



Research Article /Review Article:

Experimental Assessment of the Stability of Velocity Vectors From Short-Term Campaign GnsS Observations Using Continuous GnsS Stations

Abdurahmonov Boburbek Gayratjon-ugli^{*1}, Kuchkarov Qodirjon Isroilovich², Alimukhamedov Ilkhom Mizratovich³, Vakhobov Jurabek Akmaljon-ugli⁴

^{1&4} Republican Center of seismic Forecasting Monitoring of the Ministry of Emergency Situations, Tashkent, 100052, Uzbekistan; e-mail: bobur.cn@gmail.com vakhobovjurabek@329gmail.com

² Faculty of Geology and Engineering Geology, National University of Uzbekistan named after Mirzo Ulugbek, Tashkent, 100174, Uzbekistan; e-mail: qambarovotabek@gmail.com ,

³ Institute of Seismology named after G.O. Mavlonov, Tashkent, 100128, Uzbekistan; e-mail: ilhom75@mail.ru

* Correspondence: bobur.cn@gmail.com ; Tel.: +998 93 108 61 11

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Abstract

This study aims to assess the stability and reliability of velocity vectors derived from short-term campaign GNSS observations. Data from the continuous GNSS station TVQS, installed on bedrock, and the MINT and KIT3 stations, located in sedimentary formations, were used in the experiment. To simulate campaign surveys using continuous observations, only epochs corresponding to days of year (DOY) 001, 090, 180, 270, and 360 of 2024 and DOY 090 and 180 of 2025 were selected; all intermediate days were excluded from the processing. The selected data were processed using the GAMIT/GLOBK software package, and six independent approximately 3-month solutions as well as cumulative 3-, 6-, 9-, 12-, 15-, and 18-month velocity solutions were estimated. The results show pronounced changes in both the magnitude and direction of the V_E and V_N components over 3-month intervals, whereas the velocity vectors progressively stabilize as the observation span increases, accompanied by an 83.3–85.3% reduction in formal uncertainties. The findings demonstrate that velocities derived from short-term campaign GNSS observations should be interpreted with caution when used as estimates of tectonic or technogenic deformation rates.

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Contribution to the field statement:

This study experimentally evaluates how observation duration affects the stability of velocity vectors derived from campaign-style GNSS measurements. By simulating periodic surveys using continuous station data, it demonstrates substantial short-term vector variability and an 83–85% reduction in formal uncertainties over 18 months, highlighting the limitations of interpreting short-term velocities as long-term deformation rates.

Highlights:

- Continuous GNSS data were subsampled to simulate periodic campaign surveys.
- Three-month observations produced substantial velocity magnitude and direction changes.
- Extending observations to 18 months reduced formal uncertainties by 83–85%.
- Short-term velocity changes alone cannot establish real ground deformation.

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1. INTRODUCTION

Monitoring ground-surface deformation at mining and oil-and-gas facilities is an important component of geotechnical safety and the sustainable management of production operations. GNSS technologies enable high-precision monitoring of spatial displacements in open-pit and underground mines, subsidence zones, and other deforming areas (Nguyen et al. 2024). Similar investigations have also been conducted in Uzbekistan, where GNSS



observations were applied at the Shurtan gas field to assess vertical displacements associated with production activities (Fazilova et al. 2025).

In practical applications, equipping every monitoring point with a permanent GNSS station is often economically and technically difficult; therefore, periodic campaign observations are commonly used. For such surveys, the velocity derived from the coordinate difference between two epochs can be expressed as:

$$\hat{V} = \frac{X(t_2) - X(t_1)}{t_2 - t_1}.$$

However, when the observation span is short, seasonal signals and coordinate uncertainties can significantly affect the annualized velocity estimate (mm/yr). Blewitt and Lavallée showed that horizontal annual signals in GPS time series are typically at the millimeter level and can substantially degrade velocity accuracy when time series are shorter than 2.5 years (Blewitt and Lavallée 2002). Furthermore, GNSS time series are not composed solely of random white noise. Mao et al. demonstrated that GPS coordinate time series contain a combination of white and flicker noise and that velocity uncertainty may be substantially underestimated when only a white-noise model is assumed (Mao et al. 1999). These effects require caution when velocity vectors derived from short-term campaign observations are interpreted directly as long-term tectonic or technogenic deformation. In this study, the problem was evaluated experimentally using the TVQS, MINT, and KIT3 (IGS) continuous GNSS stations. Only epochs corresponding to the campaign-observation schedule were extracted from the continuous records, while all intermediate days were excluded. The objective was to quantify the variability of velocity vectors in short 3-month solutions and to evaluate how the velocity components and their formal uncertainties stabilize as the observation span increases from 3 to 18 months.

2. METHOD

GNSS technologies are widely used to monitor surface displacement, subsidence, and deformation in mining areas. Nguyen et al. showed that GNSS methods are effective for monitoring deformation and subsidence in open-pit and underground mines, abandoned mines, and waste dumps (Nguyen et al. 2024). An important advantage of continuous GNSS monitoring is its ability to record the temporal evolution of deformation without interruption (Lian et al. 2024). GNSS observations are also widely applied at oil-and-gas facilities to assess production-related ground-surface deformation.

Nevertheless, equipping all monitoring points at industrial facilities as continuous stations is not always technically or economically feasible. Campaign GNSS observations are therefore repeated at specified time intervals. In such surveys, velocity accuracy depends not only on the precision of individual observations but also on the total time span between campaign measurements and on their temporal distribution. Studies based on CORS (Continuously Operating Reference Station) data have shown that both campaign interval and total observation duration significantly affect the accuracy of station-velocity estimates (Şafak et al. 2020). In another experiment, continuous IGS (International GNSS Service) time series were artificially subsampled to emulate campaign observations; velocities obtained in campaign mode were compared with those from continuous series, demonstrating that the temporal sampling scheme directly influences the quality of deformation-rate estimates (Turen and Sanli 2019). This issue is particularly important for short observation intervals. In addition to the secular trend, GNSS coordinate time series contain annual and semiannual signals. Blewitt and Lavallée (2002) showed that the amplitude of annual signals in horizontal coordinates is typically several millimeters and that such signals can substantially bias velocities estimated from short time series. They recommended caution when interpreting tectonic velocities from data spans shorter than 2.5 years. Moreover, GNSS time-series noise is not limited to independent white noise. Mao et al. (1999) and Williams et al. (2004) demonstrated that continuous GPS time series contain temporally correlated flicker-noise components in addition to white noise. If such noise is ignored, velocity uncertainty can be underestimated.

To evaluate the practical stability of short-term velocities in campaign GNSS observations, the TVQS, MINT, and KIT3 continuous GNSS stations were selected as test stations. TVQS is installed on bedrock, whereas MINT and KIT3 are located in areas underlain by sedimentary rocks. The key feature of the experiment is that, although these stations operate continuously, their complete time series were not used in the calculations. To simulate campaign observations, only epochs corresponding to DOY 001, 090, 180, 270, and 360 of 2024 and DOY 090 and 180 of 2025 were selected, while all intermediate days were excluded. Thus, continuously recorded data from the same physical monuments were temporally subsampled to reproduce campaign-GNSS observation conditions. The selected epochs were processed in GAMIT using a uniform processing strategy, producing h-files for each day for subsequent GLOBK combination. In the next stage, velocity solutions were estimated with GLOBK. GLOBK enables the combination of multiple geodetic solutions, while GLORG is used to transform the combined solution into a selected reference frame and stabilize the velocity field (Herring et al. 2018). In this study, horizontal velocities were estimated in the IGB14 realization and stabilized relative to the Eurasian plate in the EURA reference frame.

The experiment was conducted in two stages. In the first stage, consecutive epochs were paired to obtain six independent, approximately 3-month GLOBK solutions for the intervals 2024/001–090, 090–180, 180–270, 270–



360, 2025/360–2025/090, and 2025/090–180. This experiment was designed to determine how strongly the magnitude and direction of the east (V_E) and north (V_N) velocity components of the same continuous station can vary when estimated from short seasonal intervals. In the second stage, the initial 2024/001 epoch was kept fixed while subsequent epochs were added progressively, producing cumulative 3-, 6-, 9-, 12-, 15-, and 18-month solutions. For each solution, the east V_E and north V_N velocity components and their formal standard uncertainties, σ_E and σ_N , were estimated. This approach enabled a quantitative assessment of the convergence of velocity magnitude and direction and of the reduction in formal uncertainty as the observation span increased.

3. RESULTS

Calculations performed by temporally subsampling the continuous records from TVQS, MINT, and KIT3 to emulate campaign observations revealed substantial variability in short-term velocity estimates. The results were analyzed in two ways. First, six independent, approximately 3-month velocity solutions between consecutive epochs were compared. Second, starting from the same initial epoch, the observation span was progressively extended to 3, 6, 9, 12, 15, and 18 months. This design made it possible to evaluate both the variability of short-interval apparent velocities and the stabilization of the solution with increasing observation duration at the same physical monuments.

In the independent 3-month solutions, the velocity components were accompanied by large formal uncertainties (Table 1). In several intervals, σ_E and σ_N exceeded the magnitude of the corresponding velocity component, indicating that such solutions cannot be interpreted reliably as physical deformation rates. In most of the remaining 3-month solutions, the absolute magnitude of a velocity component was comparable to its formal uncertainty, and the direction of a short-term vector should therefore not be directly attributed to a tectonic or technogenic process without additional evidence.

Table 1. Variations in V_E and V_N velocity components for independent approximately 3-month observation intervals, mm/yr.

Period	TVQS		MINT		KIT3	
	$V_E \pm \sigma_E$	$V_N \pm \sigma_N$	$V_E \pm \sigma_E$	$V_N \pm \sigma_N$	$V_E \pm \sigma_E$	$V_N \pm \sigma_N$
001-090 (2024)	-0.34 ± 4.86	$+10.18 \pm 5.32$	$+7.30 \pm 6.14$	$+16.39 \pm 6.66$	-7.11 ± 9.60	-7.67 ± 10.61
090-180 (2024)	$+2.38 \pm 6.23$	-11.09 ± 6.75	$+5.87 \pm 7.25$	$+1.67 \pm 7.58$	$+22.18 \pm 10.63$	$+31.01 \pm 11.52$
180-270 (2024)	-0.79 ± 7.36	$+1.85 \pm 7.34$	$+0.73 \pm 6.54$	$+6.20 \pm 8.13$	-0.58 ± 8.67	$+1.58 \pm 8.98$
270-360 (2024)	$+7.37 \pm 4.97$	-9.99 ± 5.50	-6.77 ± 6.04	$+2.59 \pm 6.52$	-15.72 ± 9.41	$+23.75 \pm 10.38$
360 (2024)- 090(2025)	$+0.04 \pm 5.40$	$+6.98 \pm 5.88$	$+7.33 \pm 5.91$	$+8.00 \pm 6.31$	-18.87 ± 10.25	$+0.43 \pm 11.42$
090-180 (2025)	-7.45 ± 8.69	$+13.14 \pm 9.47$	-3.17 ± 8.16	$+15.93 \pm 8.68$	$+25.20 \pm 14.59$	-14.34 ± 16.07

The geometric representation of the velocity vectors in the horizontal velocity field also clearly illustrates this variability (Fig. 1). Three-month vectors drawn from a common origin point in opposite directions during some epochs. Large angular and amplitude differences among vectors from different 3-month intervals are especially evident at KIT3. This result demonstrates that even at the same physical monument, the direction of a velocity vector estimated over a short time interval can vary substantially.

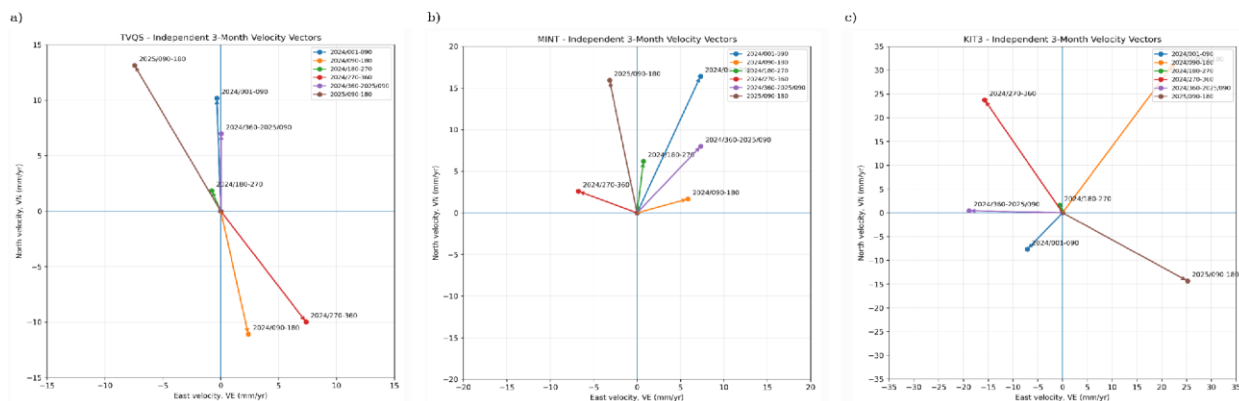


Figure 1. Distribution of independent approximately 3-month solutions for TVQS(a), MINT(b), and KIT3(c) in East–North velocity space.



To evaluate the dependence of velocity estimates on observation duration, subsequent epochs were added sequentially while keeping the initial 2025/001 epoch fixed. This produced cumulative 3-, 6-, 9-, 12-, 15-, and 18-month velocity solutions (Table 2).

Table 2. Changes in cumulative V_E and V_N velocity components with increasing observation duration (mm/yr).

Duration	TVQS		MINT		KIT3	
	$V_E \pm \sigma_E$	$V_N \pm \sigma_N$	$V_E \pm \sigma_E$	$V_N \pm \sigma_N$	$V_E \pm \sigma_E$	$V_N \pm \sigma_N$
3 months	-0.34 ± 4.86	$+10.18 \pm 5.32$	$+7.30 \pm 6.14$	$+16.39 \pm 6.66$	-7.11 ± 9.60	-7.67 ± 10.61
6 months	-5.47 ± 2.87	$+7.32 \pm 3.15$	$+4.17 \pm 3.41$	$+11.10 \pm 3.62$	$+6.94 \pm 5.58$	$+0.53 \pm 6.09$
9 months	-4.33 ± 1.60	$+5.40 \pm 1.77$	$+3.30 \pm 1.96$	$+8.48 \pm 2.13$	$+5.44 \pm 3.31$	-1.21 ± 3.64
12 months	-4.02 ± 1.08	$+3.64 \pm 1.18$	$+0.18 \pm 1.34$	$+7.12 \pm 1.44$	$+2.33 \pm 2.08$	-0.77 ± 2.29
15 months	-3.12 ± 0.90	$+3.02 \pm 0.98$	$+0.28 \pm 1.06$	$+6.95 \pm 1.14$	-0.86 ± 1.69	-0.14 ± 1.87
18 months	-3.10 ± 0.81	$+3.15 \pm 0.89$	$+0.33 \pm 0.91$	$+6.87 \pm 0.98$	$+0.07 \pm 1.51$	$+0.74 \pm 1.68$

At TVQS, the 3-month solution was $(-0.34; +10.18)$ mm/yr, changing to $(-4.02; +3.64)$ mm/yr at 12 months and $(-3.12; +3.02)$ mm/yr at 15 months. The 18-month solution was $(-3.10; +3.15)$ mm/yr, and the difference between the 15- and 18-month values became small. A similar tendency was observed at MINT: the 3-month solution of $(+7.30; +16.39)$ mm/yr approached $(+0.18; +7.12)$ mm/yr by 12 months and $(+0.33; +6.87)$ mm/yr by 18 months. Convergence was more complex at KIT3. The 3-month solution was $(-7.11; -7.67)$ mm/yr; the east component became positive at 6 and 9 months and returned to a negative value at 15 months. Nevertheless, as the observation span increased, the absolute changes in the components and their formal uncertainties decreased, and the 18-month solution reached $(+0.07; +0.74)$ mm/yr. The two-component difference between the 3-month cumulative solution and the 18-month solution was 7.55 mm/yr for TVQS, 11.80 mm/yr for MINT, and 11.06 mm/yr for KIT3. In particular, at TVQS and MINT, both vector magnitude and direction visibly approached the 18-month solution from the 12–15-month stages onward (Fig. 2).

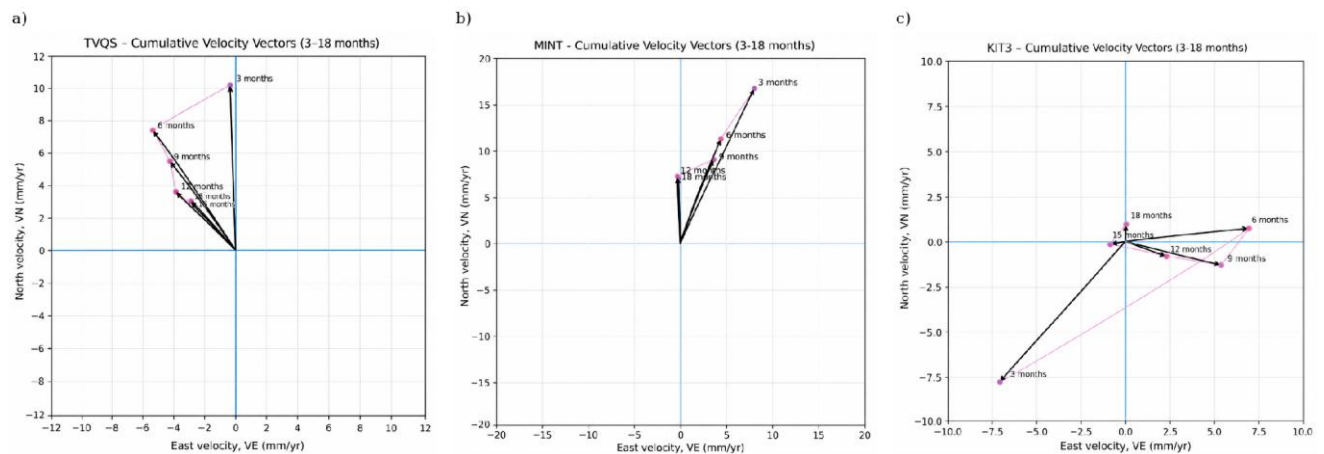


Figure 2. Convergence of cumulative velocity vectors at TVQS(a), MINT(b), and KIT3(c) as the observation span increases from 3 to 18 months.

The effect of observation duration on velocity estimation was also evaluated through the formal standard uncertainties σ_E and σ_N of the V_E and V_N components. At all three stations, the formal uncertainties decreased consistently as the observation span increased. At TVQS, σ_E decreased from 4.86 mm/yr in the 3-month solution to 0.81 mm/yr at 18 months, while σ_N decreased from 5.32 to 0.89 mm/yr. At MINT, the corresponding reductions were 6.14 to 0.91 mm/yr and 6.66 to 0.98 mm/yr, respectively; at KIT3, they were 9.60 to 1.51 mm/yr and 10.61 to 1.68 mm/yr (Fig. 3).

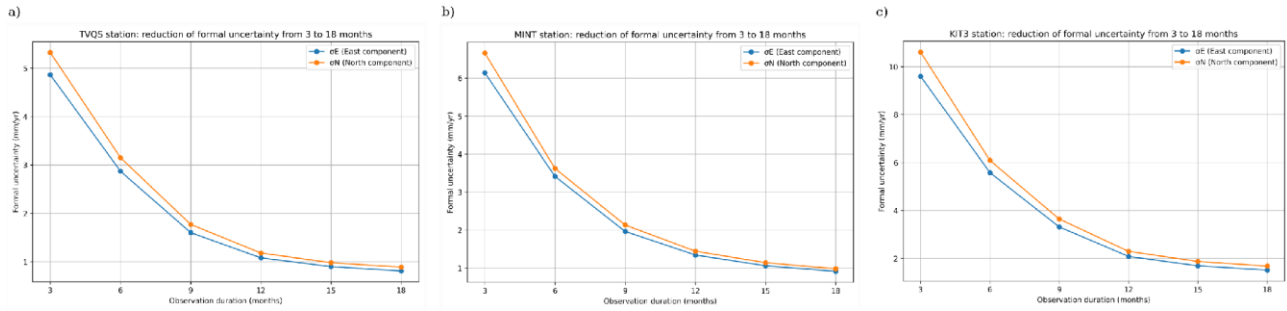


Figure 3. Reduction in the formal uncertainties of the V_E and V_N velocity components with increasing observation duration.

4. DISCUSSION

A GNSS coordinate time series is not composed solely of tectonic or technogenic linear motion. In general, a horizontal coordinate component can be represented as:

$$X(t) = X_0 + Vt + S(t) + C(t) + \varepsilon(t),$$

where X_0 is the initial coordinate, V is the long-term secular velocity, $S(t)$ is the seasonal component, $C(t)$ is the spatially correlated or common-mode signal, and $\varepsilon(t)$ is the residual noise associated with measurement and modeling.

Blewitt and Lavallée showed that annual signal amplitudes in GPS coordinate time series are typically about 2 mm in the horizontal components and about 4 mm in the vertical component. Atmospheric and hydrological loading are among the main sources of these signals; if seasonal components are not accounted for, velocity estimates can be significantly biased, particularly for short time series (Blewitt and Lavallée 2002).

For campaign observations in which velocity is estimated from only two epochs:

$$\hat{V} = \frac{X(t_2) - X(t_1)}{t_2 - t_1}.$$

Substituting the time-series model above into this equation gives:

$$\hat{V} = V + \frac{S(t_2) - S(t_1)}{\Delta t} + \frac{C(t_2) - C(t_1)}{\Delta t} + \frac{\varepsilon(t_2) - \varepsilon(t_1)}{\Delta t},$$

where:

$$\Delta t = t_2 - t_1$$

This expression illustrates the mathematical basis of the variability in short-term GNSS velocities. Even when the secular velocity V remains unchanged, epoch-to-epoch differences in the seasonal signal, common-mode component, and coordinate residuals are divided by Δt and added to the estimated velocity. As the observation interval decreases:

$$\Delta t \downarrow \Rightarrow \frac{\Delta X_{\text{res}}}{\Delta t}$$

and the influence of residual terms on the annualized velocity estimate increases.

For example, over a 3-month interval ($\Delta t \approx 0.25$ yr), a 5 mm difference between two coordinate solutions produces an annualized apparent velocity of $5/0.25 = 20$ mm/yr. This value does not imply that the point is actually moving at 20 mm/yr. The same effect was observed in the present experiment. When continuous stations installed on the same physical monuments were artificially subsampled into campaign mode, the direction and magnitude of the independent 3-month solutions changed markedly. At KIT3, the range of V_E across the 3-month solutions reached 44.07 mm/yr and the range of V_N reached 45.35 mm/yr; sign reversals in the components were also observed during some intervals at TVQS and MINT. There is therefore insufficient basis to interpret such vector-direction changes directly as real changes in the direction of geodynamic motion.

The cumulative results of the experiment are consistent with this theoretical relationship. When the observation span was extended from 3 to 18 months, the formal standard uncertainties decreased by 83.3% at TVQS, by 85.2–85.3% at MINT, and by 84.2–84.3% at KIT3. At the same time, the magnitude and direction of the velocity vectors converged toward the 18-month solution, with particularly clear stabilization at TVQS and MINT from the 12–15-month stages onward. These results are also consistent with international campaign-GNSS studies. Turen and Sanli (2019) artificially subsampled continuous IGS station data into campaign mode and assessed the effects of campaign frequency, session duration, and antenna set-up errors on deformation-rate estimates. Their results likewise demonstrate that generating synthetic campaign series from continuous GNSS data is a valid experimental approach for evaluating campaign-monitoring accuracy. The present experiment shows that, in campaign GNSS monitoring, a short-term velocity vector should not be equated methodologically with a secular deformation rate. Short-interval results must first be evaluated together with temporal sampling, seasonal



components, coordinate noise, and velocity uncertainty; conclusions regarding tectonic or technogenic deformations should be drawn only when the signal is temporally stable and spatially coherent.

5. CONCLUSION

The most important result of this experiment is that when continuous data from permanent GNSS stations installed on the same physical monuments are temporally subsampled to mimic campaign observations, both the magnitude and direction of the velocity vectors vary substantially in 3-month solutions. However, when the observation span is extended to 6, 9, 12, 15, and 18 months, the vectors progressively converge toward stable values. At the same time, the formal uncertainties of the V_E and V_N components decrease by approximately 83–85% from the 3-month to the 18-month solutions at TVQS, MINT, and KIT3. This behavior provides strong experimental evidence against interpreting short-period changes in vector direction as systematic changes in the direction of real natural tectonic motion. If the pronounced quarter-to-quarter vector reversals represented a true secular tectonic process, such regular convergence toward a single stable solution and the associated sharp reduction in uncertainty with increasing observation span would not be expected in this consistent form.

The independent 3-month solutions further support this conclusion. At KIT3, the total range of V_E values reached 44.07 mm/yr and the range of V_N values reached 45.35 mm/yr; at TVQS and MINT, the signs of the components also changed during some intervals. Importantly, these results were obtained not at different campaign points or with repeatedly re-installed antennas, but at the same continuously operating GNSS monuments. Therefore, a change in vector direction by itself does not indicate that a rock mass or tectonic block changes its direction of motion every three months; it can be consistently explained by the short time baseline, temporal sampling, seasonal components, and uncertainty of the coordinate solution.

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Author contributions

The author contributed to data collection, data processing using specialized software, development of the methodological concept, analysis of the results, and preparation of the manuscript.

Conflicts of interest

The author declares no conflict of interest.

Statement of Research and Publication Ethics

The study was conducted in accordance with the principles of research and publication ethics.

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