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Determination of the correlation degree between GNSS stations of Ukraine based on time series

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Using GNSS for many years is the most common technology for the collection, processing, and interpretation of Earth observation data, in particular for the high-precision study of plate tectonics. The results of GNSS observations, such as coordinate time series, allow us to do continuous monitoring of stations, and modern methods of satellite observation processing provide high-precision results for geodynamic interpretation. The aim of our study is to process the results of observations by DD and PPP methods and determine the degree of correlation between GNSS stations based on coordinate time series. For our study, we selected 10 GNSS stations, which merged into two networks — Lviv (SAMB, ST0Y, STRY, SULP та ZLRS) and Ukrainian (BCRV, CHTK, CNIV, CRNI, GLSV та SULP). The duration of observations on each of them is about 1.5 years (2019–2020). The downloaded observation files were processed in two software packages: Gamit and GipsyX. After applying the “cleaned” procedures based on the iGPS software package, the residual time series were obtained and the coefficients of the interstation correlation matrices were calculated. After the procedure of “cleaning” the time series, we obtained the RMS value decrease for all components of the coordinates by an average of 7–30%, and some stations by 55%. Based on the obtained RMS values, we can conclude that the influence of unextracted or incorrectly modeled errors can significantly affect the results of satellite observations. The obtained interstation correlation coefficients for both networks show different results depending on the used method for processing satellite observations. The larger correlation values of the DD method can be explained by the fact that the effect of errors is distributed evenly to all network stations, whereas in the PPP method errors for each station are individual. The obtained graphs of the common-mode errors values, after their removal from the residual time series, confirm the more uniform nature of the DD method. The results of our study indicate the feasibility of using the PPP method, as the autonomous processing of stations allows you to see the real geodynamic picture of the studied region.

Keywords: GNSS data processing; GNSS time series; PCA; CME; noise analysis

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1. Introduction

Today, GNSS (Global Navigation Satellite Systems) is the most common space research technology to solve a wide range of problems in the Earth sciences: Earth orientation parameters, determining the deformation of the Earth's crust, climate research, remote sensing, plate tectonics. Also, continuous satellite observations allow recording changes in the earth's surface due to atmospheric pressure, tidal loads, and unmodelled systematic errors, including incorrect modeling of satellite orbits, correction of the phase center of the satellite antenna, and multipath signal (Dong et al., 2006; Fu, Freymueller, 2012). Influence and disregard for such effects can lead to errors, the magnitude of which sometimes exceeds the magnitude of tectonic movements, which does not allow to obtain the qualitative necessary information that underlies the initial data of observations (Ji, Herring, 2011).

Regarding the statistical analysis of the need to take into account several of sources of systematic errors, it is possible to use a wide range of mathematical approaches, such as spatio-

temporal filtering, analysis of basic components (PCA), which allow removing common-mode errors (CME) (Dong et al., 2002; Tian, Shen, 2011; Savchuk et al., 2020). All these methods are suitable if we assume that all measurements are maximally correlated with each other, as in the relative method of determining the station's coordinates. However, if the observations are independent, as in the absolute method of coordinate determination, and each of them is considered as an independent component, there is no need to decompose PCA.

The DD method is a coordinate determination strategy for a baseline relative to a station with well-known coordinates. Equations for solving coordinates are formed by taking the differences between receivers and satellites (Hofmann-Wellenhof et al., 2007). Since it is necessary to observe the same satellites at two points at the same time to determine the coordinates, ie we get a network solution, it is assumed that the residual error values will be the same for each network station.

The PPP method, in contrast to the relative method, allows you to determine the coordinates using only one receiver. The approach of this method uses undifferentiated double pseudo-phase and phase observations with accurate satellite orbits and clock readings, to obtain an accuracy of a few millimeters to a few centimeters (Zumberge et al., 1997). The DD method is usually more accurate than the PPP, but not always more reliable.

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For example, network configuration or signal multiplicity in the observations of one station may affect other network stations. While the PPP method allows us to explore stations autonomously from each other, which will allow us to see a more realistic geodynamic picture. The aim of our work is to process satellite observations by different methods, to determine the degree of correlation between GNSS stations based on the time series of coordinates, to remove the common-mode errors, and to compare the obtained results.

2. Methods

For our study, we selected 10 GNSS stations, which merged into two networks — Lviv (SAMB, STOY, STRY, SULP та ZLRS) and Ukrainian (BCRV, CHTK, CNIV, CRNI, GLSV та SULP) (Fig. 1). The duration of observations on each of them is about 1.5 years (2019–2020). The feature of the choice of stations was the length of the baselines, for the Lviv network they range from 55–143 km, and for the Ukrainian — 68–547 km.

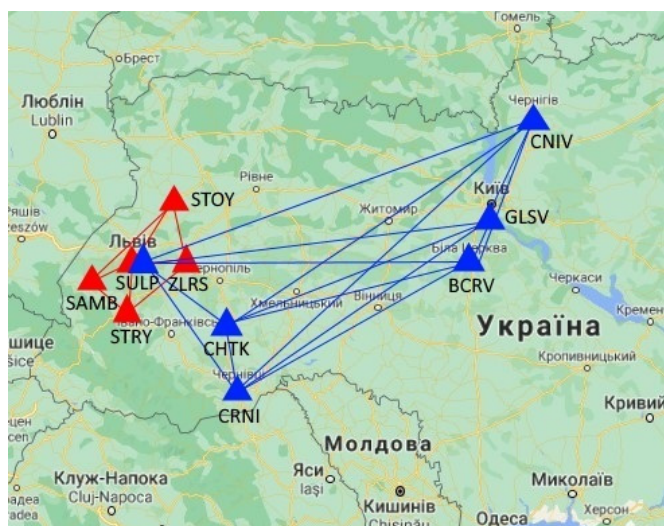


Fig. 1. Map of GNSS stations location (red — stations of the Lviv network, blue — stations of the Ukrainian network)

Observation files (RINEX) were downloaded from the LPI Analysis Center server and processed in two software packages — Gamit and GipsyX.

The Gamit software package is based on the DD method of determining coordinates. During the study, we used the troposphere mapping function to estimate hydrostatic and wet zenith tropospheric delays (Herring et al., 2010). The effects of polar motion, solid Earth tides, and ocean tides were also removed during data processing.

The processing in the GipsyX software package, which is based on the PPP method, also removed all the above effects, as well as additionally loaded the precise satellite ephemeris and satellite clock corrections (GipsyXDocs, 2019).

Then time series in the topocentric coordinate system was formed.

Using the iGPS software package, in the <Graph> panel, we determined the value of the trend component of the time series, semi-annually or annually, and removed it from the series. The program also determines and displays on the graphical interface the RMS value for each coordinate component separately. We use the <Model> utility to automatically estimate the linear annual velocity and smaller ranges. If “jumps” and “outliers”

remain on the graphs after using this utility, we can easily detect them by looking at the remaining graphs of the time series. We can then define and delete them manually using the <Offset Selector> utility, saving them in a special offset file. To account for these offsets, use the <Model> utility again using the offset file (Tian, 2011).

Fig. 2 a shows a graphical example obtained based on the software package GipsyX processing, the coordinate time of the GNSS-station BCRV, and Fig. 2 b shows the result, obtained after the application of “cleaned” procedures based on iGPS.

To reduce the impact of CME, as mentioned earlier, it is necessary to filter time series using various methods. The term CME was first used in 1997 by the scientist Wdowinski, who described correlated errors in networks of GNSS stations. Assuming that the total CME value is the arithmetic mean of all residual errors for a given epoch of observations, he established an approach called “stacking”. Later, other scientists improved this approach and the name (“weighted stacking”), proving that the determined coordinates with their real errors can not equally

affect the final estimate of CME. The application of such a method involves taking into account the duration of time series and distances between stations and the correlation of residual errors between them (Nikolaidis, 2004).

3. Results

To determine the correlation coefficients for each component between two network stations, we use the formula below:

$$\text{corr}[N(t, j), N(t, k)] = \frac{\text{cov}[N(t, j), N(t, k)]}{\sigma_{N(t, j)} \sigma_{N(t, k)}}, j \neq k, \quad (1)$$

Where $N(t, j)$ — selected component of one station, $N(t, k)$ — the same component of another station for each of the epochs. The obtained values of the correlation coefficients are shown in Fig. 3.

The figure shows that depending on the applied method of observation processing, we get a different result.

The small values of the correlation coefficients can be explained by the correct modeling of the time series, which leads to the correct removal of the spatially uniform influence of CME

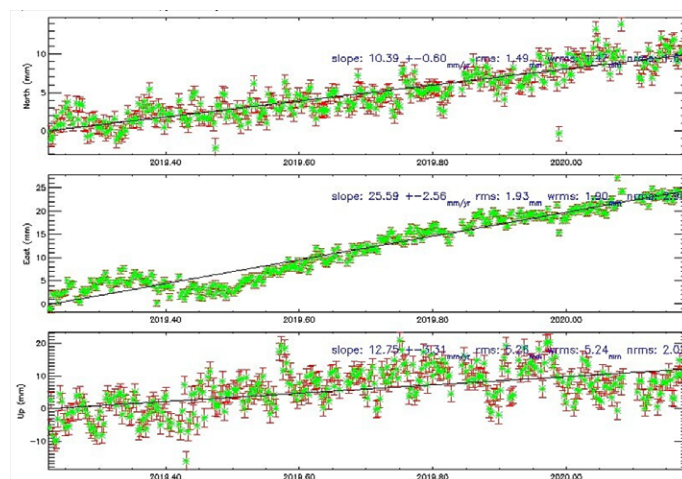


Fig. 2 a "Raw" time series of the BCRV station

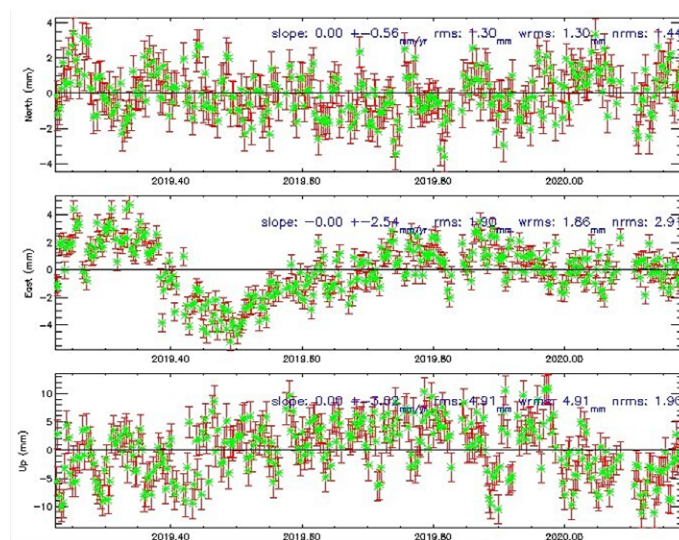


Fig. 2 b "Cleaned" time series of the BCRV station

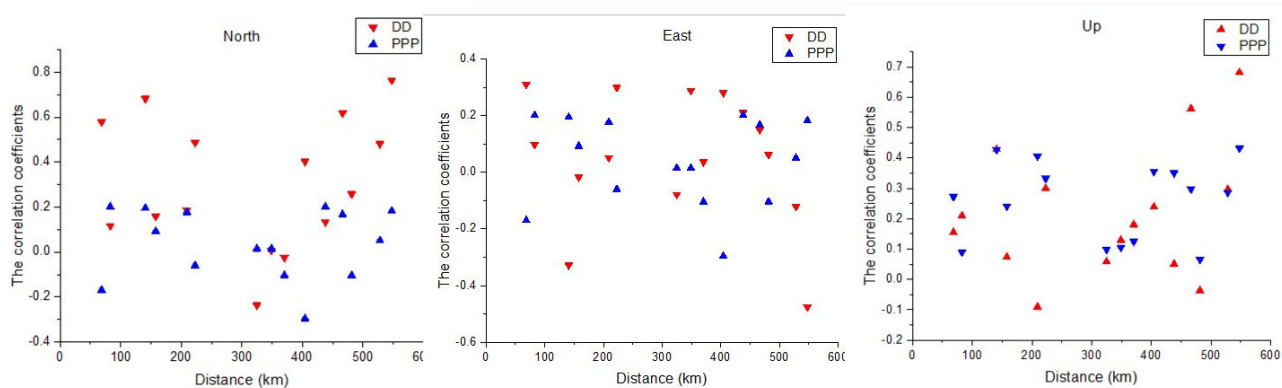


Fig. 3. Correlation coefficients for each pair of network stations

at each station. Another reason for such correlation values may be the increased estimation of various parameters, such as tropospheric delays and Earth orientation parameters, made in recent years. It is also important to note that the correlation coefficient decreases with increasing distance between stations. The average values of the correlation coefficients for each component of the two networks are shown in Table 1.

However, it should also be noted that the correlation values

Table 1.

Average values of correlation coefficients

| Method | Correlation coefficients | | |
|-------------------|--------------------------|------|-------|
| | N | E | U |
| Ukrainian network | | | |
| PPP | 0.04 | 0.30 | 0.26 |
| DD | 0.31 | 0.05 | 0.22 |
| Lviv network | | | |
| PPP | -0.03 | 0.04 | 0.11 |
| DD | 0.22 | 0.10 | -0.07 |

for the DD method are slightly larger than the values of the PPP method. Because when applying the network method, the influence of CME is evenly distributed to all stations of the network, and with the absolute method, such errors for each station are individual.

For a set of stations n , with time series for a certain epoch m , that is used in our research, it is necessary to build a matrix X dimension $n \times m$ separately for each component (N, E, U). The CME calculations are performed by the following formula:

$$CME(t)_i = \frac{\sum_{j=1}^n \frac{N(t_j, j)}{\sigma_{i,j}^2}}{\sum_{j=1}^n \frac{1}{\sigma_{j,i}^2}} \quad (2)$$

Where $CME(t)_i$ — CME for each epoch t_i , $N(t_j, j)$ — elements of the matrix X , $\sigma_{i,j}^2$ — RMS value for the separate station position at the i epoch.

The estimated CME values are considered to be spatially uniform for each epoch of observations and for each component of the time series (Bogusz et al., 2015). Extraction of the calculated CME value from the value of the unfiltered component was performed using the following equation:

$$n(t_i, j) = N(t_i, j) - CME(t)_i \quad (3)$$

$$i = 1, \dots, m, j = 1, \dots, n \quad (4)$$

Filtered values $n(t_i, j)$ calculated according to the procedure described above. Fig. 4 shows the time series before and after CME removal.

For each time series component, we determined the RMS values and the coordinates velocities before “cleaning” and after removing the trend, jumps, and CME. The average results are shown in Table 2.

The results show a significant reduction in these values for each of the stations. However, the results differ depending on the data processing method used. After removing the trend, “jumps” and “outliers”, the RMS value for the PPP method decreased by an average of 7–10%, while the data processed by the DD method show values of 25–30%. After CME extraction, the results change significantly — for DD the value is 40–60%, and for the PPP method, the RMS value has more than halved — by 60–75%.

As can be seen from Fig. 5 a and Fig. 5 b, the distance between the stations has little effect on the size of the common-mode error values. The values are almost the same for the horizontal position and increase significantly for the vertical component. It should be noted that in the series of obtained values processed by the DD method there is a shift in the northern and eastern components, while the values of the PPP method are characterized by a linear trend.

This difference can be explained, for example, by incorrect modeling of parameters during processing, because the PPP method uses accurate satellite ephemeris, which can provide more accurate results of observations.

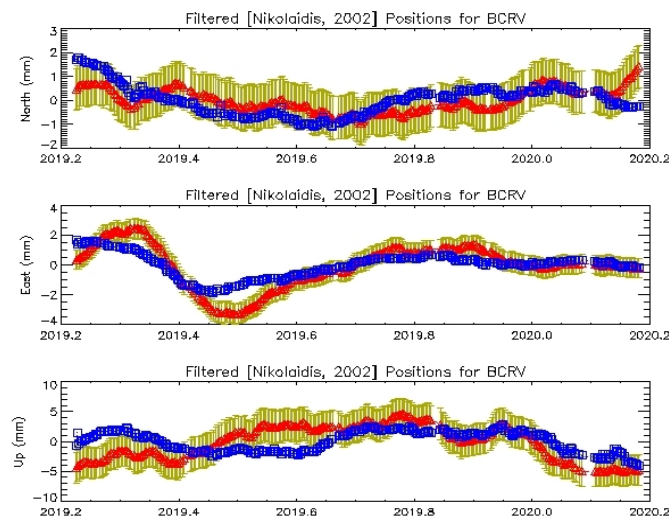


Fig. 4. Time series of the BCRV station (red — before, blue — after)

Table 2.
RMS and velocities values

| Method | | DD | | PPP | |
|-------------------|---------------|-------------|------------|-------------|------------|
| Ukrainian network | | | | | |
| Component | | Before | After | Before | After |
| N | RMS, mm | 2.0 | 1.6 | 1.5 | 1.1 |
| | Vel., mm/year | 0.00 ±1.54 | 0.31 ±1.25 | 0.00 ± 1.01 | 0.14± 1.05 |
| E | RMS, mm | 1.5 | 1.4 | 1.4 | 0.8 |
| | Vel., mm/year | 0.00 ±0.74 | 0.19± 0.64 | 0.00 ±1.25 | 0.10± 0.68 |
| U | RMS, mm | 2.8 | 2.6 | 5.3 | 2.7 |
| | Vel., mm/year | 0.00 ±1.42 | 0.25± 1.25 | 0.00 ±3.73 | 0.45± 1.63 |
| Lviv network | | | | | |
| Component | | Before | After | Before | After |
| N | RMS, mm | 1.6 | 0.9 | 1.4 | 0.9 |
| | Vel., mm/year | 0.00 ± 1.19 | 0.47± 0.42 | 0.00 ± 0.98 | 0.37± 0.55 |
| E | RMS, mm | 1.9 | 1.0 | 1.6 | 0.8 |
| | Vel., mm/year | 0.00 ±0.93 | 0.52± 0.55 | 0.00 ±1.30 | 0.24± 0.47 |
| U | RMS, mm | 3.1 | 3.0 | 5.7 | 3.8 |
| | Vel., mm/year | 0.00 ±1.17 | 0.31 ±1.66 | 0.00 ±4.11 | 1.38± 3.85 |

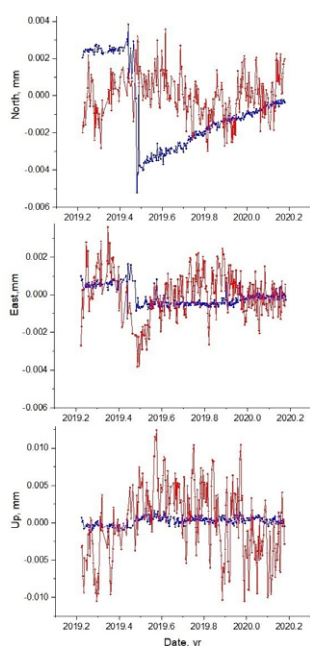


Fig. 5 a. Values of the common mode errors for the Ukrainian network (red — PPP method, blue — DD method)

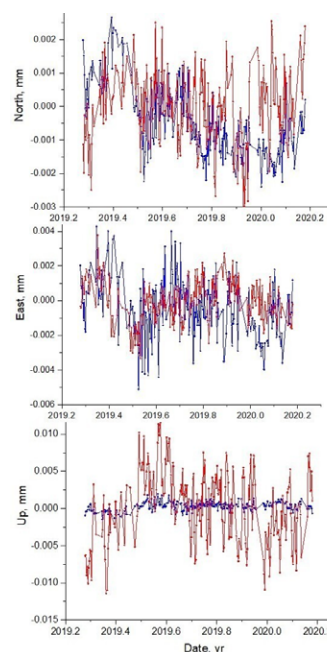


Fig. 5 b. Values of the common mode errors for the Lviv network (red — PPP method, blue — DD method)

4. Conclusions

Based on the obtained RMS values, we can conclude that the influence of unextracted or incorrectly modeled errors can significantly affect the results of the observations. After all, the RMS values for all coordinate components decreased by an average of 7–30%, and for some stations by 55%.

Depending on the chosen method of observation processing, we obtained different values of correlation coefficients between network stations. For the northern component, these values are from — 0.03 to 0.31, for the eastern component from 0.04 to

0.30, and the vertical component from — 0.07 to 0.26. Since the DD method applies the effect of errors evenly to all network stations, the correlation values for the DD method are slightly larger than the value of the PPP method.

As described earlier, the DD method is considered more accurate than the PPP method for network processing. However, the results of our study indicate the feasibility of using the PPP method, as it eliminates the influence of various errors of one station on another. Autonomous processing of each station will allow not only to receive exact results of observations but also to see a real geodynamic picture of the studied region.

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ВИЗНАЧЕННЯ СТУПЕНЮ КОРЕЛЯЦІЇ МІЖ GNSS-СТАНЦІЯМИ УКРАЇНИ НА ОСНОВІ ЧАСОВИХ СЕРІЙ КООРДИНАТ

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Вже багато років найбільш точні дані про рух тектонічних плит дають GNSS спостереження, такі як часові серії координат, дають можливість безперервного моніторингу станцій, а учасні методи опрацювання супутникових спостережень, забезпечують високоточні результати для геодинамічної інтерпретації. Метою нашого дослідження є опрацювання результатів спостережень відносним та абсолютним методами та визначення ступеню кореляції між GNSS-станціями на основі часових серій координат. Для нашого дослідження ми обрали десять GNSS-станцій, які об'єднали у дві мережі — Львівську (SAMB, ST0Y, STRY, SULP та ZLRS) та Українську (BCRV, CHTK, CNIV, CRNI, GLSV та SULP). Тривалість спостережень на кожній із них складає близько 1.5 року (2019–2020). Завантажені обсерваційні файли опрацювали в двох програмних пакетах: Gamit та GipsyX. Після застосування очищених процедур на основі програмного пакету iGPS отримано залишкові часові ряди та обчислено коефіцієнти матриць міжстанційної кореляції. Після проведеної процедури “очищення” часових серій, ми отримали зменшення величини СКП для всіх компонент координат в середньому на 7–30%, а для деяких станцій на 55%. На основі отриманих значень СКП можемо зробити висновок, що вплив невилучених, або не коректно змодельованих похибок може істотно вплинути на результати супутникових спостережень. Отримані коефіцієнти міжстанційної кореляції для обох мереж показують різні результати в залежності від використаного методу опрацювання супутникових спостережень. Більші значення кореляції методу DD можна пояснити тим, що вплив похибок рівномірно поширюється на всі станції мережі, тоді як при PPP методі помилки для кожної станції мають індивідуальний характер. Отримані графіки значень похибок загального режиму, після їх вилучення із залишкових часових серій, підтверджують більш рівномірний характер DD методу. Результати нашого дослідження вказують на доцільність використання методу PPP, оскільки автономне опрацювання станцій дозволяє побачити реальну геодинамічну картину досліджуваного регіону.

Ключові слова: опрацювання GNSS даних; часові ряди координат; PCA; CME; аналіз шуму

ОПРЕДЕЛЕНИЕ СТЕПЕНИ КОРРЕЛЯЦИИ МЕЖДУ GNSS-СТАНЦИЯМИ УКРАИНЫ НА ОСНОВЕ ВРЕМЕННЫХ СЕРИЙ КООРДИНАТ

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Применение GNSS уже много лет является самой распространенной технологией высокоточного исследования тектоники плит. Результаты GNSS наблюдений, такие как временные серии координат, дают возможность непрерывного мониторинга станций, а современные методы обработки спутниковых наблюдений, обеспечивают высокоточные результаты для геодинамической интерпретации. Целью нашего исследования является разработка результатов наблюдений относительным и абсолютным методами и определение степени корреляции между GNSS станциями на основе временных серий координат. Для нашего исследования мы выбрали десять GNSS-станций, объединили в две сети — Львовскую (SAMB, ST0Y, STRY, SULP и ZLRS) и Украинскую (BCRV, CHTK, CNIV, CRNI, GLSV и SULP). Продолжительность наблюдений на каждой из них составляет около 1.5 года (2019–2020). Загруженные обсервационные файлы обрабатывали в двух программных пакетах: Gamit и GipsyX. После применения очищенных процедур на основе программного пакета iGPS получили остаточные временные ряды и рассчитаны коэффициенты матриц межстанционной корреляции. После проведенной процедуры “очищения” временных серий, мы получили уменьшение величины СКО для всех компонент координат в среднем на 7–30%, а для некоторых станций на 55%. На основе полученных значений СКО можем сделать вывод, что влияние неизятых, или некорректно смоделированных погрешностей может существенно повлиять на результаты спутниковых наблюдений. Полученные коэффициенты межстанционной корреляции для обеих сетей показывают разные результаты в зависимости от использованного метода обработки спутниковых наблюдений. Большие значения корреляции метода DD можно объяснить тем, что влияние погрешностей равномерно распространяется на все станции сети, тогда как при PPP методе ошибки для каждой станции имеют индивидуальный характер. Полученные графики значений погрешностей общего режима, после их изъятия из остаточных временных серий, подтверждают более равномерный характер DD метода. Результаты нашего исследования указывают на целесообразность использования метода PPP, поскольку автономная обработка станций позволяет увидеть реальную геодинамическую картину исследуемого региона.

Ключевые слова: обработка GNSS данных; временные ряды координат; PCA; CME; анализ шума

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