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DETERMINATION OF THE PRECISE COORDINATES OF THE GPS REFERENCE STATION IN OF A GBAS SYSTEM IN THE AIR TRANSPORT

This paper presents results of research concerning determination of the GPS reference station coordinates located on the grounds of an EPDE airport in Deblin. The study uses a mathematical model of the PPP measurement technique in order to determine the coordinates of the reference station using the real GPS code-phase observations. The computations of the coordinates of the GPS reference station were carried out in numerical applications CSRS-PPP, APPS and GAPS. In this research was found that the accuracy of finding solutions to the XYZ geocentric coordinates of the reference station REF1 between solutions CSRS-PPP, APPS and GAPS ranges from 0.01 m to 0.13 m. In addition, the accuracy of determining the XYZ geocentric coordinates from the PPP method related to the GPS differential solution ranged from 0.01 m to 0.11 m.

Keywords: *GPS, reference station, PPP method, accuracy, XYZ geocentric coordinates*

1 Introduction

One of the elements of activating the GBAS augmentation system in air transport is the construction of a network of the RTK GPS permanent stations, located in the vicinity of both civil and military airports [1]. Ultimately, the GBAS augmentation system should consist of three components: the base station RTK GPS located at the airport, the mobile GPS receiver installed on board of an aircraft and transmission links of satellite data between the base station and the mobile receiver [2]. Such a configuration of components in the GBAS system ensures optimum utilization, during the precise positioning of an aircraft in the air transport. Within the GBAS augmentation system, it is possible to differentiate two basic methods of aircraft positioning: the DGPS differential technique and the RTK-OTF differential technique [3]. In the DGPS differential technique, the position of an aircraft is determined based on the GPS code observations, registered by the base station and the mobile receiver. On the other hand, in the RTK-OTF differential technique, the position of an aircraft is determined based on the GPS phase observations, registered by the base station and the mobile receiver [4].

The rules for the implementation and operation of the GBAS augmentation system in the air transport are clearly defined by the International Civil Aviation Organization ICAO [5]. In the framework of the ICAO guidelines and recommendations, the GBAS system finds its practical application in the procedure of a precision approach (PA) to landing. Among the types of a precision approach, it is possible to distinguish a precision approach, Category I, Category II and Category III. It is worth mentioning that the construction of the GBAS system infrastructure is costly and time consuming and it requires appropriate training for air traffic control personnel. In Poland, the GBAS system is currently being implemented for Cracow Balice Airport [6].

According to ICAO, the GPS measurements in the area of an airport should be realized with accuracy better than 0.1 m. In addition, in the carrier phase DGPS technique, typical accuracy of the GPS navigation system is about 0.01÷0.05 m, whereas, in static measurements in the post-processing mode, the GPS navigation system accuracy is around 0.01÷0.02 m [7]. The reference station coordinates in an airport must be estimated with the high level accuracy. In this way, the GPS reference station can be applied in conception of the GBAS technical infrastructure in the airport.

The aim of this article was to determine coordinates of the base station RTK GPS as one of the components of the GBAS augmentation system in the air transport. The precise coordinates of the RTK GPS reference station were determined using the PPP universal measurement technique for the GPS code-phase observations. The precise coordinates of the reference station REF1 were in calculations specified in the geocentric XYZ frame. A flight test was conducted for the reference station REF1, located within the military airport EPDE in Deblin.

2 Research method

The mathematical model of the GPS reference station coorrdinates determination is based on using the observation equations from the PPP measurement

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technique, as follows [8]:

$$\begin{cases} P_3 = \rho + c\cdot(dtr - dts) + Trop + \mathrm{R}el + M_{P3} \\ L_3 = \rho + c\cdot(dtr - dts) + Trop + Rel + B_3 + \delta_{wu} + M_{L3} \end{cases} \quad (1)$$

where:
$P_3 = \alpha_1 P1 + \alpha_2 P2$ - linear combination "Ionosphere-Free" for the GPS code measurements,
$L_3 = \alpha_1 L1 + \alpha_2 L2$ - linear combination "Ionosphere-Free" for the GPS phase measurements,
$(P1, P2)$ - GPS code measurements,
$(L1, L2)$ - GPS phase measurements,

$\alpha_1 = +\frac{f_1^2}{f_1^2 - f_2^2}$, linear coefficient,
$\alpha_2 = -\frac{f_2^2}{f_1^2 - f_2^2}$, linear coefficient,

(f_1, f_2) - carrier frequencies in the GPS system,
ρ - geometric distance between the GPS satellites and the receiver; it contains information about the parameters of the Earth's rotation, accurate coordinates of the satellite antenna and receiver, satellite antenna phase centre and receiver antenna phase centre, geodynamic and tidal effects, speed of the continental plate, etc.

$$\rho = \sqrt{(X - X_s)^2 + (Y - Y_s)^2 + (Z - Z_s)^2},$$

(X, Y, Z) - coordinates of the GPS reference station in the XYZ geocentric frame,
(X_S, Y_S, Z_S) - position of the GPS satellite in orbit,
c - speed of light,
dtr - receiver clock bias for the GPS observations,
dts - satellite clock bias for the GPS observations,
Trop- tropospheric delay for the GPS observations,
Trop = *SWD* + *SHD*,
SHD - Slant Hydrostatic Delay,
SWD - Slant Wet Delay,
$SHD = mf_H \cdot ZHD$,
$SWD = mf_W \cdot ZWD$,
(mf_H, mf_w) - mapping function for hydrostatic and wet delay,
ZHD - Zenith Hydrostatic Delay,
ZWD - Zenith Wet Delay,
R*el* - relativistic effects for the GPS observations,
δ_{wu} - phase wind up,
B_3 - real value of uncertainty phase,
M_{P3} - multipath effect for the GPS code measurements,
M_{L3} - multipath effect for GPS phase measurements.

The searched parameters in the PPP measurement technique are: coordinates of the receiver $[X, Y, Z]$ (3 parameters), receiver clock bias correction *dtr* (1 parameter), phase uncertainty principle B_3 (determined for each visible GPS satellite, from 1 to n, n-number of satellites), Zenith Wet Delay *ZWD* (1 parameter). The mentioned parameters are determined by the least squares method in the sequential process, as below [9]:

$$Sx = (A_{PPP}^T \cdot P_{PPP} \cdot A_{PPP} + C_X^{-1})\ A_{PPP}^T \cdot P_{PPP} \cdot l_{PPP}, \quad (2)$$

where:
Sx- vector of searched parameters,
A_{PPP} - matrix of plan,
P_{PPP} - matrix of weights,
C_x - variance-covariance matrix of determined parameters in the XYZ geocentric frame in the PPP measurement technique,
$C_x = (A_{PPP}^T \cdot P_{PPP} \cdot A_{PPP} + C_x^{-1})^{-1} + C_n$,
C_n - variance matrix of disturbances of the measurement process,
l_{PPP} - vector of constant terms.

In the stochastic process, in the PPP measurement technique, the determined parameters are modelled as [10]:

- coordinates of the receiver of the GPS reference station as a constant value in the stochastic model,
- receiver clock bias correction as a stochastic white noise model.
- *ZWD* parameter as a stochastic model of a random walk,
- phase uncertainty as a constant value in a stochastic model.

3 Research experiment

In the research experiment, the authors verified an application of the described research method in an accurate determination of coordinates of the reference station RTK GPS. In the analyzed example, coordinates of the reference station REF1 were determined, located at the military airfield in Deblin EPDE (see Figure 1). In test, the daily GPS observations data from REF1 GNSS station were applied, with time interval of 1 s. The experiment was realized on 1st June 2010.

The research experiment exploited the GPS navigation data recorded by the Topcon HiperPro receiver, mounted at the reference station REF1 in Deblin. In particular, in this research the P1/P2 and phase L1/L2 code measurements in the GPS system were used. In the calculations, there was the PPP precise measurement technique was used in order to determine coordinates of the reference station REF1 in the XYZ geocentric frame. Within the conducted studies, the numerical calculations were made in three independent geodetic programmes, using the PPP measurement technique in order to determine the position of the GPS receiver in a static mode. In the calculations, the available free geodetic programmes were used: CSRS-PPP, APPS and GAPS [12].

For the purposes of the conducted numerical calculations, the configuration of the CSRS-PPP programme was set, as below:

- GNSS system: GPS,
- linear combination: „Ionosphere-Free",
- type of positioning: PPP absolute method,
- positioning mode: static,
- computational mode: post-processing,

Figure 1 *Localization of the REF1 reference station [11]*

- type of GPS observation: dual-frequency, non-difference, code-phase observations,
- format of GPS observations: RINEX 2.xx,
- precise satellite ephemerides and satellite clocks: NRCan „Final"-type precise products,
- characteristics of the phase centre of the satellite/receiver antenna: based on the IGS ANTEX file,
- ultimate coordinate frame: ITRF2008 (reference epoch 2005.0),
- elevation mask: 10°,
- interval of calculations: 1 s,
- confidence level of the solution: 95%
- source of ephemeris and clock data: based on "SP3" and "CLK" formats
- weighting of measurement results: applied;
- gross error detection in the GPS measurements: applied,
- multipath effect: applied,
- relativistic effects: applied,
- Sagnac effect: applied
- correction of the GPS signal time from satellite to receiver: applied
- meteorological data for the tropospheric model: based on the GPT model
- model of troposphere: GPT (Global Pressure and Temperature) model,
- mapping function: GMF (Global Mapping Function),
- ionospheric delay: eliminated with the linear combination "Ionosphere-Free"
- accuracy of the GPS code observations a priori: 2 m,
- accuracy of the GPS phase observations a priori: 0.015 m,
- correction of receiver clock: determined,
- final recording of determined coordinates of the receiver: geocentric XYZ and ellipsoidal BLh coordinates.
- ZWD parameter: the hydrostatic delay is determined,
- uncertainty phase: determined for each tracked satellite,
- time of observation: GPS Time,
- hardware delay DCB: eliminated with the linear combination „Ionosphere-Free".

For the purposes of the conducted numerical calculations, the configuration of the APPS programme was set, as below:

- GNSS system: GPS,
- linear combination: „Ionosphere-Free",
- positioning mode: absolute method PPP,
- positioning mode: static,
- computational mode: post-processing,
- type of the GPS observations: dual-frequency, non-difference, code-phase observations,
- format of the GPS observations: RINEX 2.xx,
- precise satellite ephemerides and satellite clocks: JPL „Final"-type precise products,
- characteristics of the phase centre of the satellite/receiver antenna: based on the IGS ANTEX file,
- ultimate coordinate frame: ITRF2008 (reference epoch 2005.0),
- elevation mask: 7.5°,
- interval of calculations: 1 s,
- confidence level of solution: 95%
- final recording of determined coordinates of the receiver antenna: geocentric XYZ and ellipsoidal BLh coordinates,
- gross error detection with the GPS measurements: based on the programme TurboEdit,
- multipath effect: applied,
- relativistic effects: applied,
- Sagnac effect: applied
- the receiver clock bias: determined at an interval of 300 s,
- tropospheric delay: ZWD parameter (Zenith Wet Delay) and tropospheric gradients are determined at an interval of 300 s,
- uncertainty phase: determined for each tracked satellite,

- ionospheric delay: eliminated with the linear combination “Ionosphere-Free”
- time of observation: GPS Time,
- hardware delay DCB: eliminated with the linear combination „Ionosphere-Free“.

For the purposes of the conducted numerical calculations, the configuration of the GAPS programme was set, as below:

- GNSS system: GPS system,
- File Type: RINEX: RINEX 2.xx,
- positioning mode: static,
- computational mode: post-processing,
- source of precise orbital data and GPS satellite clocks: IGS „Final" type precision ephemeris,
- intervals of precision orbital data and the GPS satellite clocks: 15 minutes,
- method of determining the satellite position and the GPS clocks from precision ephemeris: Lagrange polynomial model,
- used GPS observations: code observations (P1/P2) and phase observations (L1/L2)
- linear combination: Ionosphere-Free,
- weighting of the GPS observations: applied, in the function of the elevation angle,
- a priori standard deviation of code observations: 2 m,
- a priori standard deviation of phase observations: 1.5 cm,
- elevation cutoff angle (elevation mask): 10 degrees,
- interval of calculations: 1 s,
- maximum number of iterations in the stochastic process: 5,
- characteristics of the phase centre of the satellite/GPS receiver antenna: based on the IGS ANTEX file,
- initial values of aircraft coordinates: based on the RINEX file header,
- reference frame: global system ITRF2008,
- correction of receiver clock: eliminated,
- method of determination of the uncertainty phase: real Float value,
- final coordinates of the aircraft: geocentric coordinates (XYZ) and ellipsoidal coordinates (BLh)
- reference time: GPS Time,
- hardware delay DCB P1-P2: eliminated in the linear combination „Ionosphere-Free“.
- ionospheric delay VTEC: first term of expansion of ionospheric delay, eliminated in the linear combination Ionosphere-Free,
- higher order ionospheric effects: not applied,
- satellite receiver orientation effect: applied,
- relativistic effect: applied
- movement of the pole correction, tidal effects, sea level and atmospheric pressure, movement of the continental plate, etc.: applied,
- Sagnac effect: applied
- model of troposphere: VMF1-gridded - VMFG_20100601,
- Zenith Hydrostatic Delay parameter: determined,
- value of the hydrostatic part of the tropospheric delay (ZHD) a priori: 2.332 m,
- mapping function of the tropospheric delay: Vienna mapping function.

4 Results and discussion

Findings of obtained results of the reference station REF1 coordinates, based on the CSRS-PPP, APPS and GAPS are shown in Tables 1, 2 and 3, respectively.

Table 1 shows results of the X coordinate for the reference station REF1. The scatter of results of the X coordinate, for the reference station REF1, in the solution CSRS-PPP, APPS and GAPS, equals approximately ±0.02÷0.03 m. Table 2 shows the results of the Y coordinate for the reference station REF1. The scatter of results for the Y coordinate, for the reference station REF1, in the solution CSRS-PPP, APPS and GAPS, also equals approximately ± 0.02÷0.13 m.

Table 3 shows results of the Z coordinate for the reference station REF1. The scatter of results for the Z coordinate, for the reference station REF1, in the solution CSRS-PPP, APPS and GAPS, also equals approximately ± 0.01÷0.06 m.

In Tables 4, 5 and 6 are presented the accuracy values in the form of standard deviations of determining the X, Y and Z coordinates of the reference station REF1, respectively. In Table 4 are shown results of the X coordinate mean values for the reference station REF1 in the CSRS-PPP, APPS and GAPS solution. The smallest value of the standard deviation for the X coordinate equals 0.01 m in the GAPS programme, whereas the largest one is equal to 0.03 m in the CSRS-PPP programme.

In Table 5 are presented results of the Y coordinate mean values for the reference station REF1 in the CSRS-PPP, APPS and GAPS solution. The smallest value of the standard deviation for the Y coordinate equals 0.02 m in the GAPS programme, whereas the largest one is equal to 0.07 m in the CSRS-PPP programme. In Table 6, there are results of mean values of the Z coordinate for the reference station REF1 in the CSRS-PPP, APPS and GAPS solution. The smallest value of the standard deviation for the Z coordinate equals 0.01 m in the GAPS programme, whereas the largest one is equal to 0.03 m in the CSRS-PPP programme.

Within the conducted experimental research, the authors verified the determined coordinates of the reference station REF1 in the PPP measurement technique. In the control test, the coordinate values of the reference station REF1, in the PPP measurement technique, were compared to the catalogue coordinates determined in the AUSPOS programme. In particular, the article compared the values of determined coordinates of the REF1 station in the geodetic XYZ frame. The catalogue coordinates of the REF1 reference station were determined in the AUSPOS programme. The programme AUSPOS ver. 2.2 is a free application tool to make computations of the GNSS receiver in a static mode, for the GPS phase observations [13]. The computational strategy for the determination of

***Table 1** Results of the X coordinate of the REF1 reference station*

Software	X coordinate [m]
CSRS-PPP	3687932.49
APPS	3687932.46
GAPS	3687932.47

***Table 2** Results of the Y coordinate of the REF1 reference station*

Software	Y coordinate [m]
CSRS-PPP	1480229.26
APPS	1480229.13
GAPS	1480229.24

***Table 3** Results of the Z coordinate of the REF1 reference station*

Software	Z coordinate [m]
CSRS-PPP	4972325.89
APPS	4972325.83
GAPS	4972325.88

***Table 4** Results of the X coordinate standard deviation of the REF1 reference station*

Software	Standard deviation of X coordinate [m]
CSRS-PPP	0.03
APPS	0.02
GAPS	0.01

***Table 5** Results of the Y coordinate standard deviation of the REF1 reference station*

Software	Standard deviation of Y coordinate [m]
CSRS-PPP	0.07
APPS	0.06
GAPS	0.02

***Table 6** Results of the Z coordinate standard deviation of the REF1 reference station*

Software	Standard deviation of Z coordinate [m]
CSRS-PPP	0.03
APPS	0.02
GAPS	0.01

the GNSS receiver coordinates in the AUSPOS programme is as follows:

- applied source software: Bernese GNSS Software Version 5.2,
- GNSS system: GPS system,
- preliminary GNSS data processing: elimination and repairing of cycle slips by means of triple difference phase technique for the phase observations L1/L2 in the GPS system; it is also possible to use various linear combinations to detect phase cycle slips,
- elevation mask: 7^0,
- interval of calculations: every 3 minutes, data cleaning every 30 seconds,
- weighting of the GPS observations: in the function of the elevation angle, $1/\sin^2(e)$, e- elevation angle,
- solution strategy: phase double-difference for the linear combination "Ionosphere-Free",
- characteristics of the phase centre of the satellite/receiver antenna: based on the ANTEX file,
- model of tropospheric delay: for the Zenith Hydrostatic Delay (ZHD), GMF model with DRY-GMF mapping function, tropospheric gradients G_N and G_E determined every 24 hours, Zenith Hydrostatic Delay determined every 2 hours with Wet-GMF mapping function,
- mapping function: GMF for tropospheric delay,
- ionospheric delay: the first term of expansion of ionospheric delay eliminated in the linear combination Ionosphere-Free, the 2nd and 3rd order ionospheric effects are used; moreover, it is possible to determine the global ionospheric maps to determine the uncertainty phase,
- tidal effects: on the recommendation of IERS 2010, effect of sea-level pressure is disregarded,
- atmospheric pressure: applied,
- source of orbital data: on the basis of IGS products,
- information about the parameters of the Earth's rotation: based on the IGS products,
- reference frame: ultimately ITRF2008,
- confidence level of solution: 95%,
- geoid model: EGM2008,
- method of determination of coordinates: method of least squares in the stochastic process,
- stochastic model of determining the GNSS receiver coordinates: modelling with boundary conditions imposed on the parameters, the change in horizontal deviation of horizontal coordinates equals 1 mm and for the vertical coordinate it is 2 mm.
- uncertainty phase solution: for vector's length of 180-6,000 km there is a strategy „Code-Based", for vector's length of 18-200 km there is a strategy „Phase-Based L5/L3", for vector's length of 18-2,000 km there is a strategy „Quasi-Ionosphere-Free (QIF)," for vector's length of 0-20 km there is a strategy „Direct L1/L2".
- final recording of determined coordinates of the receiver: geocentric XYZ and ellipsoidal BLh coordinates.

The catalogue coordinates of the reference station REF1 from the AUSPOS programme are as follows:

- for the X coordinate: 3687932.48 m with the standard deviation of 0.01 m,
- for the Y coordinate: 1480229.15 m with the standard deviation of 0.01 m,

Table 7 The positioning accuracy of the REF1 reference station

Parameter	CSRS-PPP vs AUSPOS	APPS vs AUSPOS	GAPS vs AUSPOS
dX [m]	0.01	-0.02	-0.01
dY [m]	0.11	-0.02	0.09
dZ [m]	0.02	-0.04	0.01

- for the Z coordinate: 4972325.87 m with the standard deviation of 0.02 m.

Owing to determination of the catalogue coordinates in the AUSPOS programme, it was possible to make a reliable evaluation of use of the PPP measurement technique in the static positioning. In particular, the verification process assesses the PPP positioning accuracy assessment in the GPS static mode. Based on that, it was possible to determine the difference in geocentric XYZ coordinates for the reference station REF1, as below [14]:

$$\begin{aligned} dX &= X_i - X_{AUSPOS} \\ dY &= Y_i - Y_{AUSPOS} \, , \\ dZ &= Z_i - Z_{AUSPOS} \end{aligned} \tag{3}$$

where:
(dX, dY, dZ) - parameters of accuracy positioning in the geocentric XYZ coordinates,
X_i - the X coordinate of the reference station REF1 from the solution of the CSRS-PPP, APPS and GAPS,
Y_i - the Y coordinate of the reference station REF1 from the solution of the CSRS-PPP, APPS and GAPS,
Z_i - the Z coordinate of the reference station REF1 from the solution of the CSRS-PPP, APPS and GAPS,
X_{AUSPOS} - the X catalogue coordinate of the reference station REF1 from the AUSPOS solution,
Y_{AUSPOS} - the Y catalogue of the reference station REF1, from the AUSPOS solution,
Z_{AUSPOS} - the Z catalogue coordinate of the reference station REF1 from the AUSPOS solution.

Table 7 shows results of the GPS accuracy positioning for the reference station REF1. Based on the obtained comparative results from Equation (3), it can be concluded that the highest positioning accuracy by means of the PPP measurement technique is visible along the X axis, being equal to approximately ±0.01÷0.02 m. On the other hand, the lowest accuracy of the GPS positioning is noticeable along the Y axis, particularly in the case of the CSRS-PPP and GAPS solution. Along the Z axis, the GPS positioning accuracy equals ± 0.01÷0.04 m.

5 Conclusions

The article presents results of determination of accurate GPS coordinates of the GPS reference station as one of the GBAS augmentation system elements in the air transport. The GPS reference station coordinates were determined using the PPP measurement technique for the GPS code-phase observations. In the research test, the authors determined the coordinates of the reference station REF1, localized on the grounds of the military airport EPDE in Deblin. Calculations of the reference station REF1 coordinates were performed in the CSRS-PPP, APPS and GAPS programmes. The paper presents results of determining the geocentric XYZ coordinates for the reference station REF1, in the PPP measurement technique. In addition, the article presents results of the geocentric XYZ coordinates standard deviations for the reference station REF1, in the PPP measurement technique. The article verifies the determined XYZ geocentric coordinates for the reference station REF1, in the PPP measurement technique against the catalogue coordinates, obtained in the AUSPOS programme. Based on the conducted examinations, it was found that the accuracy of the GPS positioning in the PPP measurement technique equals

- along the X axis up to ± 0.02m,
- along the Y axis up to ± 0.11m,
- along the Z axis up to ± 0.04my.

The research method presented in this paper can be fully exploited in the creation of the GBAS system for development of the air transport. Therefore, it is justified to use the PPP measurement technique for accurate determination of coordinates of the GPS reference stations, installed at airports. Determined coordinates of the GPS reference station in the PPP measurement technique seem to be reliable and accurate in relation to the catalogue coordinates, calculated using the dual-frequency differentiation of the phase observations. It must be stressed that the GBAS system in Poland is at the stage of construction, which means that its particular components must be properly verified so that their quality should be the best possible in the age of development of aviation. In the future, the authors plan to perform further research tests on use of the PPP measurement technique in determining the GPS reference stations located in the vicinity of civil airports in Mielec and Chelm, in south-eastern Poland.

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Annex - Nomenclature

The abbreviation	The full name
EPDE	ICAO airport code
GPS	Global Positioning System
PPP	Precise Point Positioning
CSRS-PPP	Canadian Spatial Reference System - Precise Point Positioning
GAPS	GPS Analysis and Positioning Software
APPS	Automatic Precise Positioning Service
GBAS	Ground Based Augmentation System
RTK	Real Time Kinematic
DGPS	Differential GPS
OTF	On The Fly
ICAO	International Civil Aviation Organization
PA	Precision Approach
RINEX	Receiver Independent Exchange System
ANTEX	Antenna Exchange Format
NRCan	Natural Resources Canada
ITRF	International Terrestrial Reference Frame
DCB	Differential Code Biases
VTEC	Vertical TEC
VMF	Vienna Mapping Functions
AUSPOS	The Australian Surveying and Land Information Group‘s Online GPS Processing Service
IERS	International Earth Rotation and Reference Systems Service
IGS	International GNSS Service
XYZ	Global geocentric coordinates
BLh	Latitude, Longitude, ellipsoidal height
EGM	The Earth Gravitational Model
GNSS	Global Navigation Satellite System
JPL	Jet Propulsion Laboratory