GIS Odyssey Journal

2025 • Volume 5 • Number 1

https://doi.org/10.57599/gisoj.2025.5.1.213

Karol Dawidowicz[1], Radosław Baryła[2]

ELEVATION ONLY VS FULL PCC MODELS – THE IMPACT ON POSITIONING

Abstract: Antenna phase center corrections (PCC) are now mandatory for high-accuracy Global Navigation Satellite System (GNSS) applications. Such corrections are being created nowadays using an anechoic chamber or an outdoor robot calibration method. Based on these two methods, PCCs are created in the function of the zenith angle and azimuth of the incoming GNSS signal. However, some antennas still lack complete PCC as both approaches are time and money-consuming. In the case of some antennas, mostly low-cost ones, no real phase center location information is provided. For another group of antennas, so-called elevation-only PCC derived from relative outdoor calibration is available. Elevation-only PCC, after transformation, could be utilized together with full PCC models in common GNSS observation processing. In the publication, the authors analyzed the differences resulting from the use of elevation-only instead of full PCC models. Values of such differences can be treated as a bias introduced into the solution due to the use of simplified PCCs. The results obtained prove that in the analyzed case study, such biases are negligible and do not exceed 1 mm in any case.

Keywords: phase center corrections (PCC); Global Navigation Satellite System (GNSS); positioning

Received: 5 May 2025; accepted: 22 May 2025

[1] University of Warmia and Mazury, Faculty of Geoengineering, Department of Geodesy, Olsztyn, ORCID ID: http://orcid.org/0000-0002-8837-700X, email: karol.dawidowicz@uwm.edu.pl

[2] University of Warmia and Mazury, Faculty of Geoengineering, Department of Geodesy, Olsztyn, ORCID ID: http://orcid.org/0000-0003-1897-7939, email: radoslaw.baryla@uwm.edu.pl

Introduction

The phase center of a Global Navigation Satellite System (GNSS) antenna is defined as the point in space where the signal is received. However, the position of this point is not fixed and depends on the direction of the incoming signal. For practical purposes, some additional points and vectors were defined. The first one is the so-called mean phase center (MPC) position of the antenna. The height of the antenna above the measurement point is usually measured to the so-called antenna reference point (ARP). The International GNSS Service (IGS) defines the ARP as the point of intersection of the vertical axis of symmetry of the antenna with the lower plane of the antenna. The phase center offset vector (PCO) is defined as the difference between the ARP and MPC positions. The difference between the MPC position and the actual point where the GNSS signal is registered is called, on the other hand, the phase center variations (PCV). The total phase center correction (PCC) for a given signal is the sum of the PCO and PCV vectors expressed in the direction of the incoming signal (Fig. 1). Changes in the position of the antenna's phase center can have an amplitude of several centimeters, and ignoring these changes can lead to significant errors in determining both the vertical and horizontal components of the position (Dawidowicz, 2011).

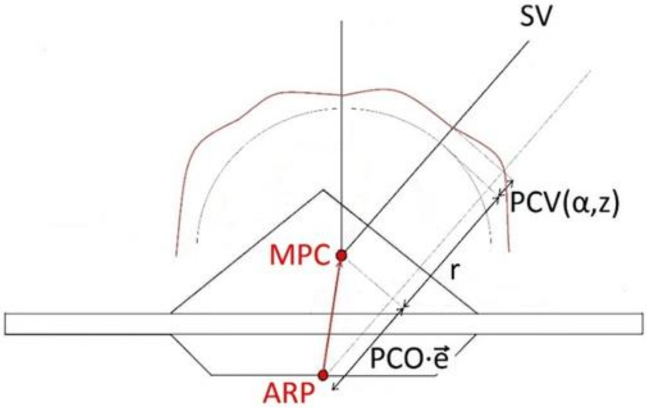

Fig. 1. Phase center of GNSS antenna location
Source: own study

The best method today to avoid this effect is to use during GNSS observations processing antenna's PCCs. Such corrections are created during antenna calibration. GNSS antenna calibration methodology goes back to the 1980s. Generally, calibration methods are divided into absolute and relative, or field and laboratory procedures (Zeimetz & Kuhlmann, 2008). Relative PCCs are estimated when the phase center position of the calibrated GNSS antenna is determined relative to a reference antenna. In the past, for such an antenna, a Dorne Margolin T was accepted officiously. Additionally, for relative calibration purposes, it assumes the phase center variation of the reference antenna is zero. Absolute methods are referred to when PCCs are determined independently of a reference antenna. For this type of method, the calibrated antenna is mounted on a special robot that rotates and tilts it during the procedure. The field method is based on tracking actual satellite signals (Wubbena et al., 2000; Bilich &

Mader, 2010), while the laboratory method is conducted in an anechoic chamber and utilizes simulated, artificial GNSS signals (Gorres et al., 2006). Additionally, PCC models are divided into individual and type-mean. An individual antenna PCC model exists when a specific antenna unit, along with its radome, is calibrated. In the case of the type-mean model, several antennas of the same type are calibrated, and the final PCC model is created by combining all the results into a single file. It should be mentioned that depending on the calibration method, GNSS antenna PCCs may differ by several millimeters (Bilich & Mader, 2010; Baire et al., 2013; Dawidowicz & Krzan 2016; Krzan et al., 2020; Kersten et al., 2022), which can significantly affect the final positional results.

The further challenge with PCC models is that only a few centers worldwide are involved in GNSS antenna calibration. This makes the whole procedure expensive and time-consuming. The first two countries where antenna calibration was initiated were the United States (National Geodetic Survey) and Germany (the University of Bonn, SenB of Berlin, Geo++, or the Institute of Geodesy from Hannover). In the early twenty-first century, Geoscience Australia became the new calibration facility, the only one in the Southern Hemisphere (Riddell et al., 2015). A few years later, the calibration results for antennas obtained at Wuhan University (Hu et al., 2015) and ETH Zurich (Willi et al., 2018) have been published. Calibration systems are also being developed i.a. at UWM Olsztyn (Dawidowicz et al., 2021) or the University of Zagreb (Tupek et al., 2023).

As is widely known, some antennas still lack complete PCC. In the case of some antennas, mostly low-cost ones, no real phase center location information is provided. For another group of antennas, so-called elevation-only PCC derived from relative outdoor calibration is available. The advantage of such a case is that elevation-only PCC, after transformation, could be utilized together with full PCC models in common GNSS observation processing. In the publication, the authors analyzed the differences resulting from the use of elevation-only instead of full PCC models. Values of such differences can be treated as a bias introduced into the solution due to the use of simplified PCCs. The results of the analysis can be especially useful in the case of common geodetic surveys (Dawidowicz, 2014; Bakuła et al., 2015; Siejka, 2015; Dawidowicz, 2019), performed for Geodetic Information System (GIS) needs. GNSS observation processing in such cases is mostly done with the use of commercial or open-source software, where some simplifications are implied in the algorithms, for example, the possibility to use PCC only as a function of the elevation of the incoming signal.

Methodology

The analysis is based on multi-frequency Global Positioning System (GPS) and GLObalnaya NAvigatsionnaya Sputnikovaya Sistema (GLONASS) observations recorded at sample EUREF Permanent Network (EPN) station AUBG from January 1st to January 10th, 2021. At the time of the measurements, a LEICA GR50 receiver was operating at the station together with LEIAR25.R4 LEIT antenna.

Daily observations were divided into 30-minute observation windows, resulting in 480 half-hour sessions. Observing was processed using the open-source GAMP software package (Zhou et al., 2018). The observations were processed using type-mean PCC (igs14_2035.atx) recommended by IGS. Additionally, for the purposes of analysis, calculations were made using elevation-only PCC derived from the igs14_2035.atx model. Notably, for the type-mean and individual models at igs14_2035.atx file, the PCCs are available only for observations on frequencies L1 and L2 for GPS and GLONASS signals. This was the main reason for reducing the analysis to only GPS and GLONASS observations. The open-source software GAMP was used to process GNSS observations. GAMP is a program based on RTKLib but includes enhancements such as cycle slip detection, receiver clock jump repair, and handling of GLONASS inter-frequency errors. The characteristics of the software and its capabilities are presented in (Zhou et al., 2018). The main parameters adopted for processing observations using the GAMP are presented in Table 1.

Table 1. GAMP processing parameters

Basic observables	Undifferenced carrier phase & pseudorange;
Orbit & clock products	CODE MGEX orbits and clocks;
Ionospheric delay	The undifferenced and uncombined (UC) dual-frequency observations were used in PPP processing to extract ionospheric delays and avoid noise amplification (Pengfei et al., 2011);
Tropospheric delay	Zenith dry delay estimated as a parameter; Wet delay estimated using the wet GMF mapping function;
Ocean loadings	FES2004 model using ONSALA ocean loading service (Lyard et al., 2006);
Differential Code Biases	Daily multi-GNSS differential code biases (DCBs) are derived from observations of MGEX/iGMAS networks with local ionospheric TEC modeling technique entitled MGTS. A description of MGTS algorithms is provided in Wang et al. (2016);
Other	Observation sampling rate: 30 sec.; Elevation angle cut-off 10°; Daily observations from the period 01.01.2021-10.01.2021; Ambiguity float solution.

Source: own study

PCC comparison

In the chapter, the differences between elevation-only and full PCC models were analyzed. For the purpose of this comparison, type-mean PCCs, in full and elevation-only form, obtained from the igs14_2035.atx model was used. As both compared versions of PCCs utilize the same MPC vector for differences calculation, it was enough to subtract the corresponding corrections (Fig. 2).

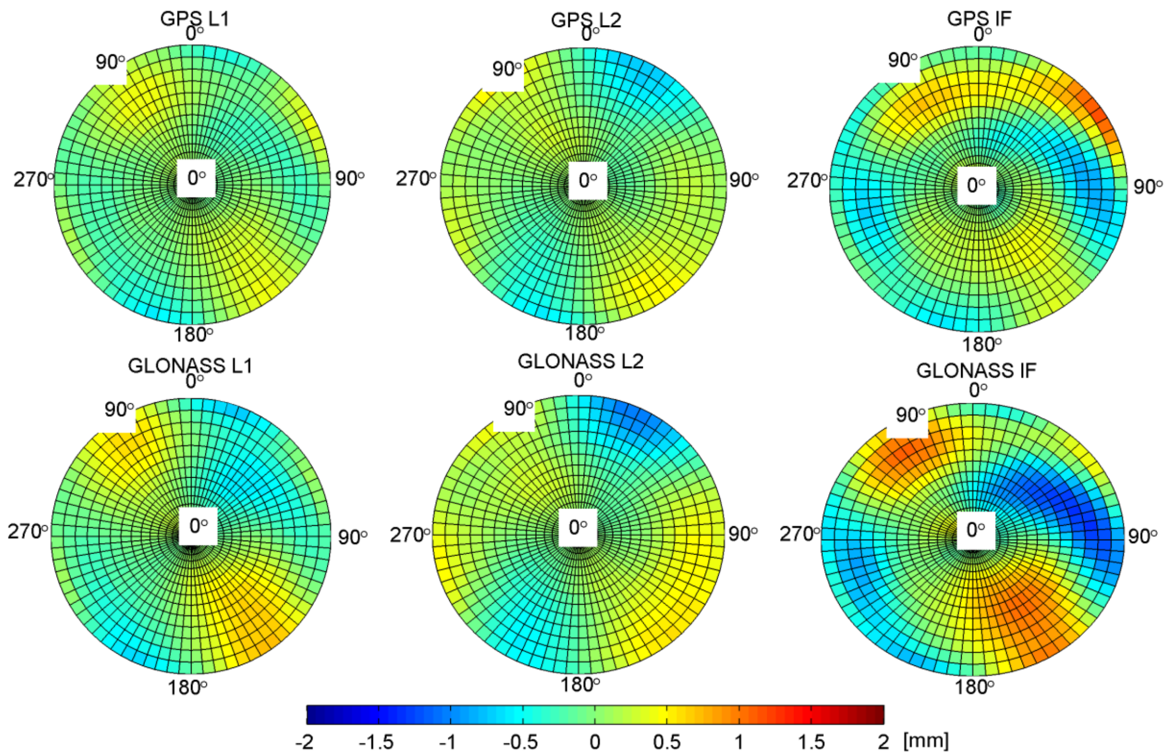

Fig. 2. Elevation-only vs full PCC differences for GPS and GLONASS signals
Source: own study

Differences were calculated for two primary GPS and GLONASS frequencies as well as for iono-free (IF) combinations. The IF combination is commonly used in static observation processing. As a result of forming the IF combination, the first order of ionospheric path delay is virtually eliminated (Sieradzki & Paziewski, 2015). The general formula of IF combination for code and phase observations has the following form:

$$P_{IF}^{r,s} = \alpha_{ij} P_i^{r,s} + \beta_{ij} P_j^{r,s} \tag{1}$$

$$L_{IF}^{r,s} = \alpha_{ij} L_i^{r,s} + \beta_{ij} L_j^{r,s} \tag{2}$$

where:
$P_{IF}^{r,s}$, $L_{IF}^{r,s}$ – IF combination for code and phase observations between satellite s and receiver r;α_{ij}, β_{ij} – coefficients of theIF combination; $P_i^{r,s}$, $P_j^{r,s}$, $L_i^{r,s}$, $L_j^{r,s}$are pseudorange and phase observations in meters for f_i and f_j frequencies, respectively.
The resulting coefficients α_{ij}, β_{ij} for L1/L2 IF combination are equal to 2.55 and -1.55, respectively and can be expressed as:

$$\alpha_{ij} = \frac{f_1^2}{f_1^2 - f_2^2}, \quad \beta_{ij} = \frac{-f_2^2}{f_1^2 - f_2^2} \tag{3}$$

where f_1 and $f_2$indicate the frequencies of the L1 and L2 signal, respectively.
However, in addition to removing the effects of the ionosphere from observations, the IF combination increases the observation noise. In comparison to the solutions for

individual L1 and L2 frequencies, PCC values for IF combination increase almost threefold.

As is seen from Fig. 2, the smallest differences were obtained when comparing full models with elevation-only models in the case of two primary frequencies, i.e., L1 and L2. In these cases, the differences for both GPS and GLONASS signals do not exceed 1 mm in any antenna area. Small differences were expected, as elevation-only models can be considered a first approximation of full models. Elevation-only models are still used in some older versions of software. Slightly larger differences were obtained in the case of IF combinations. This is also expected based on formulas 1-3. Nonetheless, even in this case, the differences do not exceed 2 mm in any LEIAR25.R4 LEIT antenna area.

Results

This part of the work presents differences in comparing position components determined using the igs14.atx type-mean model and the so-called elevation-only model derived from igs14.atx.

All observations were processed using the "free network" method in the IGb08 system (aligned with the International Terrestrial Reference Frame 2008 (ITRF2008)). Since the time series analysis mainly concerns topocentric coordinates (horizontal components N, E, and vertical component U), the obtained time series were converted to the topocentric system.

Figures 3 and 4 depict the mean differences obtained from daily and 0.5-hourly solutions for all processing variants, along with their corresponding standard deviations (STD).

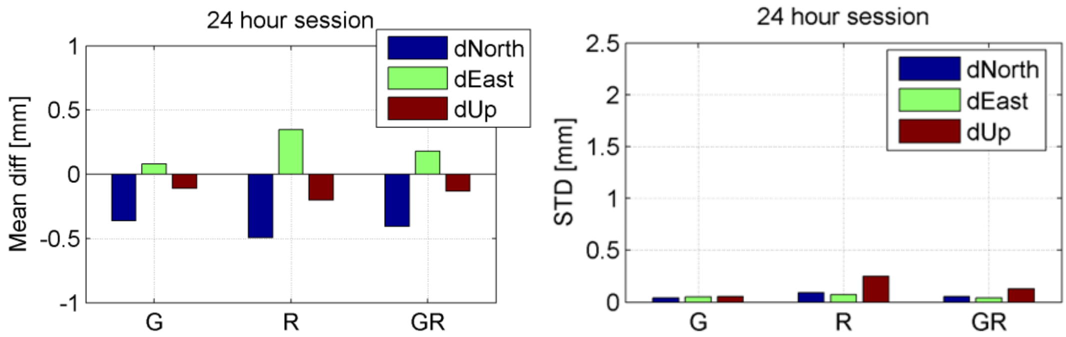

Fig. 3. Mean differences and STD of differences for daily solutions. Values of dNorth, dEast and dUp present differences from comparing position components determined using the igs14.atx type-mean model and the elevation-only model derived from igs14.atx
Source: own study

For the daily solution (Fig. 3), switching from a full PCC model to an elevation-only model generates mean differences of up to 0.5 mm for the North component, up to 0.3 mm for the East component, and up to 0.2 mm for the Up component. All these maximum values happened in the case of GLONASS-only solution. The smallest differences were obtained for GPS-only solution. The reason is the bigger differences in both PCCs used in the case of GLONASS signals and the smallest in the case of GPS ones

(Fig. 2). Analyzing STD, it was found that the highest values were obtained also for the GLONASS-only solution. On the other hand, when we focused on the position component, it could be noticed that in all processing variants, the biggest STD was achieved for the Up coordinate. This goes in line with a general rule, as the vertical coordinate is determined with the lowest accuracy due to the conditioning of the GNSS measurement.

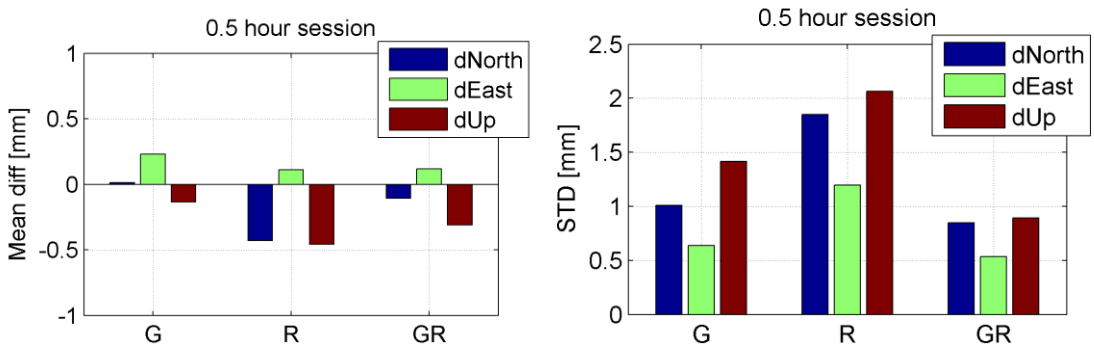

Fig. 4. Mean differences and STD of differences for 0.5-hour observation window solutions. Values of dNorth, dEast and dUp present differences from comparing position components determined using the igs14.atx type-mean model and the elevation-only model derived from igs14.atx
Source: own study

For the 0.5-hour observation window solution (Fig. 4), mean differences are comparable to those obtained from daily solutions. In this case, switching from a full PCC model to an elevation-only model generates mean differences of up to 0.5 mm for the North and Up components in the GLONASS-only solution and up to 0.3 mm for the East component in the case of the GPS-only solution. The biggest differences can be seen in the case of STD. The values of STD are much larger in the case of 0.5-hour solutions. This is obvious as solutions from shorter sessions are characterized by lower accuracy. On the other hand, there are some clear similarities. As previously, the highest values were obtained for GLONASS-only solution. Also, when we focused on the position component, it could be noticed that in all processing variants, the biggest STD was achieved for the Up coordinate.

Thirty-minute observation windows were used to study short-period oscillations.

Figure 5 illustrates coordinate time series differences (dNdEdU). Switching from a full (14) PCC model to an elevation-only (14e) model generates, in general, the biggest differences for the Up component. Additionally, in the case of the GLONASS-only solution, it can be observed high differences for the North position component. Analyzing the obtained differences, it can also be observed that the results agree with the results presented in Fig. 4, where mean differences were shown. The highest values of differences, reaching above 5 mm and consequently the biggest STD, were obtained in the case of GLONASS-only solution. In the case of both remaining processing variants, the differences are evidently smaller and do not exceed 5 mm. Finally, in some cases, e.g., Up position component differences for GPS-only solution, a periodicity in results can be observed. This phenomenon will be analyzed afterward.

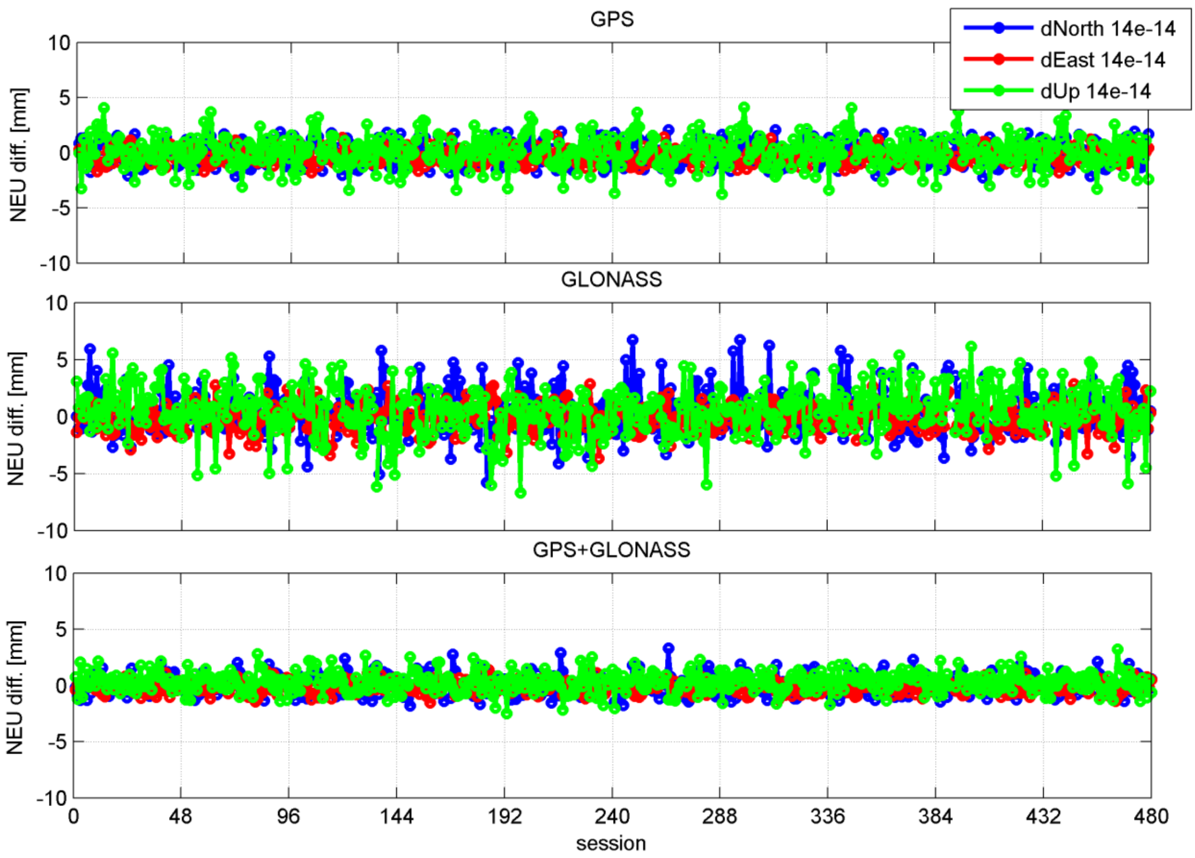

Fig. 5. Time series of NEU differences from 0.5-hour observation window. Values of dNorth 14e-14, dEast 14e-14 and dUp 14e-14 present differences from comparing position components determined using the igs14.atx type-mean model and the elevation-only model derived from igs14.atx
Source: own study

Firstly, the results obtained for the short 0.5-hour session were presented using cumulative histograms in Fig. 6. This was done to get a more detailed insight into differences visible in the results obtained in the three processing variants.

Comparing the graphs showing the distribution of residuals for three solution variants shows that adding GLONASS observations to the GPS one positively affects the solution. If we focus on the 80% relative frequency, it can be seen that residual deviations are reduced when GLONASS observables are added. This is especially visible for the Up position component. From the graphs, it can also be seen a significantly faster trend of residuals to 100% for the GPS-only in comparison to GLONASS-only observations. Also, it can be observed that the East component has a better distribution of residues than the North and Up components.

Finally, the periodicity in the analyzed position component differences was studied. The coordinate time series, in addition to the measurement signal, also contains some systematic influences that can show a certain periodicity.

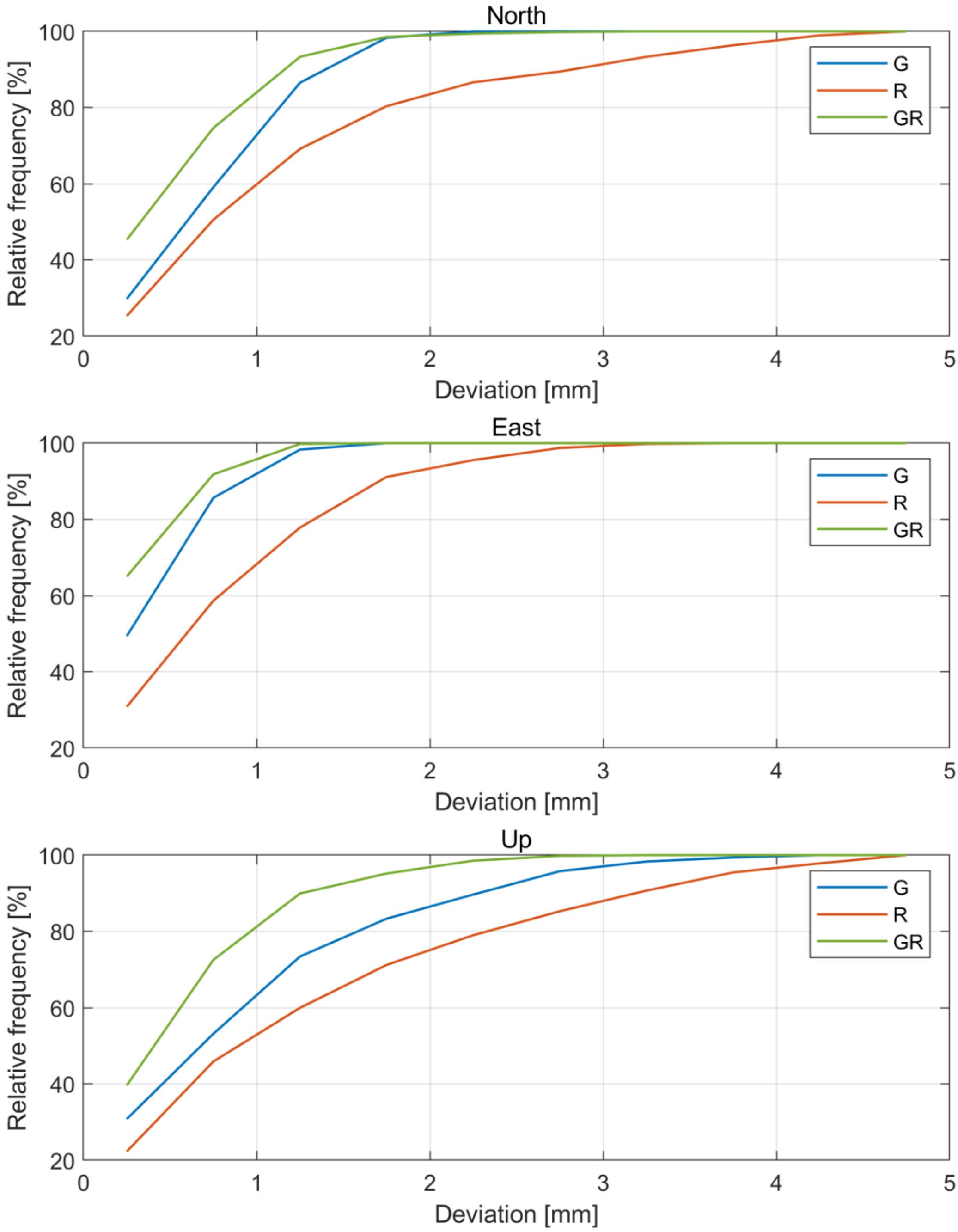

Fig. 6. Cumulative histograms for 0.5-hour session results for GPS-only (G), GLONASS-only (R) and GPS+GLONASS (GR) solutions
Source: own study

Because PPP, as an autonomous positioning method, is predisposed to detect such signals, an analysis of the time series of NEU component differences was performed using the Lomb-Scargle periodogram (Scargle, 1982). For a time series involving N_t measurements $X_j \equiv X(t_j)$, sampled in time $t_j (j = 1,\ldots, N_t)$, rescaled and concentrated in such a way that their mean is equal zero $(\sum_j X_j = 0)$, the power of the normalized Lomba-Scargle periodogram, for the chosen frequency, is expressed by the formula (Townsend, 2010):

$$P_n(f)=\frac{1}{2}\left\{\frac{[\sum_j X_j\cos\omega(t_j-\tau)]^2}{\sum_j\cos^2\omega(t_j-\tau)}+\frac{[\sum_j X_j\sin\omega(t_j-\tau)]^2}{\sum_j\sin^2\omega(t_j-\tau)}\right\} \quad (4)$$

where $\omega \equiv 2\pi f$ is the pulsation and τ is the time delay calculated for the chosen frequency.

Figure 7 shows the periodograms obtained for time series of the position components of the three processing variants. A simple rule for interpreting the power of the Lomb-Scargle periodogram can be found in Bozza et al. (2016). According to this principle, in a case when power <6 periodicity is most likely non-existent; for the range 6 <power<10 – periodicity can exist but with very low probability; in the case of 10 <power<14 – periodicity may exist, it is worth performing further analyses; for the range 14 <power <20 – the periodicity most likely exists; and the last case: power> 20-30 – periodicity definitely exists. This rule was used to interpret the obtained results.
If we consider only cases where the normalized spectral density exceeds 20 (periodicity definitely exists), in the obtained results, we can identify some periodic signals.

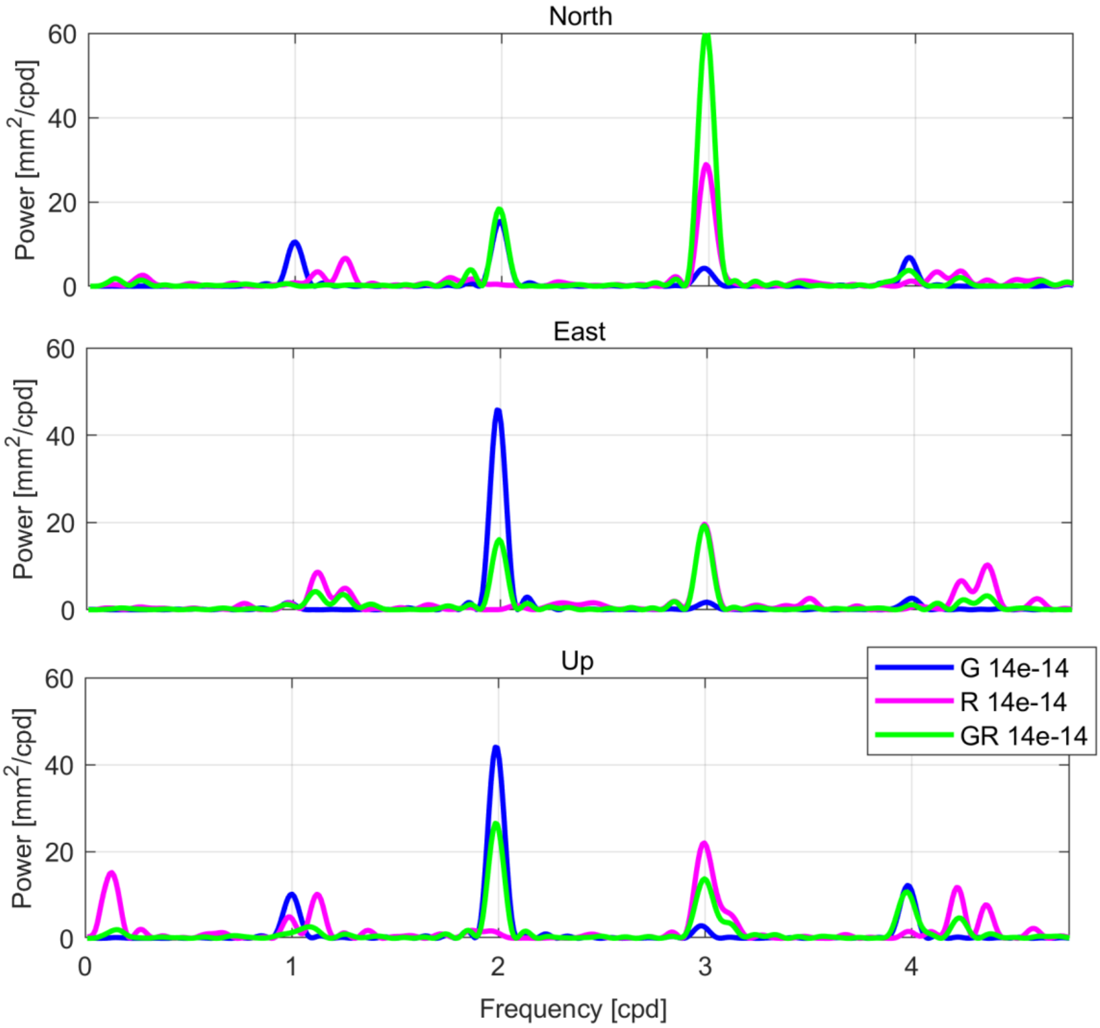

Fig. 7. Lomba-Scargle Periodograms for position component time series obtained in three analyzed observation processing scenarios. Values of G 14e-14, R 14e-14, and GR 14e-14 refer to solution differences obtained by comparing results with the igs14.atx type-mean model and the elevation-only model derived from igs14.atx for GPS-only (G), GLONASS-only (R) and GPS+GLONAS (GR) data
Source: own study

For the processing strategies where GPS signals were involved (GPS-only or GPS/GLONASS), in most cases, there is periodicity on frequencies 1, 2, 3 and 4 cycles per day (cpd). All of these frequencies correspond to multiples of half the orbital period of GPS satellites. In the case of the GLONASS-only solution, the periodicity was observed on the frequency equal to 3 cpd, which may also correspond to the GLONASS satellite constellation above the measured station. For example, the analysis of the GLONASS satellite visibility diagrams shows that the satellite constellation above the measured stations significantly changed. There were some periods when almost all satellites at medium elevations were observed, and periods when satellites were observed on low and high elevations only (about an 8-hour repeatability period). As is well known, some models (e.g., antenna Phase Center Corrections) are satellite elevation (and azimuth) dependent. Any imperfection in these models can be the reason for the observed periodicity.

The results presented in Fig. 7 prove that all three position component differences, obtained from sub-hourly PPP solutions, show a clear periodicity. Based on the obtained results, it can be concluded:

– the position components show visible systematic changes in time,
– the amplitudes of these changes reach up to 5 mm for the vertical component and 3 mm for the horizontal components (Fig. 5).

Conclusions

The study presented the differences in position components resulting from using full or elevation-only PCC models. Position components were determined using the igs14_2035.atx model, which contains type-mean calibration results as well as the type-mean elevation-only model derived from it. EPN AUBG station daily GNSS observations from ten days were used for the study. Time series of positions (sub-daily – 30 min and daily) were obtained using the Precise Point Positioning technique with the open-source software GAMP.

It was found that differences for horizontal components generally do not exceed 0.2 mm when the results obtained using full and elevation-only PCC models were compared. However, the vertical component reaches up to 0.5 mm in some cases. It should be noted that such differences are negligible in most surveying work. In consequence, for measurements not demanding the highest accuracy, elevation-only models can be used.

On the other hand, it should be remembered that the results obtained are derived from comparing the values obtained from GNSS observations processing using the full PCC model and the elevation-only one included in it. In such a case, both types of models have the same values of the MPC vector. When the model derived from the relative calibration and transformed to the absolute one is used, some additional differences between the components of the MPC vector should be expected, which in turn will result in larger differences in the position components. This issue is worth further study.

Acknowledgments

The authors acknowledge the EPN providers for the RINEX observation files. We also thank the Centre of Orbit Determination in Europe (CODE) for providing high accurate GNSS products. Special thanks to Zhou et al. for the free sharing of the GAMP software.

References

Baire Q., Bruyninx C., Legrand J., Pottiaux E., Aerts W., Defraigne P., Bergeot N., Chevalier J.M. (2013). Influence of different GPS receiver antenna calibration models on geodetic positioning. GPS Solution, vol. 18, pp. 529–539. https://doi.org/10.1007/s1029 1-013-0349-1.

Bakuła M., Przestrzelski P., Kaźmierczak R. (2015) Reliable Technology of Centimeter GPS/GLONASS Surveying in Forest Environments. IEEE Transactions on Geoscience and Remote Sensing, vol. 53, no. 2, pp. 1029–1038. https://doi.org/10.1109/TGRS.2014.2332372.

Bartolomé J., Maufroid X., Fernandez-Hernandez I., López-Salcedo J., Seco-Granados G. (2014). Overview of Galileo System. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-1830-2_2.

Bilich A., Mader G. (2010). GNSS absolute antenna calibration at the National Geodetic Survey. In: Proceedings ION GNSS 2010, Institute of Navigation, Portland, Oregon, OR, 21–24 Sepetember 2010, pp. 1369–1377.

Bozza V., Mancini L., Sozzetti A. (2016) Methods of detecting Exoplanets, chapter one: The Radial Velocity Method for the Detection of Exoplanets. Springer International Publishing, pp. 3–86. https://doi.org/10.1007/978-3-319-27458-4_1.

Dawidowicz K. (2011) Comparison of Using Relative and Absolute PCV Corrections in Short Baseline GNSS Observation Processing. Artificial Satellites, vol. 46, no. 1, pp. 19–31. https://doi.org/10.2478/v10018-011-0009-z.

Dawidowicz K., Krzan G., Świątek K. (2014) Urban area GPS positioning accuracy using ASG-EUPOS POZGEO service as a function of session duration. Artificial Satellites, vol. 49, no. 1, pp. 33–42. https://doi.org/10.2478/arsa-2014-0003.

Dawidowicz K., Krzan G. (2016). Analysis of PCC model dependent periodic signals in GLONASS position time series using Lomb–Scargle periodogram. Acta Geodynamica et Geomaterialia, vol. 13, pp. 299–314. https://doi.org/10.13168/AGG.2016.0012.

Dawidowicz K. (2019) Sub-hourly precise point positioning accuracy analysis – case study for selected ASG-EUPOS stations. Survey Review, vol. 52, no. 373, pp. 341–351. https://doi.org/10.1080/00396265.2019.1579988.

Dawidowicz K., Rapiński J., Śmieja M., Wielgosz P., Kwaśniak D., Jarmołowski W., Grzegory T., Tomaszewski D., Janicka J., Gołaszewski P., et al. (2021). Preliminary Results of an Astri/UWM EGNSS Receiver Antenna Calibration Facility. Sensors, vol. 21, no. 4639. https://doi.org/10.3390/s21144639.

Görres B., Campbell J., Becker M., Siemes M. (2006). Absolute calibration of GPS antennas: laboratory results and comparison with field and robot techniques. GPS Solution, vol. 10, pp. 136–145. https://doi.org/10.1007/s10291-005-0015-3.

Hu Z., Zhao Q., Chen G., Wang G., Dai Z., Li T. (2015). First Results of Field Absolute Calibration of the GPS Receiver Antenna at Wuhan University. Sensors, vol. 15, pp. 28717–28731. https://doi.org/10.3390/s151128717.

Kersten T., Krzan G., Dawidowicz K., Schön, S. (2022). On the Effect of Antenna Calibration Errors on Geodetic Estimates. In: J.T. Freymueller, L. Sánchez (ed.), Geodesy for a Sustainable Earth. International Association of Geodesy Symposia, vol. 154. Springer, Cham. https://doi.org/10.1007/1345_2022_153.

Krzan G., Dawidowicz K., Wielgosz P. (2020). Antenna phase center correction differences from robot and chamber calibrations: The case study LEIAR25. GPS Solution, vol. 24. https://doi.org/10.1007/s10291-020-0957-5.

Lyard F., Lefevre F., Letellier T., Francis O. (2006). Modelling the global ocean tides: modern insights from FES2004. Ocean Dynamics, vol. 56, pp. 394–415. https://doi.org/10.1007/s10236-006-0086-x.

Pengfei C., Wei L., Jinzhong B., Hanjiang W., Yanhui C., Hua W. (2011). Performance of precise point positioning (PPP) based on uncombined dual-frequency GPS observables. Survey Review, vol. 43, pp. 343–350. https://doi.org/10.1179/003962611X13055561708588.

Riddell A., Moore M., Hu G. (2015). Geoscience Australia's GNSS Antenna Calibration Facility: Initial Results. In Proceedings of the International Global Navigation Satellite Systems Society IGNSS Symposium, Gold Coast, Australia, 14–16 July 2015.

Scargle J.D. (1998) Studies in astronomical time series analysis. Astrophysical Journal, vol. 26, pp. 835–853. https://doi.org/10.1086/160554.

Schön S., Kersten T. (2013). On Adequate Comparison of Antenna Phase Center Variations. AGU Fall Meeting, 09–13 December, San Francisco, USA. Washington D.C. American Geophysical Union. https://doi.org/10.15488/4619.

Siejka Z. (2016) Opracowanie sieci wektorowej GNSS, zintegrowanej z pomiarami klasycznymi na przykładzie osnowy kolejowej (*Adjustment od GNSS vector network, integrated woth classic surveying on the example of railway network*). Journal of Civil Engineering, Environment and Architecture, vol. 62, no. 4, pp. 417–426. https://doi.org/10.7862/rb.2015.206.

Sieradzki R., Paziewski J. (2015) Study on reliable GNSS positioning with intense TEC fluctuations at high latitudes. GPS Solutions, vol. 20, pp. 553–563. https://doi.org/10.1007/s10291-015-0466-0.

Townsend R.H.D. (2010) Fast calculation of Lomb-Scargle periodogram using graphics processing units. Astrophysical Journal, vol. 191, pp. 247–253. https://doi.org/10.1088/0067-0049/191/2/247.

Tupek A., Zrinjski M., Švaco M., Barković Đ. (2023). GNSS Receiver Antenna Absolute Field Calibration System Development: Testing and Preliminary Results. Remote Sensing, vol. 15, no. 4622. https://doi.org/10.3390/rs15184622.

Vaníček P. (1971) Further development and properties of the spectral analysis by least-squares. Astrophysics Space Science, vol. 12, pp. 10–33. https://doi.org/10.1007/BF00656134.

Wang N., Yuan Y., Li Z., Montenbruck O., Tan B. (2016). Determination of differential code biases with multi-GNSS observations. Journal of Geodesy, vol. 90, no. 3, pp. 209–228. https://doi.org/10.1007/s00190-015-0867-4.

Willi D., Lutz S., Brockmann E., Rothacher M. (2020). Absolute field calibration for multi-GNSS receiver antennas at ETH Zurich. GPS Solution, vol. 24, no. 28. https://doi.org/10.1007/s10291-019-0941-0.

Wübbena G., Menge F., Schmitz M., Seeber G., Volksen C. (2000). A NewApproach for Field Calibration of Absolute Antenna Phase Centre Variations. Navigation Journal of the Institute of Navigation, vol. 44. https://doi.org/10.1002/j.2161-4296.1997.tb02346.x.

Zeimetz P., Kuhlmann H. (2008). On the Accuracy of Absolute GNSS Antenna Calibration and the Conception of a New Anechoic Chamber. In: Proceedings of the FIG Working Week 2008, Stockholm, Sweden, 14–19 June.

Zhou F., Dong D., Li W., Jiang X., Wickert J., Schuh H. (2018). GAMP: An open-source software of multi-GNSS precise point positioning using undifferenced and uncombined observations. GPS Solution, vol. 22, no. 33. https://doi.org/10.1007/s10291-018-0699-9.