.0	15.9	TREB	21.7186	48.6195	22.8	14.4
JARO	22.6678	50.0170	21.0	14.2	USDL	22.5858	49.4329	21.6	14.1
JRSL	22.6678	50.0170	21.0	14.2	UZHL	22.2976	48.6320	22.0	13.9
MIZ1	23.5036	48.5274	22.3	14.5	VAMO	25.5752	47.6516	19.7	14.8
MIZG	23.5013	48.5257	22.3	14.5	VELS	22.1528	48.5127	24.7	14.6
MKRS	22.7093	48.3787	23.3	12.8	VISE	24.4317	47.7082	22.0	13.4
MUK2	22.7224	48.4458	22.5	13.8	VRHV	24.7862	48.1484	22.7	14.5
MUKA	22.7224	48.4458	22.5	13.8	WLDW	23.5576	51.5448	21.3	14.6
NADA	24.5761	48.6378	21.9	13.8	WTZR	12.8789	49.1442	20.2	15.5
RAH1	24.2053	48.0548	21.5	12.1	ZAST	25.8304	48.5273	22.3	13.4

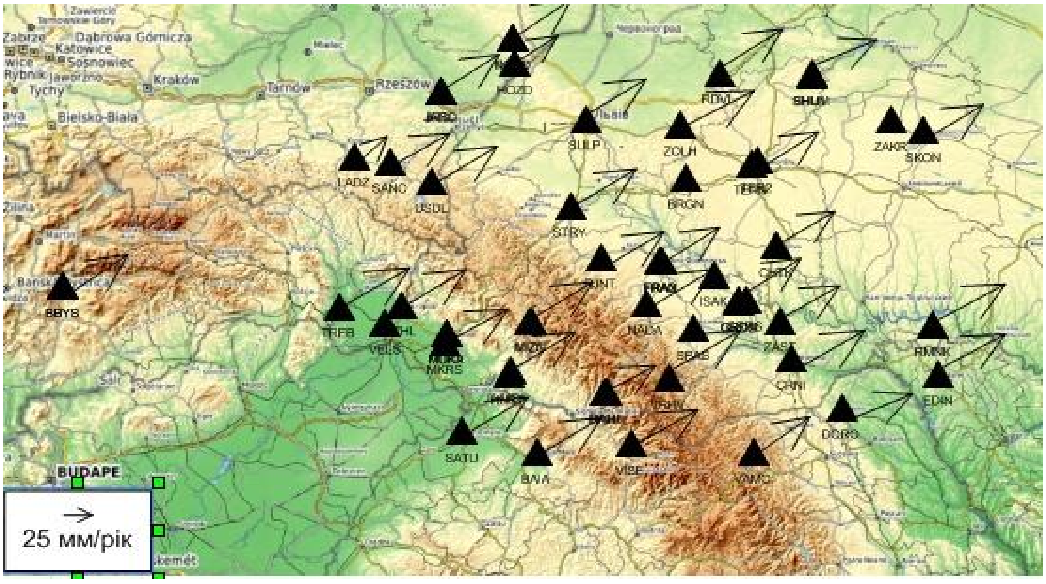

Fig. 1. Map of horizontal velocities of GNSS stations in the Carpathian region and adjacent areas

In Fig. 1 shows a map of horizontal velocities of GNSS stations in the Carpathian region and adjacent areas (included in Table 2), which is used to calculate two-dimensional deformations. The arrows in the figure show the direction of the velocity vectors, and the velocity values are characterized by the length of the arrows according to the scale.

On a large scale, the field of velocities of GNSS observations clearly illustrates the movement of the Earth's crust in a north-easterly direction.

Results

Modern movements observed on the Earth's surface reflect tectonic processes within the Earth's crust. Deformation of the Earth's crust can be considered continuous and considered as a change in the shape and volume of the body, then each point of the Earth's crust and its surface will correspond to the deformation tensor attributed to this point in time [Kadyrov, & Safarov, 2013]. When analyzing only the horizontal components of modern movements of the Earth's surface, it is possible to estimate a flat deformation – a state of deformation in which one of the main deformations is constant. In this paper, for these purposes, the horizontal components of GNSS velocities are used. During the research, the method of triangles, the vertices of which are GNSS stations and the software "GPS Triangle Strain Calculator" [Official site of UNAVCO] was used to determine the velocities of horizontal deformation of the

Carpathian region. This program was developed at the Plate Boundary Observatory in collaboration with the University Consortium (UNAVCO, USA). The "GPS Triangle Strain Calculator" takes the velocity at each of the three GPS stations, and determines what types of transformations the region between them is undergoing. It breaks the total measured GPS velocities into components of the different types of transformations—translation, rotation, extension, and strain. Fig. 2 shows the final configuration of the formed triangles to determine the deformation field.

For each triangle shown in Fig. 2, the corresponding calculations were performed: the translation vector, the angle of rotation and the curvature ellipse (maximum shear strain and area strain). The results are presented in Table 3.

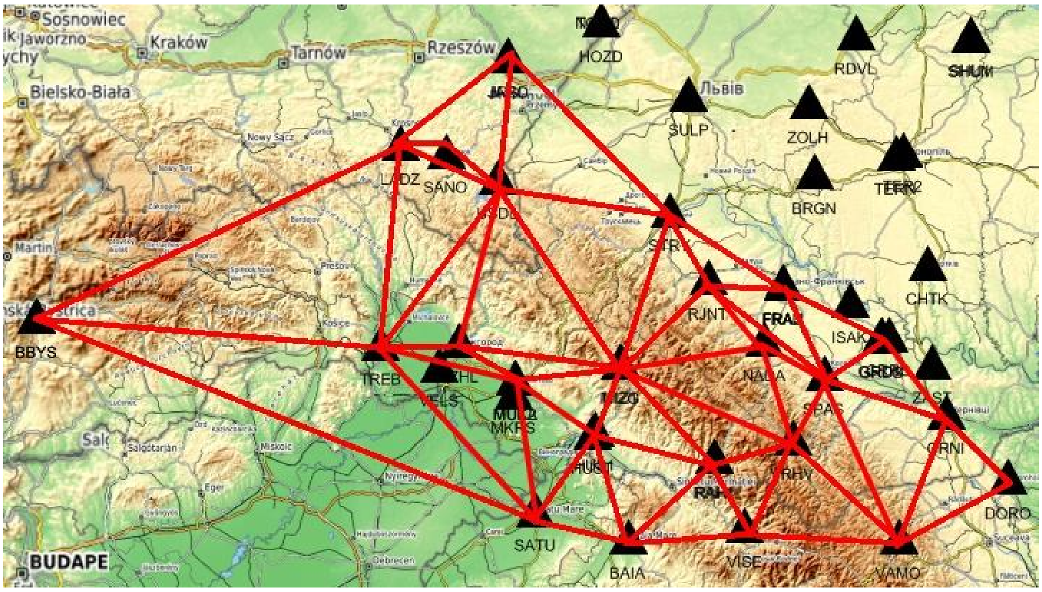

Fig. 2. Configuration of triangles

Table 3

Results of calculating the deformations of the Earth's crust

Triangle	Translation Vector			Rotation nano-rad/yr (C- clockwise, A - anti-clockwise)	Max shear strain (nano-strain)	Area strain (nano-strain)
	E component (mm/yr)	N component (mm/yr)	Speed (mm/yr)			
1	2	3	4	5	6	7
TREB-MUKA-SATU	14.1	22.5	26.5	-5.4688 (A)	4.8287	-6.8045
TREB-BBYS-SATU	14.5	22.1	26.4	-9.6096(A)	15.5641	11.7182
TREB-BBYS-LADZ	14.8	20.0	24.7	30.2976(A)	65.7491	8.3817
TREB-USDL-LADZ	14.5	20.1	24.8	26.7102(A)	116.5837	90.9770
SANO-USDL-LADZ	14.3	19.6	24.3	177.4678(A)	478.2362	298.1121
JARO-USDL-LADZ	14.3	19.5	24.2	-0.9998(C)	106.8448	103.4547
JARO-USDL-STRY	14.0	21.5	25.7	4.8332(A)	9.8690	1.9890
USDL-STRY-MIZG	14.0	21.9	26.0	2.3004(A)	5.3797	2.7882
RJNT-STRY-MIZG	14.0	22.0	26.1	1.1590(A)	5.6502	-5.1529
RJNT-STRY-FRAN	14.0	21.7	25.8	5.2421(A)	21.3002	-18.5412
RJNT-SPAS-FRAN	14.0	21.7	25.8	13.4950(A)	34.3199	-21.1991
NADA-SPAS-VRHV	14.0	22.2	26.2	7.5150(A)	15.3681	-3.2062
NADA-MIZG-VRHV	14.0	22.3	26.3	7.5993(A)	15.3216	-1.9373
RAH1-MIZG-VRHV	13.3	22.1	25.8	-4.3497(C)	80.4622	86.6200
RAH1-VISE-VRHV	13.0	22.0	25.6	24.7891(A)	56.9728	21.5093
VAMO-VISE-VRHV	14.0	21.4	25.6	-2.0248(C)	60.4981	-17.1453

Continuation of the Table 3

1	2	3	4	5	6	7
VAMO-SPAS-VRHV	14.3	21.5	25.8	2.4461(C)	43.0634	-50.9733
VAMO-SPAS-CRNI	14.3	21.5	25.8	-19.3383(C)	44.2019	7.0044
VAMO-DORO-CRNI	13.0	21.7	25.3	-60.3795(C)	66.7792	59.4590
RAH1-VISE-BAIA	13.0	21.9	25.5	2.3413(A)	39.0378	-35.2672
RAH1-HUS1-BAIA	13.3	21.9	25.6	-10.6023(C)	42.9437	-19.0063
SATU-HUS1-BAIA	14.0	22.1	26.2	3.8271(A)	7.7503	1.2171
SATU-HUS1-MUKA	14.0	22.2	26.2	-0.8716(C)	12.2737	-12.1493
MIZG-HUS1-MUKA	14.0	22.2	26.2	-6.3963(C)	13.9159	-5.4773
MIZG-UZHL-MUKA	14.0	22.2	26.3	11.2031(A)	22.4264	0.9508
MIZG-UZHL-USDL	14.0	22.0	26.0	2.2685(A)	5.3733	2.8787
MUKA-UZHL-TREB	14.0	22.4	26.4	25.6763(A)	54.2027	-17.3445
NADA-SPAS-RJNT	14.0	22.0	26.0	-6.4572(C)	18.8456	13.7250
GRD2 -SPAS-FRAN	14.0	21.4	25.6	12.4386(A)	29.6883	-16.2024
GRD2 -SPAS-CRNI	14.0	21.9	26.0	20.6811(A)	41.8073	-6.0843
RAH1-HUS1-MIZG	13.3	21.9	25.6	-20.1392(C)	20.7643	5.7560
RJNT-NADA-MIZG	14.0	22.0	26.1	1.5624(A)	5.3549	-4.3487

The value of the maximum shear strain is an indicator of geodynamic changes in the Earth's crust in the area of the studied triangle. It is noticeable that of all the triangles, the most active are the triangles SANO-USDL-LADZ, TREB-USDL-LADZ, JARO-USDL-LADZ and RAH1-MIZG-VRHV. And the triangles TREB-MUKA-SATU, USDL-STRY-MIZG and RJNT-NADA-MIZG are the least active.

Regarding the magnitude of area strain, the positive value indicates an increase in the triangle area, the negative – indicates a decrease. Based on the obtained results, we built a map of area strain.

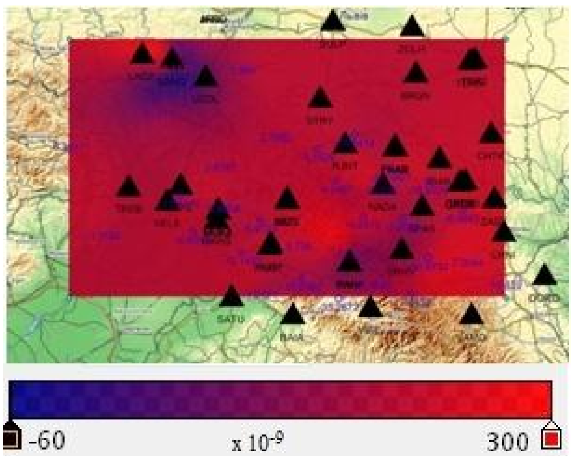

Fig. 3. Map of area strain

From the results, it is noticeable that a significant increase in area is shown by the identical active triangles SANO-USDL-LADZ, TREB-USDL-LADZ, JARO-USDL-LADZ and RAH1-MIZG-VRHV. The triangles VAMO-SPAS-VRHV, RAH1-VISE-BAIA and RAH1-HUS1-BAIA show a decrease in area.

The article was prepared in memory of the outstanding Ukrainian scientist and patriot Yuriy Verbytsky, Hero of the Heavenly Hundred and Hero of Ukraine, within the annual competition of scientific works Distinctions in honour of the Hero.

Conclusions

The development of GNSS technologies has made it possible to research the deformations of the Earth's crust in the Carpathian region according to observations on a network of permanent stations. The method of triangles, the vertices of which are GNSS stations, was used to determine the deformations. The results showed a different geodynamic picture, depending on the location of the triangles. In particular, active zones of tension (Rakhiv-Verkhovyna and Syanok-Ustryky-Dolishni) and compression (Rakhiv-Khust-Mukachevo) were identified. Of course, for further analysis and interpretation of the obtained results, it is necessary to include geophysical data to obtain a more reliable picture of the deformation field of the Carpathian region. In the future, it is planned to further monitor and process observations from the network of GNSS stations in the Carpathian region, as well as combining the obtained satellite, geophysical and geological observations, and it is planned to create a regional geodynamic model of the Carpathian folded system.

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Софія ДОСКІЧ

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ДЕФОРМАЦІЇ ЗЕМНОЇ КОРИ КАРПАТСЬКОГО РЕГІОНУ ЗА ДАНИМИ GNSS СПОСТЕРЕЖЕНЬ

Поява супутникових геодезичних спостережень ознаменувалася їх широким використанням для визначення швидкостей і спрямованості горизонтальних рухів літосферних плит (сучасної кінематики літосферних плит), що дозволило вивчати деформаційні процеси на глобальному і регіональному рівні. Сьогодні постійно діючими GNSS станціями покрита значна частина території суші. Оскільки багато з цих станцій накопичили великий обсяг щоденних вимірювань періодом до 20 років, з'являється можливість відстежити деформаційні процеси певних територій. Звісно ж, залишається проблема правильної ідентифікації результатів спостережень за істинними параметрами деформаційного процесу. Це питання потребує спільної роботи геофізиків та геодезистів. Але високоточні часові ряди координат і значення швидкостей зміщень GNSS станцій є важливими і перспективними даними для інтерпретації геодинамічних процесів, отримання яких є набагато простіше, ніж геофізичні чи геологічні дані, не потребує спеціальних затрат і активно розвивається, тобто кількість таких станцій стрімко збільшується. Сьогодні за неофіційними даними на території України працює вже більше 300 референцних станцій. Мета – виявити деформації земної кори на території Карпатської складчастої системи за допомогою GNSS технології. Вхідними даними для дослідження слугували результати спостережень тривалістю вісім років (2013–2020 рр.) на референцних станціях України (мережа ZAKPOS). З цих спостережень за допомогою наукового програмного забезпечення GAMIT/GLOBK обчислено об'єднаний в часі розв'язок (часові ряди координат та швидкості змін координат). За отриманими даними побудовано вектори горизонтальних зміщень GNSS станцій, та обчислено деформації земної кори методом трикутників, вершинами яких є GNSS станції, за допомогою програмного забезпечення "GPS Triangle Strain Calculator". Обчислені значення деформацій показали різну геодинамічну картину в залежності від розташування трикутників. Зокрема, виділено активні зони розтягу (Рахів–Верховина та Сянок–Устрики–Долішні) та стиснення (Рахів–Хуст–Мукачево). Результати проведених дослідження дають можливість встановити особливості просторового розподілу руху земної кори в Карпатському регіоні та в майбутньому при спільній інтерпретації з геофізичними даними створити регіональну геодинамічну модель Карпатської складчастої системи.

Ключові слова: GNSS, референцні GNSS станції, деформації земної кори, GAMIT/GLOBK.

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