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The first Ukrainian permanent GNSS station in Antarctica: processing and analysis of observation data

Abstract. The main purpose of this work is to study and analyze the coordinate time series of the first Ukrainian permanent Global Navigation Satellite System (GNSS) station in Antarctica — Antarctic Station Academic Vernadsky (ASAV). We also aimed to do a comprehensive study of geophysical factors on the coordinate time series values and determine the values of the displacement components of this GNSS station. Processing of measurements was performed using the software Bernese GNSS Software v.5.2. The Bernese Processing Engine (BPE) module and the RNX2SNX (RINEX-TO-SINEX) processing algorithm were used to obtain daily solutions of permanent GNSS station ASAV. Daily solutions of the permanent GNSS station ASAV and the vector of its displacements were determined in the coordinate system IGb08. The vector of the permanent GNSS station ASAV has a northeasterly direction. The obtained results are consistent with the model of tectonic plate movements of this region. To study the characteristic periods of harmonic oscillations of coordinate time series of permanent GNSS station ASAV due to various geophysical factors. A set of studies was conducted, which included the development of an algorithm and a package of applications for processing time series and determining optimal curves that most accurately describe them. Thus, for each time series, the original equation is used to determine the optimal period of oscillation. As a result, an anomalous distribution of fluctuations in the values of permanent GNSS station ASAV with different periods was revealed — this indicates the complex nature of the influence of geophysical factors on the spatial location and confirms the need for systematic studies of such factors on the stability and displacement of GNSS station. It is established that the permanent GNSS station ASAV is exposed to seasonal oscillations, associated with changes in environmental conditions.

Keywords: coordinate time series, geophysical factors, harmonic oscillations, permanent GNSS station ASAV

1 Introduction

Overall, a Global Navigation Satellite System (GNSS) station's coordinates based on the results of daily and weekly solutions of time series change linearly due to the motion of the tectonic plate bearing it. Besides that, for most coordinate time series of the GNSS stations, periodic oscillations are observed caused by exogenous and endogenous factors. The former includes tide effects (by the Sun and the Moon and the tidal loading); the planet's rotation; atmospheric conditions (changes in pressure, temperature, and air masses' movements); postglacial release and balance of the glacial and snow masses; thermal expansion of the Earth's surface. The latter comprise plate tectonics, seismic activity, changes in the gravity field, and changes in the groundwater levels. The factors' interaction significantly influences the GNSS stations' positions. Thus, the stations' instantaneous coordinates must be accordingly processed to be used to monitor and model the planet's current motion and forecast dangerous phenomena (Tretyak et al., 2012).

As the Antarctic continent is mostly unaffected by technogenic factors, it is a unique place to study the current geodynamic processes. GNSS measurements make a substantial contribution to this research. For example, Zanutta et al. (2017; 2018) used the GNSS data over 20 years to determine the parameters of Victoria Land (East Antarctica) and showed the territory to be moving to SE. Special attention is paid to West Antarctica, part of which used to be tectonically active in the past, and the other part currently exhibits volcanic phenomena. Dietrich et al. (2004), Jiang et al. (2009), and Berrocoso et al. (2016) employed GNSS measurements to monitor the geodynamics of an area in West Antarctica defined by the South Shetland Islands, Bransfield Basin, and the Antarctic Peninsula. The geotectonics of this region includes extremely complex and unique processes. The researchers established that the absolute horizontal velocity vectors are pointed to NE and span the range of 15–25 mm. Berrocoso et al. (2016), based on the GNSS measurements, state that the absolute vertical velocity vectors suggest a dip in the NE part of the South Shetlands, unlike the uplift motion reported by Dietrich et al. (2004). Rosado et al. (2019) used the GNSS measurements at 15 sites to monitor the behaviour of tectonic and volcanic rocks on Deception Island (West Antarctica). According to their results, Deception and Livingston Islands have similar plate tectonics tied to the Bransfield Basin expansion and subduction of the Phoenix microplate. Deception Island is also influenced by volcanism.

However, despite the abundance of the GNSS networks on the Antarctic Peninsula, they are unevenly placed. Let us consider the example of the Penola Strait and Lemaire Channel. According to Bakhmutov (1998), the area along Penola Strait consists of two parts: the synclinal zone of the Antarctic Peninsula and the anticline zone of the Wilhelm Archipelago. Between these two zones Curtis (1966) and the Geological map of the Southern Graham Land (British Antarctic Survey, 1981), based on geological and paleomagnetic research, predict a rupturing fault aligned with the fairway of the Penola Strait and Lemaire Channel.

According to Kylchitskiy et al. (2010), Tretyak et al. (2016), and Savchyn et al. (2021), active local geodynamic processes are occurring in the Penola-Lemaire fault area. The authors also note that periodic satellite measurements do not detect short-term current local geodynamic processes, meaning that to track and interpret them, one would need to make more frequent measurement cycles; for continuous monitoring and evaluation of danger, a permanent GNSS network should be installed. However, to study geodynamic processes, it is important to separate exactly the geophysical factors' effects and not the noise by applying the relevant noise filters. According to Tretyak et al. (2012), such noise can be similar to the manifestations of geophysical phenomena. Yet, its effects in every case might depend on the observation conditions (satellite configuration, tropospheric and ionospheric delays), equipment specifics (receiver and antennae errors, satellite and receiver clocks' errors), the software, or errors of data treatment. It is also essential to consider geophysical loadings of different nature separately plate tectonics, postglaciation, cyclical earthquakes: pre-seismic, co-seismic, and post-seismic deformations and seasonal loadings. A comprehensive study of the planet's geodynamics as a whole needs to encompass all external and internal geophysical factors since every one of them is in some way reflected in the coordinate time series of the GNSS stations. Thus, the main aims of our work were the processing and analysis of coordinate time series of the first Ukrainian permanent GNSS station in Antarctica, Antarctic Station Academic Vernadsky (ASAV) (65°14′44″S, 64°15′26″W), and a comprehensive study of the effect of geophysical factors on the coordinate time series of and determination of the velocity's changes of this GNSS station.

2 Data and methods

As part of the 24th Ukrainian Antarctic Expedition (January–April 2019), there was installed and put into operation a permanent GNSS station ASAV near the Ukrainian Antarctic Akademik Vernadsky station (Savchyn et al., 2021). The installed GNSS station was equipped with a GNSS receiver NovAtel PwrPak7 and GNSS antenna NovAtel Nov702GG (Canada) (Fig. 1).

The measurements obtained by the permanent GNSS station ASAV were processed using Bernese GNSS Software v.5.2. We used the Bernese Processing Engine (BPE) module and the RNX2SNX (RINEX-TO-SINEX) processing algorithm to obtain daily coordinate solutions for the station. RNX2SNX is the standard processing based on analysis of double differences of the static dual-frequency data (Dach et al., 2015). The main goal of this algorithm is to obtain precise coordinates and tropospheric parameters for the situations in a given coordinate system.

The RNX2SNX processing algorithm included seven steps.

• *Step 1. Uploading the data.* Were uploaded following data: RINEX files, CODE Final precise orbits, polar motion parameters, satellite clock corrections, station information files, Ocean Tides Model (FES2004), Ocean Loading Model (FES2014b + TPXO8-Atlas), Nutation Model (IAU2000R06).

• *Step 2. Transforming the data.* The uploaded data are re-formatted into a Bernese internal format.

• *Step 3. Synchronization and filtering of the observational data.* The receiver clocks are synchronized with the GNSS time. The data are filtered and smoothed if the observations contain significant signal losses and phase eccentricities, using a special algorithm RNXSMT (Clean RINEX data and smooth the code observations).

• *Step 4. Baseline processing.* Baselines are formed with the algorithm OBS-MAX (Baseline creation algorithm); among all possible combinations, there is a baseline chosen with the maximum number of continuous observations for every GNSS station. Single-difference phase observation files are created. As they are processed, the cycle slips in phase observations are identified and repaired. Afterward, the double differences are processed for every measurement, and the residual files are created. Files with significant signal losses are marked, and the observations are re-processed, considering the markings. Normal equation files (NEQ) are drawn up along with the list of the GNSS stations with too many significant signal losses.

Figure 1. The permanent GNSS station ASAV installed near the Ukrainian Antarctic Akademik Vernadsky station

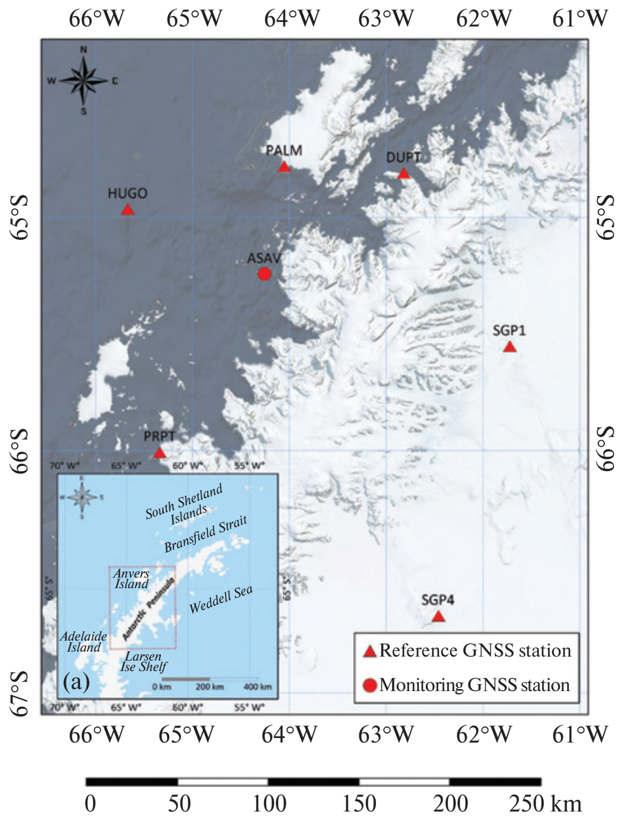

Figure 2. Location of permanent GNSS stations that fix reference frame (a — Antarctic Peninsula)

To specify IGb08 reference frame a six following permanent GNSS stations were used (Fig. 2): PALM (Palmer Station — 64°46′30.0″S 64°03′03.6″W), DUPT (Duthiers Point — 64°48′18.0″S 62°49′01.2″W), SGP1

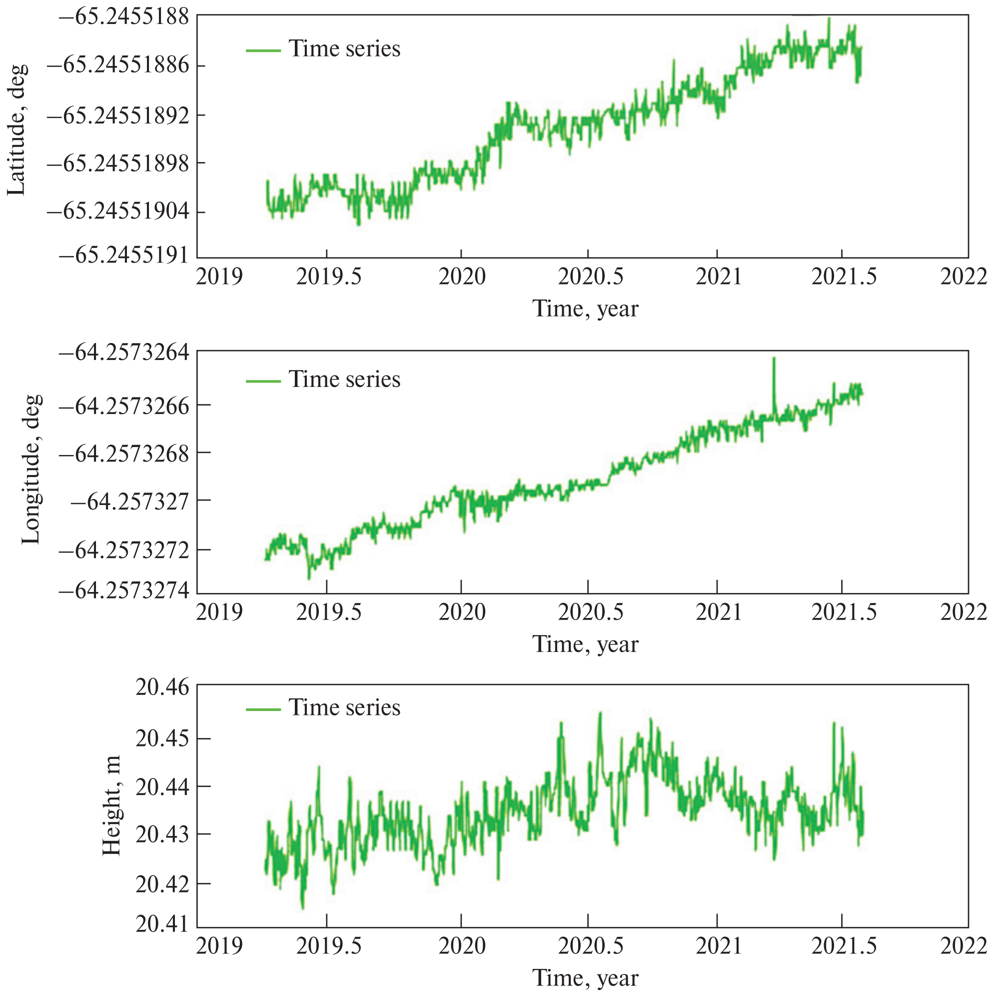

Figure 3. The time series of permanent GNSS station ASAV in a geodesic coordinate system

(Cape Disappointment — 65°33′25.2″S 61°43′19.2″W), SGP4 (Cape Alexander — 66°41′09.6″S 62°27′36.0″W), PRPT (Prospect Point — 66°00′25.2″S 65°20′20.4″W), and HUGO (Hugo Island — 64°57′46.8″S 65°40′04.8″W).

• *Step 5. Finding ambiguity-float network solutions.* Based on the NEQ files, the GNSS stations' coordinates are computed together with the regional tropospheric parameters. The data are used to solve the L1/L2 ambiguities using the Quasi-Ionosphere-Free algorithm.

• *Step 6. Finding fixed network solutions.* Under the minimum constraint conditions, solving NEQs yields the resulting station coordinates.

• *Step 7. Completing the processing.* Processing summary files are drawn, results are saved, temporary files are deleted.

As GNSS observations are processed using the RNX2-SNX algorithm, the following data are created:

• GNSS stations' final coordinates;
• final solutions;
• GNSS observations processing summary.

3 Results

Processing the data obtained by the permanent GNSS station ASAV over the whole observation period (08.04.2019–01.08.2021), we obtained daily solutions in the IGb08 reference frame. For visual assessment at Figure 3 are presented time series in a geodetic coordinate system. The presented data show

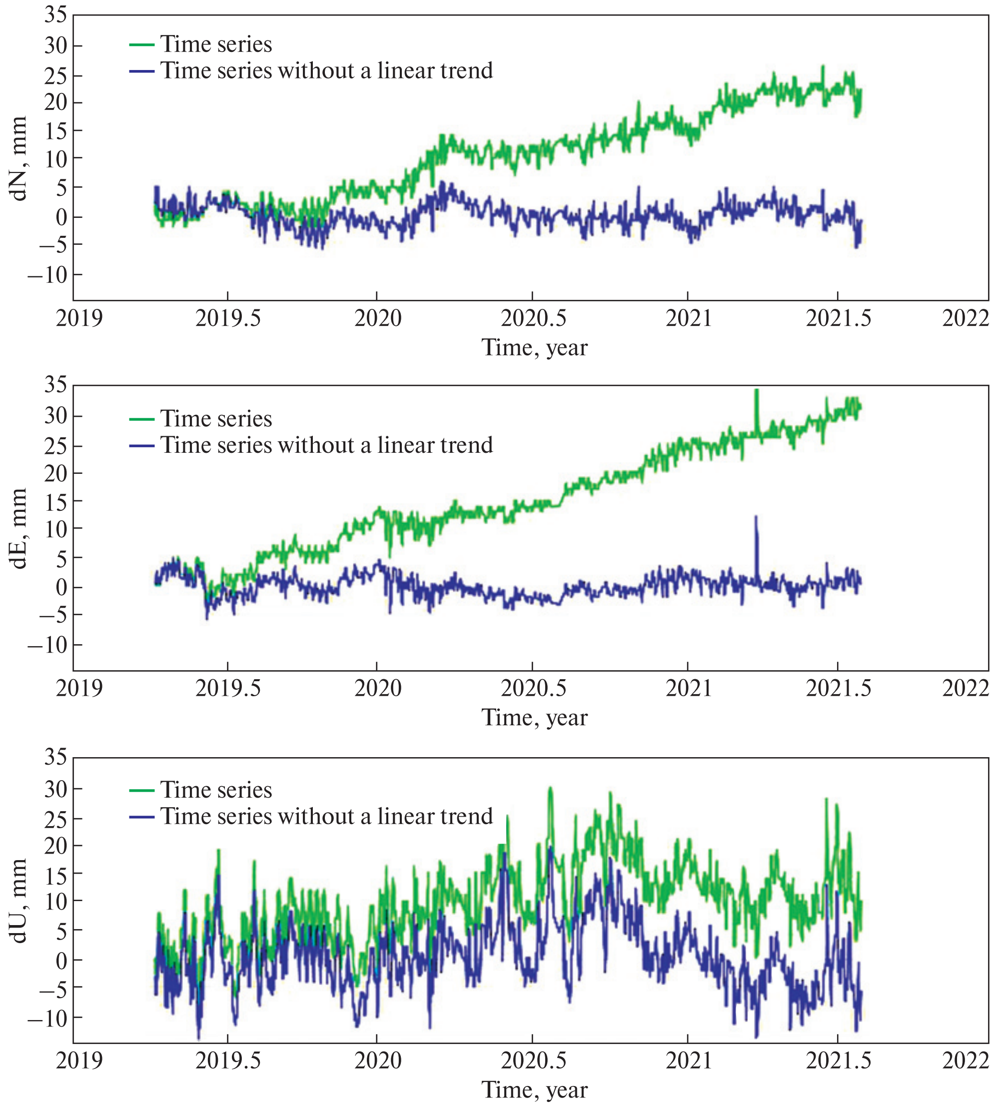

Figure 4. The time series of the permanent GNSS station ASAV with the linear components of displacements eliminated

the movement of the permanent GNSS station ASAV in the NE direction and its lifting. However, it is difficult to determine the value of such movements from these figures. Therefore, it was decided to use time series in a topocentric coordinate system for further analysis of the results.

Kinematics of any GNSS station can be presented as two components. One is the station's systematic displacement caused by the tectonic motion of the plate where it is installed, and the other is the periodic oscillations of its position. According to (Tretyak et al., 2012; Tretyak, 2013), a model of kinematics of the GNSS station can be written as the equation:

$$f(t) = at + b + c\cos[2\pi(t - t_0 - nT)/T] + \\ + s\sin[2\pi(t - t_0 - nT)/T],$$

where a, b — coefficients of the regression equation of the linear displacement of the GNSS station; c, s — harmonious coefficients, t_0, t — the initial and the current observation epochs, n — number of oscilla-

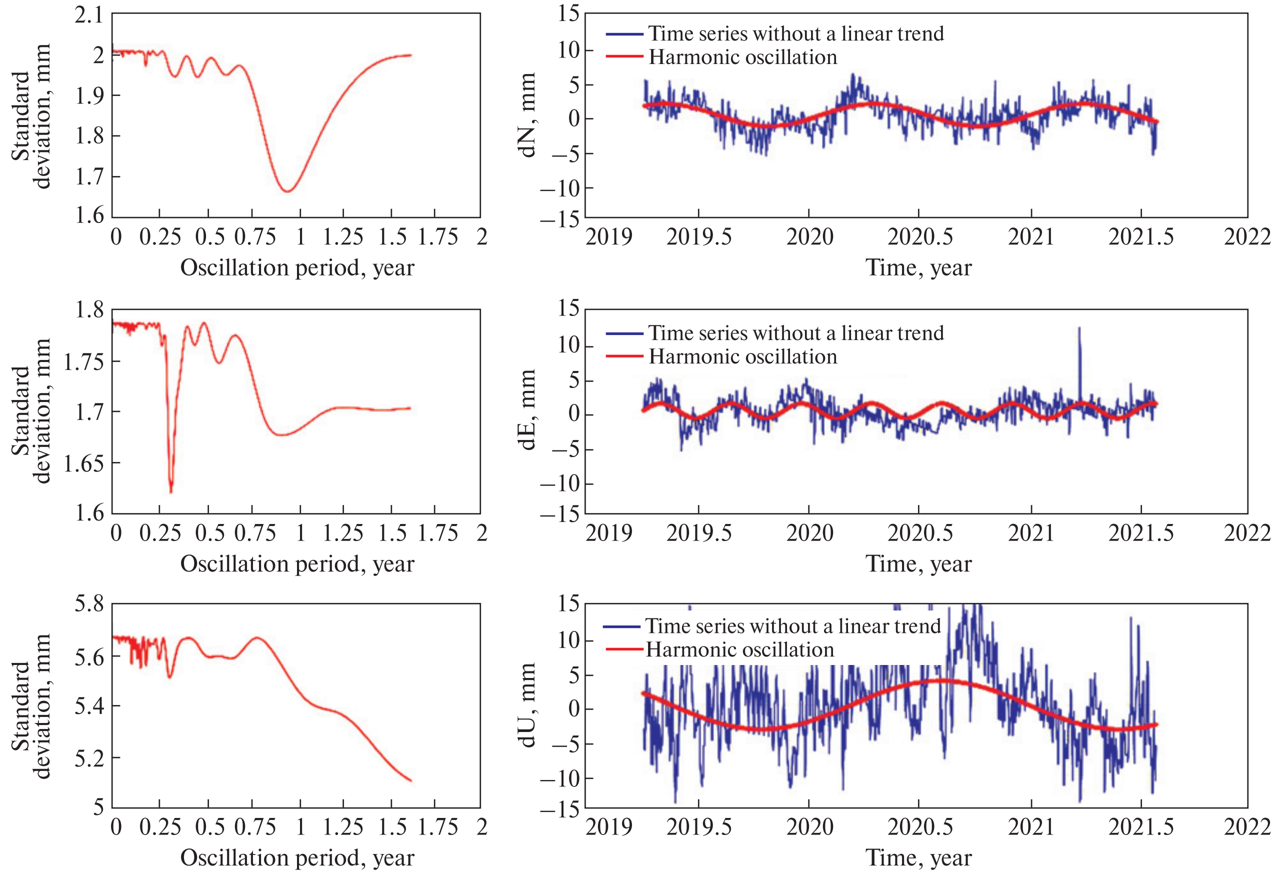

Figure 5. Approximation curves of optimal harmonic oscillations of the permanent GNSS station ASAV measurements time series with the linear trend eliminated

tion periods of the duration T during the time interval $t - t_0$.

Evidently, $f(t) = at + b$ is a linear equation that effectively describes the direction of the systematic displacement of the GNSS station. If this linear component is eliminated, there remain only the periodic oscillations of the station's GNSS coordinates caused by various geophysical factors. Figure 4 presents the time series of the permanent GNSS station ASAV station with the linear components of displacements eliminated for the northern (N), eastern (E), and vertical (U) components, respectively.

Thus, under minimal criterion values, there will be selected curves (optimal periods and amplitudes) to describe the station's displacement by both components with minimum error.

Based on the data for the permanent GNSS station ASAV, we obtained optimal coefficients for the presented equation using the least-squares approximation. Figure 5 shows approximation curves of optimal harmonic oscillations of the permanent GNSS station ASAV measurements time series with the linear trend eliminated. The results were approximated using the Fourier transform based on the optimal oscillation period for every axis.

Analyzing the curves (Fig. 5), we found that the optimal oscillation period for the N component was 0.95 year, and for the E component, 0.32 and 0.91 year. A close-to-annual oscillation period is typical for almost all GNSS stations. The 0.32-year period could be caused by the Earth's Pole oscillating, as reflected mostly in the coordinates of the E component. For the up component, we found several optimal oscillation periods. However, we think that the short periods can be caused by measurement errors; another possible cause is the changing sea levels (tidal loading). It should be noted that the determined oscillation periods have seasonal specifics, and such oscillations are connected with the changes in the environment (temperature, pressure, irradiation, wind, etc.).

Based on the daily solutions, we determined components of the displacement velocities for the permanent GNSS station ASAV: $Vn = 10.83 \pm 0.10$ mm/yr, $Ve = 13.43 \pm 0.09$ mm/yr, and $Vu = 5.39 \pm 0.29$ mm/yr. These velocities correlate very well with the velocities of the GNSS station VER1 (Matveev et al., 2015). It should be noted that the GNSS station VER1 operated during 2010–2015 close to the current position of the permanent GNSS station ASAV.

The obtained values are well-correlated with the model values for the Antarctic tectonic plate (NUVEL-1A) in the region of the Ukrainian Antarctic Akademik Vernadsky station (UNAVCO, 2021). The slight differences between the components of the measured and the model displacement velocity vectors (up to 3 mm/year) point at local tectonic processes. To study these processes, creating a GNSS network around the Ukrainian Antarctic Akademik Vernadsky station is necessary.

Notably, the modulus of the offset vector for the permanent GNSS station ASAV in the IGb08 reference frame is 17.25 mm/yr, not unlike the rates found for most nearby stations. The station is displaced to NE, which is the predominant motion direction for most GNSS stations of the Antarctic Peninsula.

It should be noted that Dietrich in 2001, Dietrich and Rülke in 2002, Dietrich et al. in 2004, and Matveev et al. in 2015 also indicate the NE direction of movement of the research area.

Hardy (2019) confirmed the determined uplift rate using a combination of time-variable gravimetry, altimetry, and GNSS. Bevis et al. in 2009 noted that the velocities of vertical movements of GNSS stations on the Antarctic Peninsula also have positive values.

4 Discussion

Epoch GNSS stations located on the Galindez Island were included in the SCAR epoch Crustal Movement Campaigns (station VER1 to SCAR1998, SCAR2003 and SCAR2005; station VER3 to SCAR2006). These epoch GNSS stations were used to establish and maintain a precise geodetic reference network in Antarctica, linked to the International Terrestrial Reference Frame ITRF (Dietrich, 2001; Dietrich & Rülke, 2002; Dietrich et al., 2004). These campaigns were part of the Geodetic Infrastructure of Antarctica (GIANT). There are plenty of examples of using epoch GNSS stations (Cisak et al., 2008; Kylchitskiy et al., 2010; Tretyak et al., 2016; Savchyn et al., 2021; Matveev et al., 2015) in this region for geodynamic research. All presented works have made a significant contribution to the GNSS research of the Antarctic Peninsula. However, these works have one thing in common: they are based mainly on (seasonal) epoch GNSS data.

The main advantage of our study is that the processing and analysis are carried out on the example of continuous data from a permanent GNSS station rather than an epoch GNSS station. Such data made it possible to identify seasonal oscillations that are very important, especially for the Antarctic region. According to the authors, the permanent GNSS station ASAV has a good location. The measurement results are stable, so every effort should be made to include it in the future to International GVSS Service (IGS). Also, such data reveal a wide range of research related to geodynamics and space weather.

5 Conclusions

We processed the results of satellite observations of the permanent GNSS station ASAV during 08.04.2019–01.08.2021 using Bernese GNSS Software v.5.2. The processing was done following the RINEX-TO-SINEX algorithm. We obtained daily solutions for the permanent GNSS station ASAV. Based on the analysis of daily solutions, it was found that the station undergoes seasonal oscillations tied to changes in its environment. Also, based on the daily solutions, we determined components of the displacement velocities for the permanent GNSS station ASAV in the IGb08 reference frame: $Vn = 10.83 \pm 0.10$ mm/yr, $Ve = 13.43 \pm 0.09$ mm/yr, and $Vu = 5.39 \pm 0.29$ mm/yr.

It was determined that the displacement vector of the station has an NE direction. The obtained results are well-correlated with the model of Antarctic plate tectonics in the region and with previous results.

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Conflicts of Interest. The authors declare no conflict of interest.

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Перша українська перманентна ГНСС-станція в Антарктиді: опрацювання та аналіз результатів спостережень

Реферат. Основною метою даної роботи є опрацювання та аналіз часових рядів координат першої української перманентної ГНСС-станції в Антарктиді — Antarctic Station Academic Vernadsky (ASAV), а також комплексне дослідження впливу геофізичних факторів на часові серії координат та визначення значень компонент швидкостей зміщень даної ГНСС-станції. Опрацювання результатів вимірювань проводилось із використанням програмного комплексу Bernese GNSS Software v. 5.2. Для отримання щоденних розв'язків координат перманентної ГНСС-станції ASAV використано модуль Bernese Processing Engine (BPE) та алгоритм опрацювання RNX2SNX (RINEX-TO-SINEX). В результаті отримано щоденні координатні розв'язки перманентної ГНСС-станції ASAV та визначено вектор її зміщень у системі координат IGb08. Вектор зміщень перманентної ГНСС-станції ASAV має північно-східний напрямок. Отримані результати узгоджуються із моделлю рухів тектонічної плити даного регіону. Для вивчення характерних періодів гармонічних коливань часових серій координат перманентної ГНСС-станції ASAV, що зумовлені різними геофізичними чинниками, проведено комплекс досліджень, який включав розроблення алгоритму, а також пакету прикладних програм для опрацювання часових серій і визначення оптимальних кривих, які максимально достовірно їх описують. Таким чином, для кожної часової серії записано оригінальне рівняння для визначення оптимального періоду коливань. В результаті виявлено аномальний розподіл коливань значень координат перманентної ГНСС-станції ASAV з різними періодами — це свідчить про складний характер впливу геофізичних факторів на просторове розташування, а також підтверджує необхідність систематичних досліджень впливу таких факторів на стійкість та зміщення ГНСС-станції. Встановлено, що перманентна ГНСС-станція ASAV піддається впливу сезонних коливань, які пов'язані із зміною умов навколишнього середовища.

Ключові слова: геофізичні фактори, періодичні коливання, перманентна ГНСС-станція ASAV, часові серії