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Renata Pelc-Mieczkowska[1]

Preliminary Analysis of the Applicability of the GPS PPP Method in Geodynamic Studies

Abstract: GNSS station movements as an indicator of the movement of the Earth's crust are determined by many researchers with the use of various position and trend determination methods. One of such methods is PPP method which allows the determination of a trend for the station without a correlation (direct determination of the position of each station separately). To achieve accuracy comparable with relative positioning, there is the need to use external, high-precision data or models (e.g. precise satellite orbits and clocks, ionosphere and troposphere models, etc.) while the PPP method is applied.

The main purpose of the presented research is preliminary analyses of the results of processing daily GPS observations from permanent stations with the use of the PPP method. Daily GPS observational data in RINEX format have been acquired from a total of nine selected GNSS permanent stations from the Polish ASG EUPOS and the Ukrainian UA-EUPOS/ZAKPOS systems. As external data for PPP solutions JPL products have been used. A seven-year time series was created for each station.

Keywords: GNSS, PPP, crustal movements

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[1] University of Warmia and Mazury in Olsztyn, Faculty of Geoengineering, Olsztyn, Poland, email: renata.pelc@uwm.edu.pl
ORCID ID: https://orcid.org/0000-0001-7064-6745

1. Introduction

The study of the movements of the Earth's crust is based on the cyclic or permanent determination of station coordinates. This determination may be implemented as a relative or absolute [1]. Precise levelling and triangulation used historically for relative vertical and horizontal crust movement determination are the methods requires repeated measurements at the same, clearly marked points under the same observational conditions and the determination of control points outside the examined area [2–4]. The Global Navigation Satellite System (GNSS) provides access to global reference network and the rapid development of the network of permanent (GNSS) stations that has been going on for decades ensures constant and permanently observed points. This is an excellent source of data for geodynamic studies. Trends of GNSS stations are determined by many researchers with the use of various GNSS data processing methods [5–7], mostly GNSS net solutions (relative positioning). However, the use of differential methods is burdened with determining a trend with correlation. That is why Precise Point Positioning (PPP) method is of interest to researchers in the study of crustal movements. The main purpose of the presented research is preliminary analyses of the results of processing GPS observations from permanent GNSS stations with the use of the PPP method to assess its applicability in geodynamic studies.

2. Precise Point Positioning

Precise Point Positioning (PPP) is a method to perform point positioning using undifferenced observations from just a single GNSS receiver at the user's position, without requiring direct access to the observational data from one or more reference stations with known coordinates. In such a way, the spatial operating range limit of differential techniques is overcome, as well as the need for simultaneous observations at both user and reference receivers [8]. In contrast to differential methods, in which an error in the base station coordinates would translate into the other stations, in the PPP method the position of each station is determined independently and this is the main advantage of the PPP method in the context of geodynamic studies [9]. On the other hand, the PPP method is widely and successfully used for other tasks like signal analysis for total neutral atmosphere delay determination [10, 11]. What is more, the PPP method seems to be a method which reduces the computation burden for applications, of course only if there is no need to determine co-variances among parameters of different stations [12].

As is widely known, the main reason why differential methods are used is their ability to limit the number of errors such as ephemeris errors, satellite clock errors, ionospheric and tropospheric delays and others. In Table 1 biases and errors affecting GNSS positioning have been listed [8]. To step forwards from single point positioning (SPP) to precise point positioning and ensure centimetre accuracy, the PPP method requires access to several, high quality, external corrections for errors sources listed in Table 1 [13–18].

Table 1. GNSS biases and errors sources

Satellite Specific Errors	Precise satellite clock corrections
	Satellite antenna phase centre offset
	Satellite antenna phase centre variations
	Precise satellite orbits
	Relativity term
	Satellite antenna phase wind-up error
	Group delay differential
Atmospheric Errors	Tropospheric delay
	Ionospheric delay
Receiver Specific Errors	Receiver antenna phase centre offset and variations
	Receiver antenna phase wind-up
Geophysical Models	Solid earth tide displacements
	Ocean loading
	Polar tides
	Plate tectonic motion

Source: own study based on [8]

To mitigate satellite specific errors, in particular, satellite clock and orbits errors precise orbits and clock products are used. The abovementioned products have been provided by IGS as Ultra-rapid, Rapid and Final products since 1994 [19]. Currently, there are nine IGS Analysis Centers (AC) contributing to the IGS final products [20]. One of those centres is the Jet Propulsion Laboratory (JPL) which also provides their products at ftp://sideshow.jpl.nasa.gov/pub/JPL_GNSS_Products/ FTP site. The format of this data is dedicated to GipsyX Software.

Other groups of errors like Atmospheric Delay, Receiver Specific Errors and that caused by geodynamics effects can be mitigated by the use of some models or external sources like IGS ionospheric TEC grid, tropospheric zenith path delay and Earth Rotation IGS products.

It should be emphasized that the use of uniform (calculated based on the same set of permanent stations, by using the same algorithm) PPP corrections and daily observations (the same constellation day after day) guarantees that high precision (within single millimetres) of the determined station positions in the time series may be obtained. This precision is crucial in the case of horizontal and vertical trend determination.

3. GipsyX Software

GipsyX software is the GNSS-Inferred Positioning System and Orbit Analysis Simulation Software package. GipsyX, like its predecessor GIPSY-OASIS, is developed by the Jet Propulsion Laboratory (JPL) of California Technical Institute, and maintained by the Near-Earth Tracking Applications and Systems groups (https://gipsy-oasis.jpl.nasa.gov). This software package is focused on GNSS post-processing in Precise Point Positioning mode for science and allows expansion to the other radio-metric data types like DORIS or SLR. Single receiver ambiguity resolution using JPL's orbit and clock products for GPS is the most important feature from which geodynamic studies benefits. What is more, there are complex models of geometric effects and models of force models for Earth orbits implemented in GipsyX package (Tab. 2).

Table 2. Models implemented in GipsyX

Complex models of geometric effects
Sub-daily and long-period Earth orientation (polar motion and UT1) variations Solid Earth body tide deformations Ocean tide loading deformations Transmitter and receiver antenna calibrations GPS and GLONASS attitude models, and preliminary attitude models for Galileo and BeiDou Phase windup Quaternion input for vehicle attitude (e.g. Earth Orbiters, aircraft) General relativity Crustal plate motion (reference frame) Second order ionosphere Dry and wet troposphere mapping functions (GPT, GMF, VMF, Niell)
Complex models of force models for Earth orbiters
High order Earth static gravity fields Atmospheric drag Solid Earth, ocean, and pole tide gravity fields Solar and terrestrial radiation pressure Relativity Third body effects from Sun, Moon, and planets Custom and general models of spacecraft shape

Source: https://gipsy-oasis.jpl.nasa.gov

The main tasks that are steps to study the Earth's crust movements, based on data from the GNSS station, can be accomplished using several GipsyX program modules. The rinexFetch.py module is used for the first task of fetching daily observations from the GNSS station. As input parameters, start data and the station name and server name should be given. The script creates a characteristic directory structure in the path indicated. In the parent directory, whose name is the same as the name of the station, there are separate directories for specific years, in which there are subdirectories for individual days to which daily observations in Hatanaka-compressed format are downloaded. Currently, among others, the following servers are supported: sideshow.jpl.nasa.gov; cddis.gsfc.nasa.gov; igs.bkg.bund.de/IGS; igs.ign.fr. To estimate the position of a GNSS station for a daily observational file, the gd2e.py module is used. As an input parameter, rinex file path should be given. The script operates in PPP mode as the default one while -rnxFile argument is called and then ocean load modelling is off what is appropriate for future geodynamics studies. The GNSS Products (antenna models, final ephemerides and clocks etc.) are downloaded from JPL server while gd2e is running by default. To get the covariance matrix -gdCov argument is required. Subsequently, there is a set of scripts (netSplit.py, staFit.py, staSeries.py, staBreak.py, staEdit.py) for creating, fitting and computing of time series for the station; breaks and outliers detection and fitting seasonal terms and finally for station velocities determination as well as its sigma as a precision indicator. As an input, a smoothFinal.gdcov file for each day is required.

4. Material and Methods

To analyse the accuracy of the PPP method to assess its applicability in geodynamic studies, nine permanent GNSS stations belong to EUREF Permanent GNSS Network (EPN) were chosen (Fig. 1). Five of these stations belong to the ASG-EUPOS system and are evenly distributed throughout Poland. The other four are located in eastern Ukraine and belong to UA-EUPOS/ZAKPOS system. The data from the period of 7 years from January 1, 2012, to December 31, 2018, was taken into consideration. The daily observational data from stations was downloaded in the compressed RINEX Hatanaka format from sideshow.jpl.nasa.gov server.

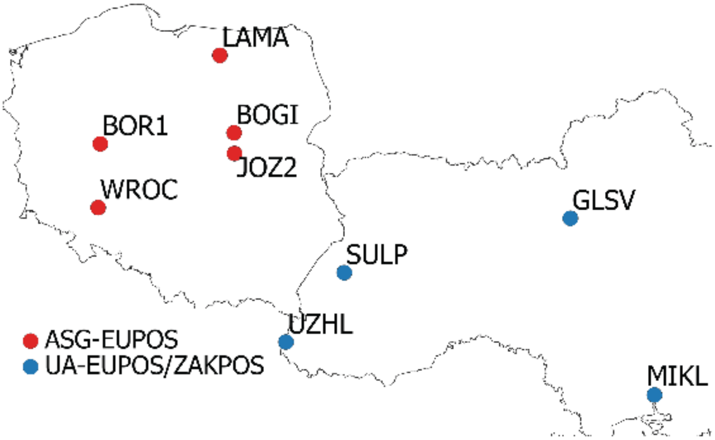

Fig. 1. Localization of chosen GNSS stations of Polish ASG-EUPOS and the Ukrainian UA-EUPOS/ZAKPOS systems

The station coordinates from daily observations as well as covariance matrices have been estimated in the GipsyX package. GPS observations and PPP mode were used. The GNSS Products (antenna models, final ephemerides and clocks and Earth orientation parameters) were downloaded automatically from the JPL server: (https://sideshow.jpl.nasa.gov/pub/JPL_GNSS_Products/Final). From June 2018, thanks to third reprocessing campaign orbits and clocks products in JPL_GNSS_Products/Final are IGS14 reference frame. This prevents the need to convert coordinates between reference systems.

To calculate dry and wet components of Zenith Tropospheric Delay, a Global Mapping Function was used. The results were obtained as geodetic (latitude, longitude and height) coordinates.

Subsequently, a time series $E(t)$, $N(t)$ and $V(t)$ for each station was created. For each time series, the least-squares trend line was fitted in the first iteration. In the next step, seasonal terms were fitted. Based on the analysis of residuals, the outlier observations were removed and breaks detected. Triple standard deviation was assumed as the outlier detection criterion.

5. Results

In the presented research, daily GPS observational data from January 1, 2012, to December 31, 2018, from nine GNSS permanent stations was used. In the analysed sets, the unavailability of observational data was up to several dozen days and there were evenly distributed in the set. The exceptions were JOZ2, SULP and UZHL stations. In the case of the JOZ2 station, there is no data from day 82 in 2012 to the first day of 2013 (over 280 days gap). For the SULP station, there were no observations from more than 100 days in 2014 (from day 240 to day 342). The largest data deficiencies occurred at the UZHL station for which observations were not available from day 116 to day 311 in the year 2012, from day 110 to day 315 in the year 2013, and from day 293 in the year 2017 to the end of 2018, what makes two data gaps, about 200 days long each and over one year long the third one. Daily positions of each of the nine permanent stations were estimated using GipsyX software package with a PPP solution, as detailed in the Materials and Methods section. Postprocessing of daily observations using the PPP method allowed the estimation of X, Y, and Z station coordinates for each day with a sigma of about 2 mm, 1 mm and 2 mm respectively (Fig. 2). Only the coordinates obtained from 2013 from the BOGI station were several times less precise.

The obtained time series were statistically analyzed, some breaks detected, seasonality was taken into account and outliers over 3σ were deleted. The time series developed are shown in the Figures 3–11.

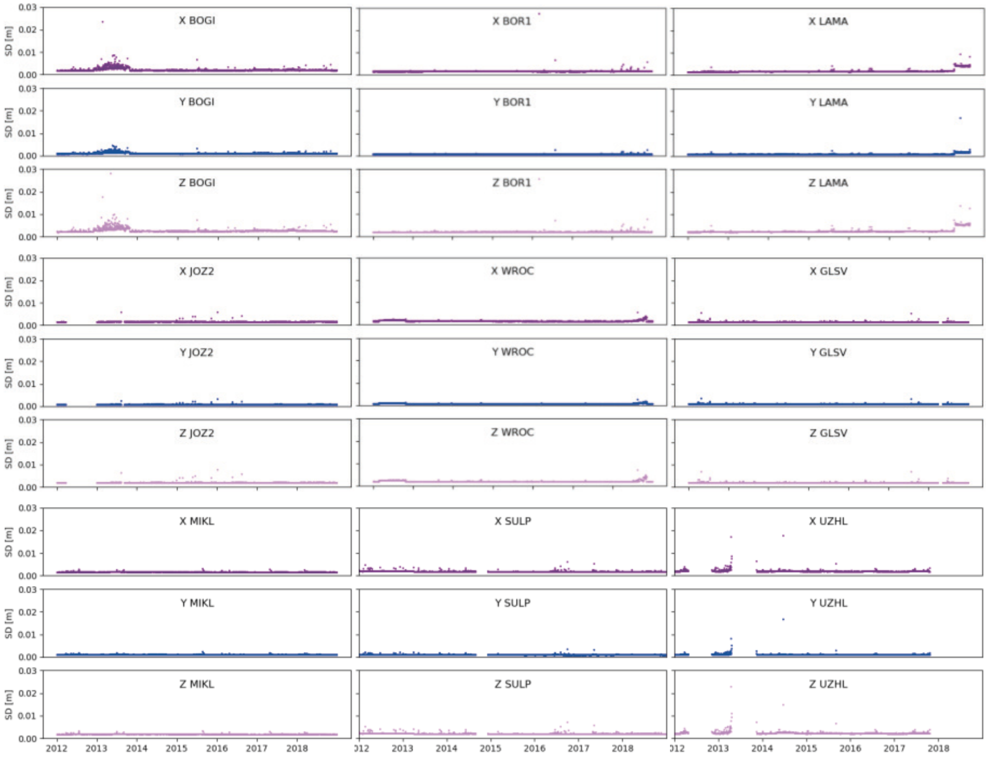

Fig. 2. Distribution of daily X, Y, Z PPP resolutions standard deviations

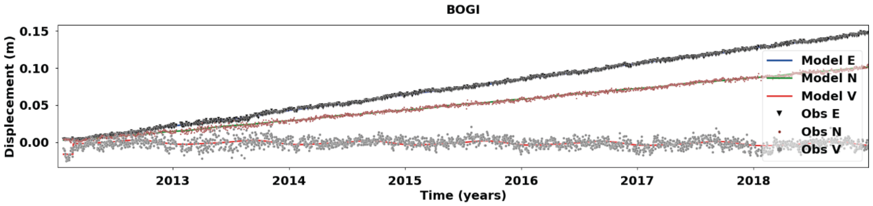

Fig. 3. Plot of observations and fit with seasonal terms BOGI station

Source: GipsyX software

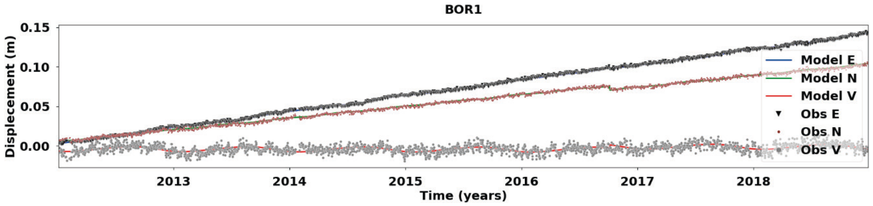

Fig. 4. Plot of observations and fit with seasonal terms BOR1 station

Source: GipsyX software

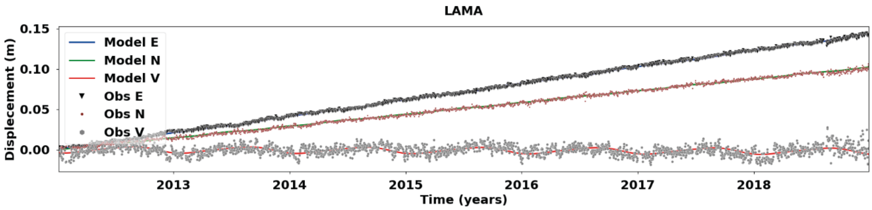

Fig. 5. Plot of observations and fit with seasonal terms LAMA station

Source: GipsyX software

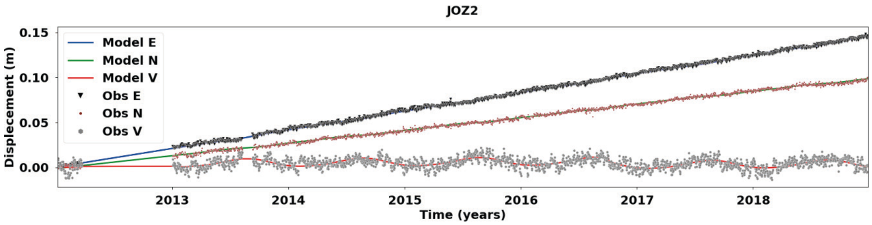

Fig. 6. Plot of observations and fit with seasonal terms JOZ2 station

Source: GipsyX software

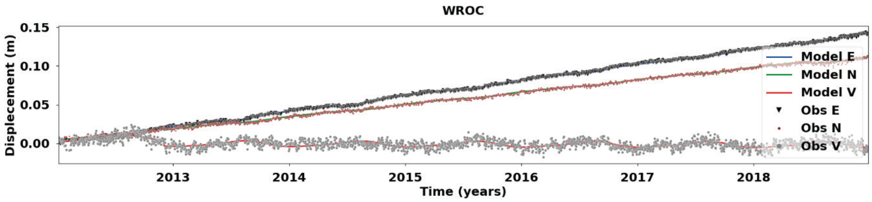

Fig. 7. Plot of observations and fit with seasonal terms WROC station

Source: GipsyX software

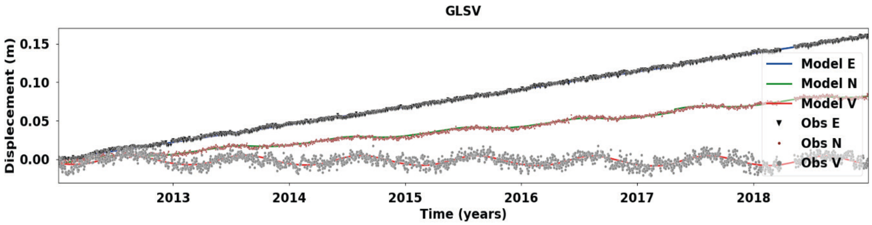

Fig. 8. Plot of observations and fit with seasonal terms GLSV station

Source: GipsyX software

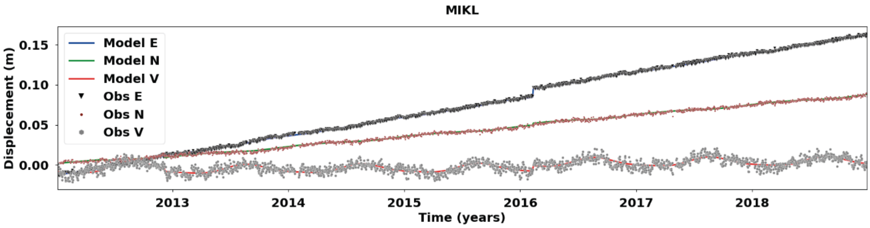

Fig. 9. Plot of observations and fit with seasonal terms MIKL station

Source: GipsyX software

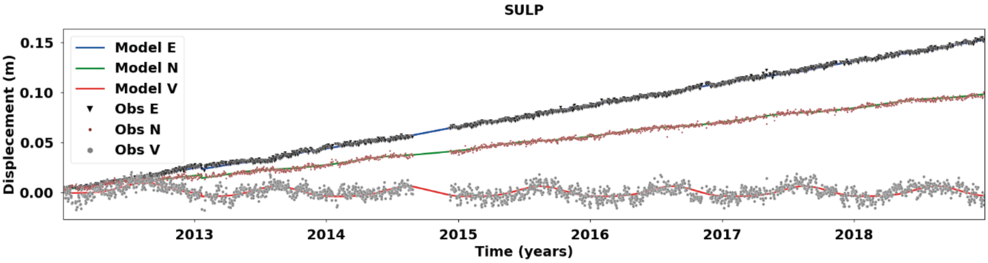

Fig. 10. Plot of observations and fit with seasonal terms SULP station

Source: GipsyX software

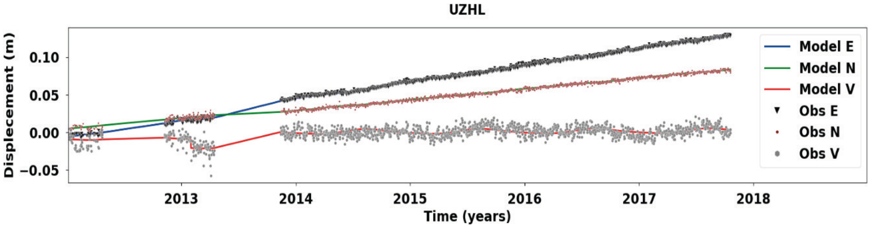

Fig. 11. Plot of observations and fit with seasonal terms UZHL station

Source: GipsyX software

Station velocities and their errors were calculated based on the time series developed. Velocities within 20 mm (Fig. 12) were obtained with a standard deviation of 0.01 mm in the east direction and with a value of several dozen mm with a standard deviation of 0.01 mm in the north direction. The Vertical velocities oscillate from −0.6 to +0.7 mm (Fig. 13) with an error of a few hundredths of a millimetre. The largest error of vertical trend determination of 0.07 mm occurred at the UZHL station, characterized by the largest lack of observational data (Tab. 3).

Table 3. GNSS stations velocities and velocities errors

Station	Velocities [mm/year]			Std [mm/year]		
	E	N	V	E	N	V
BOGI	21.10	14.51	−0.37	0.01	0.01	0.03
BOR1	20.30	14.85	−0.19	0.01	0.01	0.04
JOZ2	20.78	14.12	−0.58	0.01	0.02	0.05
LAMA	20.48	14.61	−0.29	0.01	0.01	0.03
WROC	20.19	15.87	−0.28	0.01	0.01	0.03
GLSV	22.91	12.00	−0.38	0.01	0.02	0.04
MIKL	23.19	12.54	0.68	0.01	0.02	0.06
SULP	21.78	14.19	0.04	0.01	0.01	0.04
UZHL	22.27	14.47	0.36	0.02	0.02	0.07

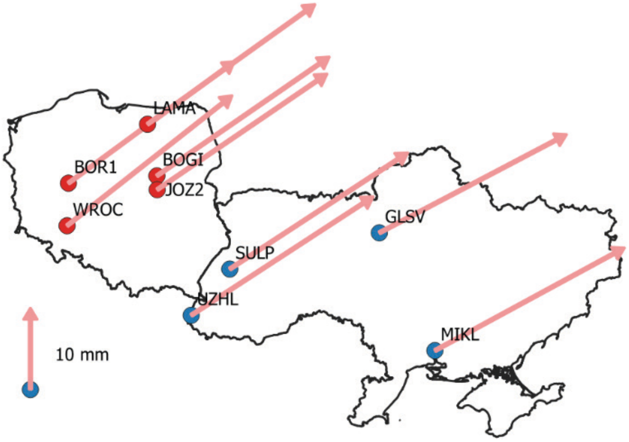

Fig. 12. East and north components of stations velocities

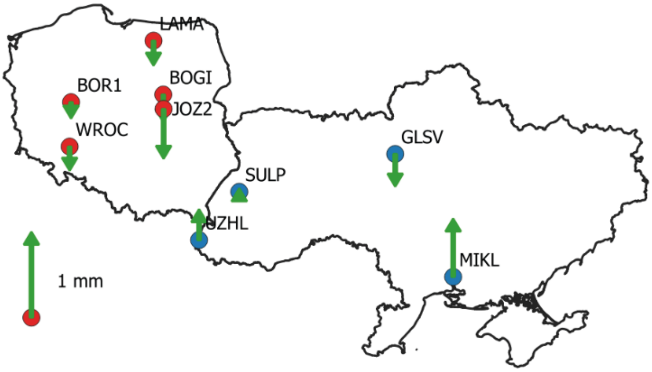

Fig. 13. Up component of stations velocities

6. Conclusions

Analysis of the PPP method accuracy to assess its applicability in geodynamic studies was the aim of the presented study. Seven years of daily GPS observations from nine GNSS permanent stations were processed. Coordinates from each daily observation set were estimated with the use of the PPP method, which was assumed to be appropriate for geodynamics research because the position of each station is computed separately. This allows the determination of the trends of each station without a correlation. According to the literature, the accuracy of position determination in the PPP method is similar to the accuracy of RTK / RTN methods and amounts to several centimetres [18]. Computing the daily stations' observations, X, Y and Z coordinates were obtained with a standard deviation of 2 mm, 1 mm and 2 mm respectively. Analysing the seven-year length time series, a horizontal trends of stations was determined with a standard deviation of 0.01 mm and a vertical movement trends with an accuracy of 0.04 mm, except for the JOZ2, GLSV and UZHL station for which the vertical trend determination errors reached 0.05 mm, 0.06 mm and 0.07 mm respectively. Such accuracies are suitable for geodynamic studies, taking into account the horizontal velocities of the tested stations within two cm per year and vertical velocities from −0.6 mm to +0.7 mm per year. Further research should analyse data from additional GNSS systems (GLONASS, GALILEO and Beidou).

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