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METHOD FOR OF DETECTING SHORT-TERM DISPLACEMENTS OF THE EARTH'S SURFACE BY STATISTICAL ANALYSIS OF GNSS TIME SERIES

Short-term geodynamic displacements of the Earth's surface are studied insufficiently because the unambiguous identification of such geodynamic processes is quite a difficult task. Short-term geodynamic processes can be observed by considering GNSS time series lasting up to 2 months. The coordinate displacements are visually almost unnoticeable comparing annual time series. In this work, an algorithm based on the results of statistical analysis of time series of several GNSS stations on purpose to find simultaneous displacements of the Earth's surface is developed. Authors propose a method for detecting short-term displacements based on sliding correlation and covariance interrelationships between the time series of two GNSS stations for short periods, which are shifted along with the entire time series. The approach allows showing the characteristic of the displacements throughout the study area based on the selection of anomalous displacements of selected GNSS stations. The high correlation coefficient between the periods of stations indicates the presence of simultaneous and identical in absolute value offsets. The high value of covariance indicates the synchronicity and unidirectionality of such displacements. As a result, the time series of 8 GNSS stations of the Geoterrace network for the period from the end of 2017 to the beginning of 2021 are studied according to the presented method. The anomalous altitude displacements in the region for the epoch of 185th day of 2018 and 20 days period is investigated. Based on the processing, maps of the spatial distribution of correlation and covariance coefficients are constructed. The proposed method could be improved and applied to the study of kinematic processes in areas with a dense network of GNSS stations with long time series similarly GNSS networks for monitoring of large electricity produced objects such as HPPs and PSPs.

Key words: Short-term geodynamic displacements, GNSS time series, statistical analysis, altitude displacements.

Introduction

Based on the analysis of short time series of daily solutions of GNSS (Global Navigation Satellite Systems) stations lasting 10–15 days, it is sometimes possible to detect abrupt changes in the spatial position of the station, as well as simultaneous similar displacements at neighboring stations or networks that cover large areas. One of such geodynamic processes is the altitude displacements of permanent GNSS stations of the European region recorded for 4–10 days in December 2019 [Brusak, & Tretyak, 2020]. The paper investigates the quantity of altitude displacements, establishes the spatial linearity and continentality of its allocation, and analyzes the values and velocities of daily displacements for more than 500 GNSS stations in Europe. It should be noted that the detection of the process was accidental. The authors drew attention to it precisely because of the increase in the standard deviation of stations' altitude position after the phenomenon.

It is important to note that such geodynamic processes can be observed in short GNSS time series (up to 2 months), while the coordinate shifts are visually almost unnoticeable comparing annual series.

Among the automatic algorithms for analyzing the time series of GNSS stations, Median Interannual Difference Adjusted for Skewness (MIDAS) [Blewitt, et al., 2016] and Hector [Bos, et al., 2019] are known. These programs are designed to analyze the time series trends of stations with time-correlated noise. MIDAS uses a robust TheilSen based on median trend estimator that includes qualities needed for accurate GNSS station velocity estimation and excludes seasonal variation [Blewitt, et al., 2016]. The Hector Software uses maximum likelihood estimation [Bos, et al., 2019].

Since these programs are only used to calculate annual trends, the study of shorter time series periods of GNSS stations has not been performed. Overview and comparison of GNSS station displacements are present in the program Finding Outliers and Discontinuities In Time Series (FODITS) implemented in the Bernese GNSS Software [Dach, et al., 2015]. The solution obtained from FODITS serves to provide metadata to detect epochs in which discontinuities occurred and abnormal displacements.

In recent years, complex softwares or algorithms for analyzing GNSS time series with further possible geodynamic interpretation have developed, but they are mainly devoted to one GNSS station apart [Tian, 2011; Wu, et al., 2017; Montillet, & Bos, 2019; Santamaría-Gómez, 2019; He, et al., 2020]. TSAnalyzer software can read and visualize GNSS position time series using least squares method, Lomb–Scargle spectrum analysis, interactive data validation for offsets or seismic events, etc [Wu, et al., 2017]. In addition to GNSS time series visualization, Interactive Signal and Noise Analysis software (SARI) also includes the following mathematical processing methods: least squares method, the Kalman filter, the Vondrák smoother, and the maximum likelihood estimation for noise analysis [Santamaría-Gómez, 2019]. However, today there are no comprehensive software or algorithms for detection and analyzing short-term displacements of GNSS networks.

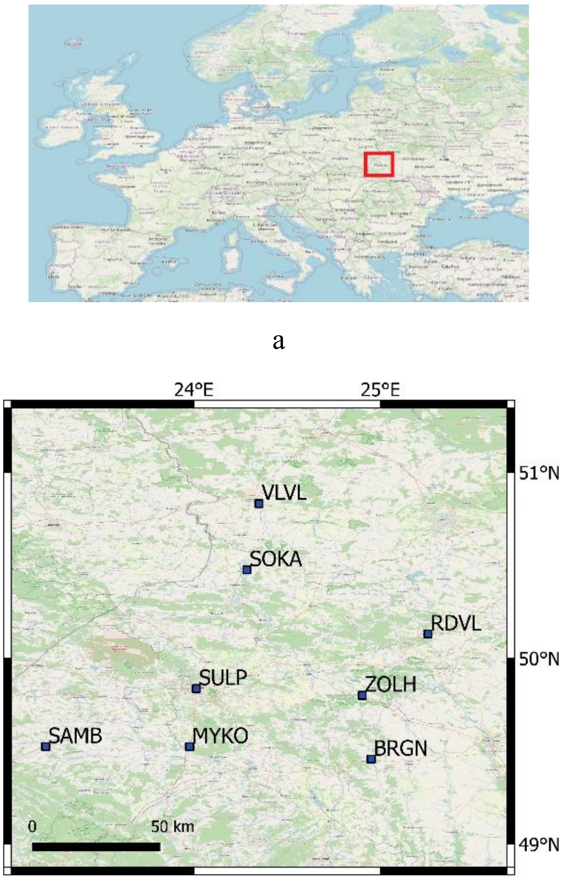
This study is devoted to the development of an algorithm that would detect correlated displacements in the coordinates of a pair of GNSS stations on short time series. Detection of such displacements and simultaneous confirmation between different pairs of GNSS stations will automate the search for local or regional geodynamic processes in the area, and further support in the study of the causes and assessment of the effects of similar spatial displacements. Such geodynamic processes could have a special impact on the results of GNSS monitoring of large electricity produced objects such as Hydroelectric Power Plants (HPP) [Tretyak, et al., 2014, 2017], Pumped Storage Power Stations (PSPS), Nuclear Power Plants (NPP), because sudden shifts can be interpreted as a dangerous situation, and also regions where active landslides occurred [Savchyn, et al., 2019].

Object of study

The object of the research is a network of permanent GNSS stations in Ukraine Geoterrace [https://geoterrace.lpnu.ua]. Geoterrace network is created and serviced by the Processing of Satellite Measurements Laboratory of Institute of Geodesy of Lviv Polytechnic National University. The network's tasks include ensuring the operation of active permanent GNSS stations, ie distributing RTK corrections to users, and conducting geodynamic studies on the stability of large electricity produced objects such as HPPs, PSPSs, NPPs, and other displacements in the network area. The first task is performed using the integrated software Leica GNSS Spider and Sino GNSS CDC.NET, and the second is provided by calculating the daily station solutions in Bernese GNSS Software [Dach, et al., 2015].

The creation of the network began in the Lviv region, but the largest expansion took place during 2019-2021. GNSS stations form a uniform network, the distance between which averages 70 km. As of May 2021, the Geoterrace network has more than 50 GNSS stations and fully or partially covers 12 regions of Ukraine.

The space-time series of 8 GNSS stations of the Geoterrace network are used for the research (Fig. 1). These stations work the longest and could be used more reliably for geodynamic research.



b

Fig. 1. Location of GNSS stations of the Geoterrace network used in the study on the map of Europe (a) and more detail (b)

Table 1 shows the GNSS antennas and receivers operating at the studied stations.

Table 1

GNSS equipment at the studied stations

Station name	Receiver	IGS antenna code
BRGN	GR10	LEAIR10 NONE
MYKO	GRX1200 GG Pro	LEIAX1202GG NONE
RDVL	NovAtel DL-V3	TPSPG_A1 TPSD
SAMB	GRX1200 +GNSS	LEIAX1202GG NONE
SOKA	GR10	LEAIS10 NONE
SULP	Trimble NetR9	TPSCR.G5 TPSH
VLVL	GR10	LEAIR10 NONE
ZOLH	GRX1200 GG Pro	LEIAX1202GG NONE

The daily solutions of the stations are calculated in Bernese GNSS Software version 5.2 [Dach, et al., 2015] using an automatic module Bernese Processing Engine. IGS stations located around the Geoterrace network are selected as reference stations. The result is a network solution based on a double difference strategy. The duration and integrity of the results of the time series of solutions of permanent GNSS stations of the Geoterrace network, which operate almost continuously from the end of 2017 to the beginning of 2021, are shown in Fig. 2.

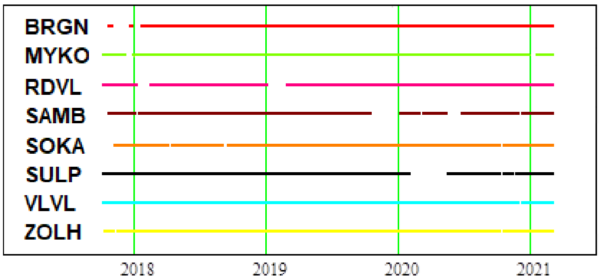


Fig. 2. Duration and integrity of time series of solutions of permanent GNSS stations of Geoterrace network

In December 2019, the altitude displacements lasting 4–10 days were recorded at all stations of the Geoterrace network [Brusak and Tretyak, 2020]. However, it is likely that similar geodynamic processes occurred during the whole network operation and were not observed. For this purpose, it is important to search statistical interrelationships between time series of GNSS stations.

Algorithm for detecting geodynamic processes

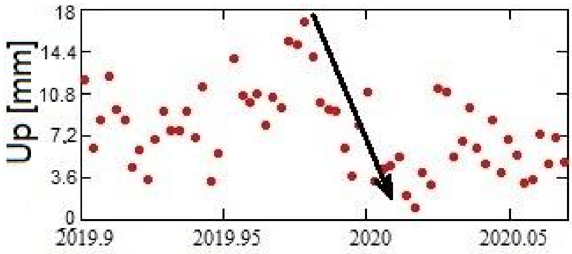
To analyze the time series of a pair of GNSS stations, we perform the following algorithm. First, there is a determination of the period length Δt within the results of two time series are compared. The length of the period can be changed. Short-term trends of displacements become noticeable at the length of the study period Δt in the range from 15 to 40 days. Second, we change the formed period for displacement analysis gradually by one day from the beginning of observations through the whole time series. Accordingly, for the middle epoch of the studied period, we perform statistical analysis of time series within this period. The first middle epoch $T_{mid}=T_{initial}+\Delta t/2$, where $T_{initial}$ – initial epoch of time series. If the period Δt is shifted by a time series with an interval of one day, T_{mid} will also change by one day. For each epoch T_{mid} and the period Δt the correlation and covariance coefficients according to the displacements of one type of the coordinates are determined.

The correlation coefficient shows the degree of linear dependence between the coordinate series on two GNSS stations and will be high if there are proportional displacements between them, but they could have different directions. Since geodynamic processes are usually characterized by unidirectional coordinate changes, it is difficult to detect the process only by the correlation coefficient. For the purpose to detect simultaneous and unidirectional displacements, covariance is implemented.

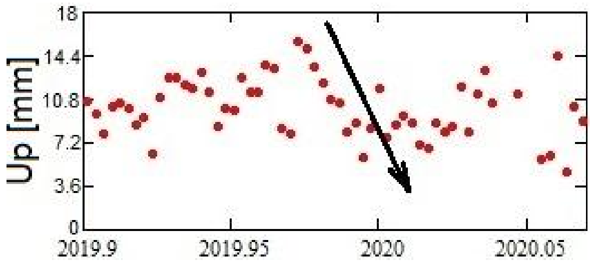
Based on the calculations performed for each epoch T_{mid} within the time series, we determine the correlation and covariance coefficients of the GNSS time series within the periods Δt. As a result, the change in correlation and covariance coefficients during the observation period is obtained.

Algorithm testing on a known geodynamic process

In order to test this method, we will apply it to the already known altitude displacements in December 2019 [Brusak, & Tretyak, 2020]. We use data from SULP and MYKO stations of Geoterrace network. Fig. 1 shows the location of these stations. The time series with altitude displacements of GNSS stations SULP and MYKO in December 2019 are shown in Fig. 3. Daily change of correlation and covariance coefficients between time series of altitude component of stations for the period from 2019.5 to 2020.5 and Δt =20 days is shown in Fig. 4.

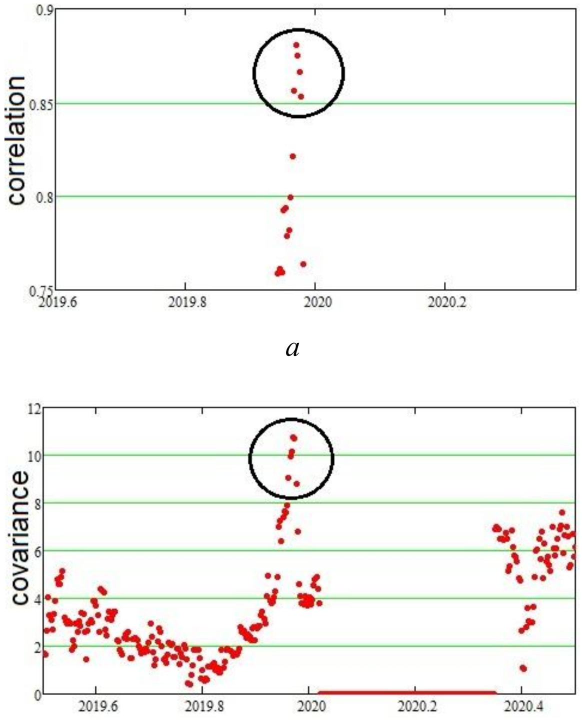


SULP



MYKO

Fig. 3. Altitude displacements of GNSS stations SULP and MYKO of Geoterrace network in December 2019



a

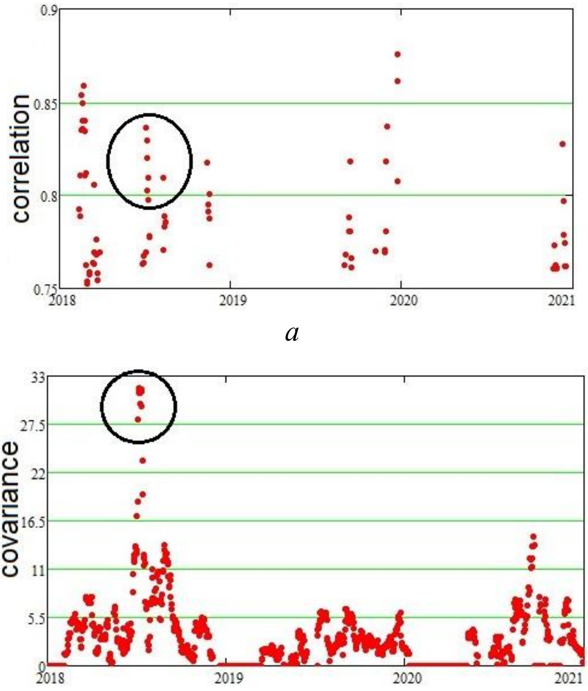
b

Fig. 4. Daily change of correlation (a) and covariance (b) between time series of altitude component of SULP and MYKO stations for the period 2019.5 to 2020.5 and Δt *=20 days*

Thus, the high correlation and covariance interrelationship between SULP and MYKO stations coincides with the recorded altitude displacements in December 2019. This suggests that the proposed algorithm can be used for detecting short-term displacements of a pair of GNSS stations in long-term time series.

Research on Geoterrace GNSS network stations

Analyzing the series according to the above algorithm, we pay attention to the periods when the correlation and covariance interrelationship undergoes a significant increase between several stations, which may indicate the manifestation of a probable geodynamic phenomenon. The connection between one pair of stations can be random.



a

b

Fig. 5. Correlation (a) and extreme covariance (b) between time series of altitude component of SULP and RDVL for the average epoch T_{mid} *(185th day of 2018) and* Δt *=20 days*

According to the presented method, the time series of selected stations of the Geoterrace network for the period from the end of 2017 to the beginning of 2021 are analyzed. There is a possible simultaneous and unidirectional altitude displacements of some stations on the average epoch T_{mid} (185th day of 2018) based on the processing with period Δt =20 days. This is evidenced by the extremely high covariance (25–33) in most pairs of stations, which provide not the highest but high correlation coefficient (0.7–0.85). For example, Fig. 5 shows a graph of covariance and correlation between time series of altitude component of SULP and RDVL stations.

Identical studies for this epoch are conducted for all pairs of GNSS stations. Table 2 shows the correlation and covariance coefficients of the time series of altitude component for epoch T_{mid} (185th day of 2018) and Δt =20 days between all possible pairs of GNSS stations of Geoterrace network.

Table 2

Correlation and covariance coefficients of the altitude time series for epoch T_{mid} (185th day of 2018) and Δt =20 days between all possible pairs of GNSS stations of Geoterrace network

No.	GNSS station		Correlation	Covariance
1	RDVL	SULP	0.84	31.68
2	MYKO	SAMB	0.83	22.57
3	BRGN	SULP	0.82	25.08
4	BRGN	MYKO	0.81	21.41
5	SULP	ZOLH	0.81	24.23
6	BRGN	RDVL	0.79	21.64
7	BRGN	ZOLH	0.79	20.20
8	MYKO	RDVL	0.78	24.43
9	BRGN	VLVL	0.76	22.17
10	MYKO	SOKA	0.75	29.69
11	MYKO	SULP	0.73	30.37
12	SAMB	ZOLH	0.73	18.22
13	RDVL	SOKA	0.71	29.81
14	RDVL	VLVL	0.71	21.22
15	VLVL	ZOLH	0.71	19.65
16	BRGN	SAMB	0.69	18.42
17	SULP	VLVL	0.69	22.99
18	MYKO	ZOLH	0.67	17.78
19	RDVL	ZOLH	0.66	21.24
20	SAMB	SULP	0.64	21.75
21	SAMB	VLVL	0.62	17.14
22	SOKA	SULP	0.61	27.53
23	BRGN	SOKA	0.57	20.29
24	MYKO	VLVL	0.56	16.19
25	RDVL	SAMB	0.56	16.26
26	SAMB	SOKA	0.56	20.66
27	SOKA	ZOLH	0.35	13.52
28	SOKA	VLVL	0.28	11.04

It can be seen from Table 2 that the highest correlation with other stations is manifested in the station SULP and MYKO, ie 3 vectors with a correlation coefficient greater than 0.8 each. Thus, these stations have the same intensity of displacements with neighboring stations. In general, the value of covariance is the highest between SULP and SOKA stations, which shows the unidirectionality of altitude displacements at these stations relative to others.

Fig. 6 shows the time series of altitude component of RDVL and SULP stations with the highest covariance between them (31.68) for average epoch T_{mid} (185th day of 2018) and period Δt =20 days.

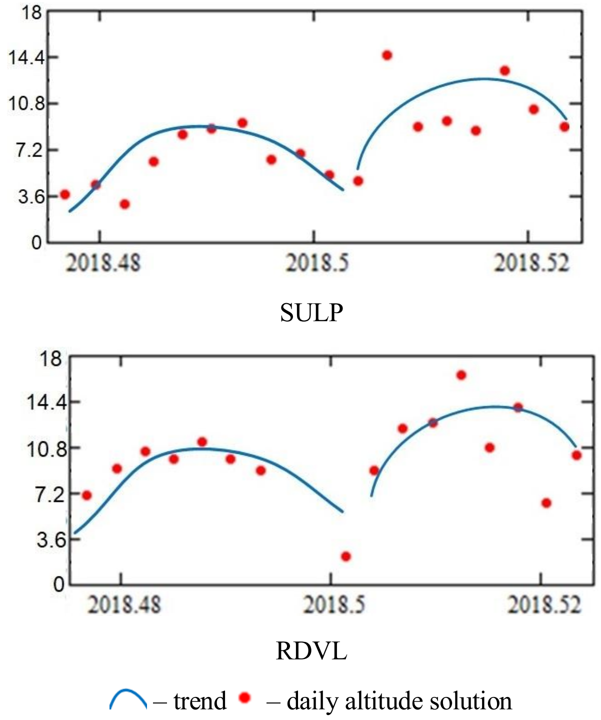


Fig. 6. Time series of altitude component of RDVL and SULP stations for epoch T_{mid} (185th day of 2018) and period Δt =20 days

As can be seen from Fig. 6, the trend lines of displacements of both GNSS stations are almost identical and have a simultaneous manifestation.

To summarize the results of Table 2, we calculate the average values of correlation and covariance for each GNSS station. However, to study the spatial distribution of the time series interrelationships of GNSS stations, it is sensible to calculate the average values of correlation and covariance from the pairs of neighboring GNSS stations. To do this, the network of GNSS stations is divided into adjacent triangles by Delaunay triangulation. We use only the sides that form these triangles for calculations (Fig. 7). Table 3 shows the average values of correlation and covariance of altitude displacements of GNSS stations for epoch T_{mid} (185th day of 2018).

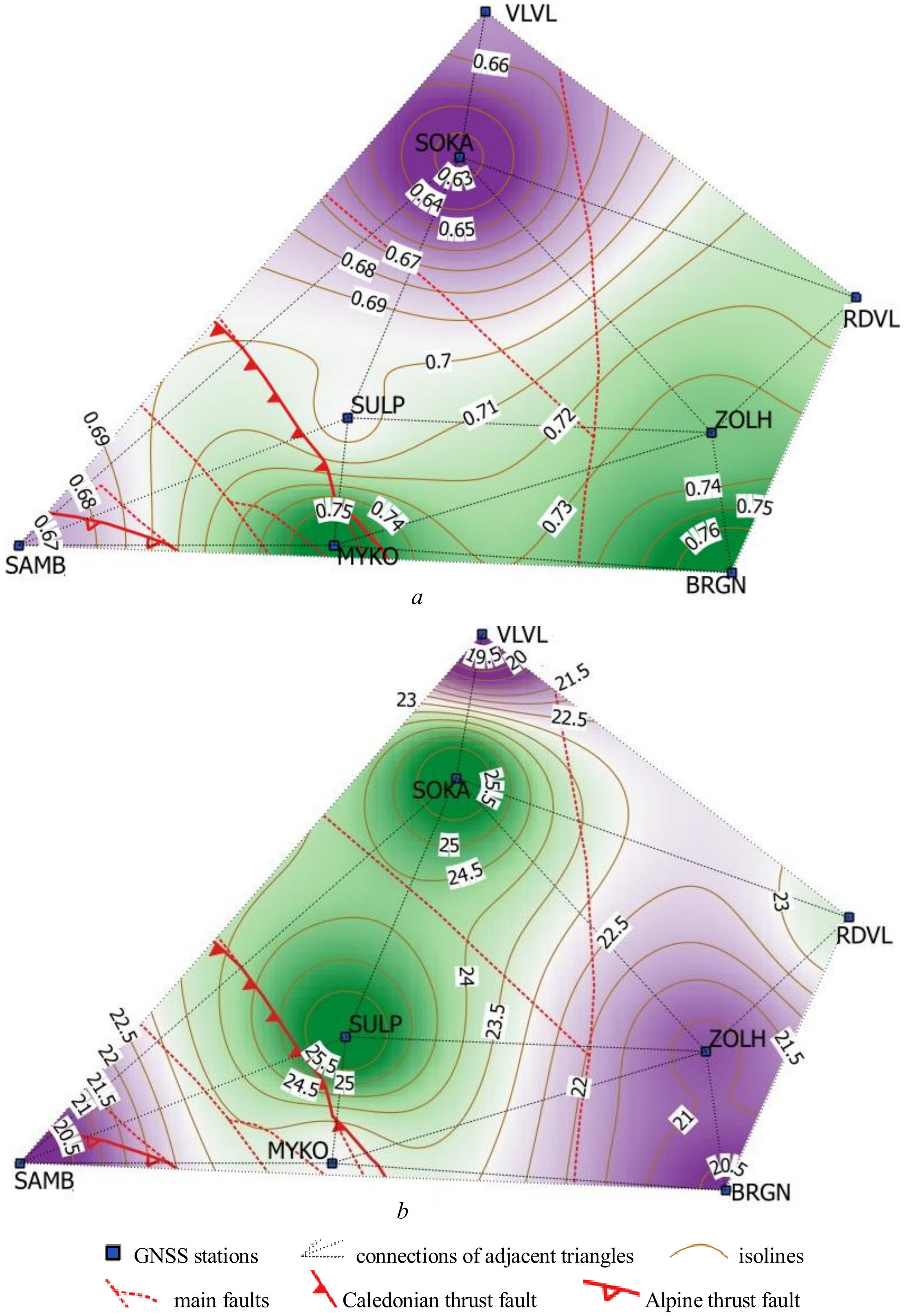


Fig. 7. Distribution of the average values of correlation (a) and covariance (b) of the altitude displacements of GNSS stations for epoch T_{mid} (185th day of 2018)

Table 3

Average values of correlation and covariance of altitude displacements of GNSS stations for epoch T_{mid} (185th day of 2018)

GNSS station		Average values	
		correlation	covariance
BRGN		0.77	20.42
MYKO		0.76	23.03
RDVL		0.72	23.48
SAMB		0.67	20.11
SOKA		0.63	26.00
SULP		0.69	25.97
VLVL		0.66	19.18
ZOLH		0.73	20.86

Fig. 7 shows the distribution of the average values of correlation and covariance of altitude displacements of GNSS stations for epoch T_{mid} (185th day of 2018).

Analyzing Fig. 7 and Table 2 we see that the best correlations are observed between stations BRGN, MYKO, ZOLH, and RDVL, which indicates a similar intensity of altitude displacements between these stations, but the displacements may have different directions. In contrast, at SOKA, VLVL, and SAMB stations, the intensity of altitude displacements is more heterogeneous. SULP and SOKA GNSS stations have the most synchronous displacements with each other and with the surrounding GNSS stations.

Summarizing the spatial distribution of the correlation and covariance, we can assume that the anomalous for the entire period of observations altitude displacements of the area covered by the network have certain patterns. In particular, the northern part of the territory is characterized by almost the same intensity of displacement, which is also confirmed by the tectonic structure, as this region is separated from other stations by tectonic faults (Fig. 7). Instead, the area adjacent to the GNSS stations SULP and SOKA is characterized by simultaneous and unidirectional displacements. The selected areas in terms of kinematic characteristics are consistent with tectonic faults. In particular, the SAMB station, which is separated from most stations by both Caledonian and Alpine thrusts, differs in intensity and direction of displacements from other stations in the network.

It should be noted that the method of the proposed technique is effective for long time series of a large number of GNSS stations, which cover a large area with a heterogeneous tectonic structure. The main purpose of this article is only to present the possibility of applying the proposed method of processing GNSS time series.

Conclusions

The study proposes a method for detecting sliding correlations and covariances between the time series of two GNSS stations when they are divided into short periods. This approach allows showing the characteristic of the displacements throughout the study area based on the selection of anomalous displacements of GNSS stations. The high correlation coefficient between the periods indicates the presence of simultaneous and identical absolute value offsets on the stations. However, these displacements can be different. The high value of covariance indicates the synchronicity and unidirectionality of such displacements. Detection of such connections and confirmation of their simultaneity between different pairs of GNSS stations allows to detect visually almost unnoticeable short-term displacements of territories and automate the search for local or regional geodynamic processes.

According to the presented method, the time series of 8 GNSS stations of the Geoterrace network for the period from the end of 2017 to the beginning of 2021 are studied. For example, the probable anomalous altitude displacements in this area for the epoch of 185th day in 2018 are processed. Based on the results of GNSS station calculations, maps of the spatial distribution of correlation and covariance coefficients are constructed. The selected areas in terms of kinematic characteristics are consistent with tectonic faults.

The proposed method should be improved and applied to the study of kinematic processes in areas with a dense network of GNSS stations and long time series of observations. These can be GNSS networks designed to monitor large electricity produced objects such as HPPs, PSPs. It is also worth considering the calculating of weights into vectors depending on their length to find local or regional geodynamic processes.

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МЕТОД ВИЯВЛЕННЯ КОРОТКОТРИВАЛИХ ЗМІЩЕНЬ ЗЕМНОЇ ПОВЕРХНІ ЗА СТАТИСТИЧНИМ АНАЛІЗОМ ЧАСОВИХ СЕРІЙ GNSS СТАНЦІЙ

Короткотривалі геодинамічні зміщення земної поверхні сьогодні недостатньо вивчені, адже їх однозначна ідентифікація є досить складною задачею. Такі геодинамічні процеси можна помітити, розглядаючи ряди спостережень GNSS станцій тривалістю до 2 місяців, а при порівнянні річних рядів ці зміщення координат візуально практично непомітні. З метою пошуку таких короткотривалих геодинамічних зміщень земної поверхні у цій роботі розроблений метод їх виявлення за статистичним аналізом часових серій GNSS станцій. Запропонований метод, який полягає у пошуку ковзаючих кореляційних і коваріаційних зв’язків між часовими рядами двох GNSS станцій за короткі періоди, що зміщуються вздовж усієї часової серії. Такий підхід дозволяє за виділенням аномальних зміщень окремих GNSS станцій показати характер зміщень на усій досліджуваній території. Високий коефіцієнт кореляції між рядами станцій свідчить про наявність одночасних та однакових за абсолютною величиною зміщень. Високе значення коваріації свідчить про синхронність та однонаправленість таких зміщень. У результаті за представленою методикою досліджено часові ряди 8-ми GNSS станцій мережі Geoterrace за період з кінця 2017 до початку 2021 року. Досліджено ймовірний аномальний висотний зсув на цій території на момент 185 дня 2018 року. За результатами опрацювання GNSS станцій побудовано карти просторового розподілу коефіцієнтів кореляції та коваріації. Запропоновану методику доцільно вдосконалювати та застосувати для дослідження кінематичних процесів на територіях з густою мережею GNSS станцій та тривалими часовими рядами спостережень. Це можуть бути GNSS мережі, призначені для моніторингу великих інженерних об’єктів, таких як ГЕС, ГАЕС.

Ключові слова: короткотривалі геодинамічні зміщення, часові серії GNSS станцій, статистичний аналіз, висотний зсув.

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