Kinematic Studies in the Field of Accuracy and Position Determination of Aircrafts Using the PPP Technique by the GPS System

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Abstract. This article discusses the results of the measurements of position accuracy in 3D space for a UAV object using real-time kinematic measurements of the GPS system. The aim of the research presented in the work was to determine all three components (x, y, z) describing the location of the UAV object during the flight and making comparative characteristics using the PPS navigation service. Comparison of the differences between the two methods showed that the obtained results are characterized by a 95% of certainty. The results obtained in this experiment showed the accuracy of height measurement using the PPS GNSS system at a level of 10-80 centimeters. The results of this study also indicate that kinematic measurements can be very useful in the work of the air traffic controller and engineers of other specialties involved in position determination using satellite techniques. The article also presents a mathematical model defining the process of determining the position of a UAV object during the flight, taking into account kinematic measurements. In the final part of the work, practical conclusions were presented based on the analysis and selected simulation tests.

1 Introduction

In the introductory part of this work, the authors focused on making a critical analysis of the subject of research, i.e. the problems, determining the accuracy of kinematic objects (aircraft, UAV), based on the precise positioning of PPP (*Precise Point Positioning*). The article also describes various work parameters in the conducted simulation tests.

In 2002 Shen and Gao published an article, in which they described the kinematic solution of PPP technique for 6 Canadian active control stations. In this aspect, the observational data were tested using two-phase receivers with a sampling frequency of 1 [s] and another convergence time of 6-8 [h].

For this purpose, precise IGS (*International GNSS Service*) orbits were used with a sampling rate of 15 [min] and IGS satellite clocks with an interval of 30 [s] were used for estimation, where the term GNSS means global navigation satellite system (*Global Navigation Satellite System*) [1]. Estimated mean square RMS (*Root Mean Square*) for static PPP information solutions, inside the preamble with corrections provided by geostationary systems, where these stations are shown 10 [cm] in the horizontal direction and 12 [cm] in the height direction [2].

In turn, Gao and Wojciechowski processed two air kinematic trajectories with the angle of reaching the signal to the receiver antenna of 10 [°] to obtain a solution to the PPP concept. The P3 software package,

which was implemented at the University of Calgary in Canada, was used primarily to obtain a PPP solution for this purpose. The first set of data had a flight time of about 4.75 [h] at a maximum speed not exceeding 310 [km/h].

Accurate data from the orbit and clock were delivered from the JPL laboratory (*Jet Propulsion Laboratory*) at intervals of 15 [min] and 1 [s] respectively. The estimated PPP solution from P3 software was compared to one obtained from GIPSY-OASIS II software, which uses both the JPL satellite and the clock data. After this comparison, the solutions showed 2.4 [cm] and 2.2 [cm] respectively for latitude and longitude and 8 [cm] in the height direction.

The second set of data had an observation time of approximately 3.75 [h] at a maximum speed of 810 [m/h]. In order to obtain a PPP solution using the P3 software package, the satellite clock apparatus and the final IGS orbit were used at intervals of 15 [min] and 5 [min] respectively. The obtained solution was compared twice, the first with a differential system solution of DGPS (*Differential Global Positioning System*) for multi-reference data stations, the second with GIPSY-OASIS II software. The first comparison with the DGPS system showed 8 [cm] in the area of latitude and longitude and 0.5 [m] in height. In the second comparison with the GIPSY-OASIS II software, it provided 5 cm horizontally and up to several meters [3].

In turn, Abdel-salam compared the accuracy of the kinematic PPP solution by a differential solution with

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GrafNavTM software in various experimental aspects. The observation data had an interval of 1 [s] and the angle of reaching the signal to the receiver antenna of 10 [°]. Satellite clocks of 5 minutes were used to estimate the PPP technique.

The first trajectory was examined by a land vehicle, in which the estimated of the standard deviation SD (*Standard Deviation*) value was 4 [cm], 10 [cm] and 15 [cm] for width, length and height, respectively. The second trajectory was observed using a sea ship for 6 hours. Reported SD was similarly estimated on the basis of the first trajectory. The third trajectory was examined using the aircraft for over 6 hours. The final SD for the PPP estimation showed 3 [cm] for latitude, 6 [cm] for longitude and 15 [cm] for height.

The last data was collected using a helicopter for two and a half hours, for which the PPP solution reached 4 [cm], 16 [cm] and 17 [cm] respectively for latitude, longitude and height [4]. To calibrate the on-board sensors, *Ovstedal* and other authors tested the accuracy of the TerraPos software compared to the DGPS system. Three hours of continuous flight observation data were processed using this software package, where observation data had an interval of 1 [s]. The estimation using the PPP technique for data with two frequencies was based on a linear combination free from the ionosphere.

In addition, precise orbits, satellite clocks and ground orientation parameters were provided from the IGS service. Estimated horizontal accuracy using the TerraPos software compared to the DGPS system was up to 10 [cm] with an average of 5 [cm].

In turn, *Schwieger* together with other authors compared the online services GIPSY-OASIS and CSRS-PPP in relation to the DGPS system. They achieved an RMS height of better than 0.5 [m] from PPP solutions with the speed of availability of observational data around 60 [%]. In contrast, *Anquela* together with other authors analyzed the kinematic trajectory with an observation interval of 5 seconds.

This kind of trajectory was tested using a car with a two-frequency GNSS system receiver, where the tests were carried out in good weather conditions, the sky was clean enough to get a good view of the satellite [5], [6].

The kinematic coordinates of the PPP solution were estimated using the MagicGNSS software, and the solution using the DGNSS system was considered as a reference solution for accuracy calculations. The estimated SD for absolute errors of the GNSS-PPP system showed 8 [cm] in the east and north. What is more, it has achieved a double accuracy dm in the upward direction [7], [8].

Further analyzing the literature on the subject of the study, it should be noted that in 2014 *Abdallah* and *Schwieger* explored the impact of the static initialization time for a kinematic solution using PPP. Two kinematic trajectories were tracked using a measuring vehicle in the open area with a dual frequency receiver, where the observation data had an interval of 1 [s].

Observation processes began after about 1 [h] as so-called time of initialization and then 30 [min] of kinematic measurements (Fig. 1).

Fig. 1. Kinematic measurement method of the UAV position.

Kinematic coordinates by the PPP technique were obtained twice. First using the GIPSY-OASIS II V 6.3 software package that uses JPL satellite products. The second of the CSRS-PPP online service that uses IGS satellite products.

The estimated coordinates of the PPP solution were compared with the solution using the DGNSS system as a reference solution. The GIPSY-OASIS software showed after the initialization time 20 minutes less than 5 [cm] accuracy in the east and north and less than 10 [cm] for height.

Online service CSRS-PPP technique achieved with initialization time from 10 [min] with the same accuracy [9], [10]. A recent *Ceylan* study together with other authors assessed the kinematic estimation using the PPP method for urban areas.

In Turkey, three kinematic trajectories were observed using a dual-frequency GNSS receiver with an angle of signal reaching the receiver antenna of 10 [°] and the observation interval of 1 [s]. The DGNSS system solution from the Leica Geo-Office 5.0 software has been recognized as a reference solution. The PPP estimation was performed using the CSRS-PPP online service.

It should be noted that the disadvantage of this kind of research is that the signals of the GNSS system have been lost due to the high buildings surrounding this area.

The three trajectories had different lengths, different numbers of observational data, and different views of satellites, and various estimates of accuracy were provided in this study according to observation conditions [11], [12].

The estimated standard deviation of differences between the DGNSS system solutions and the PPP technique showed that the first trajectory provided accuracy of 5 [cm] for east, north and 10 [cm] for height.

The second trajectory has reached less than 5 [cm] in all directions. The third displayed 10 [cm] for east and north and over 15 [cm] for height. In addition, the third trajectory provided the worst accuracy due to the low visibility of the satellite [13], [14].

In the next subsection, the authors of this work presented an estimated model for accuracy purposes, based on the PPP solution.

2 An estimated model for the solution of PPP technique

The key aspect of estimating the PPP solution depends on the application of the linear free-ionosphere combination. The next part is explained in detail with the traditional implementation of the PPP technique using the smallest quadratic estimation method [15], [16], [17].

Because accurate satellite orbit information and clock are known, satellite clock error δ^S and satellite position x_S, y_S, z_S are precisely known.

The estimation equations can be reformed as seen in subsequent equations marked as (1) and (2):

$$\begin{aligned}\rho_{IF} &= r + c\delta^R - c\delta^S + T_Z * m(E) + \varepsilon_\rho \\ &= 2.546\rho_{L1} - 1.546\rho_{L2}\end{aligned}\quad (1)$$

$$\begin{aligned}\Phi_{IF} &= r + c\delta^R - c\delta^S + T_Z * m(E) + \lambda_{IF} * N_{IF} \\ &+ \varepsilon_\Phi = 2.546\Phi_{L1} - 1.546\Phi_{L2}\end{aligned}\quad (2)$$

Because the geometrical range r is equal to the distance between the co-ordinate satellites x_S, y_S, z_S and coordinates of the receiver x_R, y_R, z_R the estimated equations are updated as shown in equations (3) and (4). Thus, known observations are satellite coordinates, pseudo-transmitters ρ_{L1}, ρ_{L2} and carrier phases Φ_{L1}, Φ_{L2} from the RINEX file.

The co-ordinates of the receiver, receiver clock error δ^R , troposphere zenith delay T_Z and variable infinities floating N_{IF} are not known.

The traditional estimation of the PPP solution is carried out by the smallest square fit. This type of estimation methodology is used in the *Bernese* GNSS system software [18], [19], [20].

$$\begin{aligned}((x_S - x_R)^2 + (y_S - y_R)^2 + (z_S - z_R)^2)^{0.5} \\ + c\delta^R + T_Z * m(E) + \varepsilon_\rho \\ - \rho_{IF} = 0\end{aligned}\quad (3)$$

$$\begin{aligned}((x_S - x_R)^2 + (y_S - y_R)^2 + (z_S - z_R)^2)^{0.5} + c\delta^R \\ + T_Z * m(E) + \lambda_{IF} * N_{IF} + \varepsilon_\Phi \\ - \Phi_{IF} = 0\end{aligned}\quad (4)$$

According to the estimate using the GNSS *Bernese* system software, receiver clock errors are initially eliminated and inserted into the final estimate as known values.

Two vectors of unknowns are defined as $\hat{x}_1$ and $\hat{x}_2$. $\hat{x}_1$ containing the coordinates of the troposphere receiver x_R, y_R, z_R troposphere and integers of ambiguity [equation (6)], and the unknown $\hat{x}_2$ refers to the receiver clock error, which is first estimated, as shown in the following equation (5):

$$\hat{x}_2 = [\delta^R]\quad (5)$$

$$\hat{x}_1 = \begin{bmatrix} x_R \\ y_R \\ z_R \\ T_Z \\ N_{IF}^1 \\ N_{IF}^2 \\ \vdots \\ N_{IF}^n \end{bmatrix}\quad (6)$$

The matrix design A_1 for the main estimation was formed in the equation (7):

$$A_1 = \begin{bmatrix} \frac{\partial f(X, \rho_{IF})}{\partial x_R} & \frac{\partial f(X, \rho_{IF})}{\partial y_R} & \frac{\partial f(X, \rho_{IF})}{\partial z_R} & \frac{\partial f(X, \rho_{IF})}{\partial T_Z} & \frac{\partial f(X, \rho_{IF})}{\partial N_{IF}^1} & \frac{\partial f(X, \rho_{IF})}{\partial N_{IF}^2} & \dots & \frac{\partial f(X, \rho_{IF})}{\partial N_{IF}^n} \\ \frac{\partial f(X, \Phi_{IF})}{\partial x_R} & \frac{\partial f(X, \Phi_{IF})}{\partial y_R} & \frac{\partial f(X, \Phi_{IF})}{\partial z_R} & \frac{\partial f(X, \Phi_{IF})}{\partial T_Z} & \frac{\partial f(X, \Phi_{IF})}{\partial N_{IF}^1} & \frac{\partial f(X, \Phi_{IF})}{\partial N_{IF}^2} & \dots & \frac{\partial f(X, \Phi_{IF})}{\partial N_{IF}^n} \end{bmatrix}\quad (7)$$

The first line refers to phase observations for one satellite and the second one also mentions about code observation. In addition, the entire designed A_1 matrix is linearized, as can be seen in equation (8), where n refers to the total number of satellites observed:

$$A_1 = \begin{bmatrix} \frac{(x_R - x_S^1)}{r^1} & \frac{(y_R - y_S^1)}{r^1} & \frac{(z_R - z_S^1)}{r^1} & m(E)^1 & \lambda_{IF}^1 & 0 & \dots & 0 \\ \frac{(x_R - x_S^2)}{r^2} & \frac{(y_R - y_S^2)}{r^2} & \frac{(z_R - z_S^2)}{r^2} & m(E)^2 & 0 & \lambda_{IF}^2 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{(x_R - x_S^n)}{r^n} & \frac{(y_R - y_S^n)}{r^n} & \frac{(z_R - z_S^n)}{r^n} & m(E)^n & 0 & 0 & 0 & \lambda_{IF}^n \\ \frac{(x_R - x_S^1)}{r^1} & \frac{(y_R - y_S^1)}{r^1} & \frac{(z_R - z_S^1)}{r^1} & m(E)^1 & 0 & 0 & \dots & 0 \\ \frac{(x_R - x_S^2)}{r^2} & \frac{(y_R - y_S^2)}{r^2} & \frac{(z_R - z_S^2)}{r^2} & m(E)^2 & 0 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{(x_R - x_S^n)}{r^n} & \frac{(y_R - y_S^n)}{r^n} & \frac{(z_R - z_S^n)}{r^n} & m(E)^n & 0 & 0 & 0 & 0 \end{bmatrix} \begin{matrix} \text{Phase date} \\ \\ \\ \text{Phase code} \end{matrix}\quad (8)$$

The second designed matrix A_2 refers to the clock error of the receiver, as shown in the following equation (9).

$$A_2 = \begin{bmatrix} \frac{\partial f(X, \rho_{IF})}{\partial x_{\delta_R}} \\ \frac{\partial f(X, \rho_{IF})}{\partial x_{\delta_R}} \\ \vdots \\ \vdots \\ \frac{\partial f(X, \rho_{IF})}{\partial x_{\delta_R}} \\ \frac{\partial f(X, \rho_{IF})}{\partial x_{\delta_R}} \\ \frac{\partial f(X, \rho_{IF})}{\partial x_{\delta_R}} \\ \vdots \\ \vdots \\ \frac{\partial f(X, \rho_{IF})}{\partial x_{\delta_R}} \end{bmatrix} = \begin{bmatrix} C \\ C \\ \vdots \\ \vdots \\ C \\ C \\ C \\ \vdots \\ \vdots \\ C \end{bmatrix}\quad (9)$$

3 Methodology of conducted research

The aim of the article was to determine the possibility of designating the spatial location of objects (aircrafts, unmanned aerial vehicles) with GPS/GNSS system

methods using different measurement modes [21], [22], [23].

Depending on the nature of GNSS system receivers and their place of mounting, the following modes of determining the position of moving objects have been distinguished:

- static (e.g. for the measurement of x , y , z coordinates of an aircraft on the surface of the airport),
- dynamic (kinematic) of moving receiver (e.g. when defining the course of an aircraft in 3D space).

It should be noted that the accuracy of determining the position of a given object in three-dimensional space depends on many factors, but mainly on the quality of the receiver itself and the number of radio channels operating the reception and processing of navigation signals of the GPS/GNSS system, antenna (external, internal) and the conditions of the measurement itself (availability of the horizon, no factors that affect the quality decrease of signal reception).

It is also important to acquire attributes (features of the measured objects), in the case of aircraft, the most decisive factor directly influencing the accuracy of the measurement is its altitude.

Extremely important in conducting measurements in difficult airspace conditions is proper planing of the measurement mission using the current file "almanac" and knowledge of obscuring the horizon of the measurement site (both vertically and horizontally). This avoids many failures and thus saves a lot of time.

In situations requiring greater precision of measurements, a differential GPS (*differential GPS*) method is applied with the use of differential corrections to data from GPS system satellites [24], [25].

The process of making measurements in mode of the so-called *post-processing* requires the use of a correction file registered by GNSS system base stations, i.e. reference stations (*base station*) at the same time as observations made in the field by a mobile receiver (*rover station*) or *movable receiver*.

This has a significant impact on increasing the accuracy and certainty of determining the position of the observed point in space. The tests were carried out on different days, months and under different atmospheric conditions.

4 Results and analysis of satellite clock research

This chapter examines the impact of the satellite clock interval. Satellite clocks of pseudo-random code signals with the interval of 5 [s] and 30 [s] were tested. To understand how the satellite clock interval affects the observation data at different sampling rates, two categories of observation data were processed.

The first category refers to observation data with a sampling rate of 5 [s]. The second category exchanges data on fast sampling with a sampling frequency of 1 [s].

To obtain an optimal solution from the kinematic solution of the PPP technique, observational data from

different sets of data was processed with an observation interval of 5 [s]. This data sampling interval is suitable for the high satellite clock rates provided by the CODE center, operating at the Astronomy Institute of the University of Bern. This means that there is no interpolation process for the needed satellite clocks. The following chapter shows the kinematic results of a PPP technique with various satellite clocks for a set of static data and real hydrographic kinematic measurements.

5 Static measurement data

Due to the huge amount of information contained within the preamble, only the observation time of 6 hours was considered for the GPS CORS (*Continuously Operating Reference Stations*). To assess the accuracy of the estimation, a kinematic solution of PPP with reference coordinates for these stations was compared. The error in the east, north and height directions was calculated.

The RMS values for all plans are summarized in the table below (Table 1), where two loops were carried out to estimate the PPP solution.

Table 1. RMS values for static measurements [sampling frequency 5s].

	East [m]	North [m]	Height [m]	Satellite clocks
0384	0.013	0.015	0.026	pseudo-random code signals [duration 5s]
	0.048	0.060	0.120	pseudo-random code signals [duration 5s-default]
	0.017	0.024	0.030	pseudo-random code signals [duration 5s-modified]
0386	0.008	0.010	0.025	pseudo-random code signals [duration 5s]
	0.023	0.030	0.068	pseudo-random code signals [duration 5s-default]
	0.014	0.021	0.030	pseudo-random code signals [duration 5s-modified]
0391	0.016	0.019	0.025	pseudo-random code signals [duration 5s]
	0.070	0.100	0.122	pseudo-random code signals [duration 5s-default]
	0.020	0.026	0.030	pseudo-random code signals [duration 5s-modified]
0400	0.015	0.024	0.058	pseudo-random code signals [duration 5s]
	0.080	0.070	0.150	pseudo-random code signals [duration 5s-default]
	0.019	0.030	0.060	pseudo-random code signals [duration 5s-modified]

The first loop aims to check the estimated residual values of each satellite for each information contained within the preamble.

The default solution using satellite clocks 5 [s] shows some eliminated observation data. On the other hand, due to the interpolation process for 30 [s] satellite clocks, observational data that have satellite debris larger than limits are marked as bad observations. The estimated accuracy in this case is significantly reduced. Therefore, the default settings for this estimate are adapted to deactivate this screening filter, which means that for the second loop all observations were considered without elimination. This solution is called a modified solution in this case [26], [27], [28]. The next results show the obtained accuracy from satellite clocks 5 [s] and 30 [s] with default and modified solutions.

In addition, the following table compares the solution consisting in the use of satellite clocks, giving pseudorandom code signals [duration 5s] and two signals with pseudorandom codes [duration 30s]. It also presents the RMS values in the east, north and at heights. With reference to station 0384, the solution using satellite clocks after 5 [s] gets the RMS values 1.30 [cm], 1.50 [cm] and 2.60 [cm] respectively for the east, north and height. On the other hand, satellite clocks with an interval of 30 [s] provide higher errors. The default solution presents an RMS error of 4.80 [cm] in the east and 6.00 [cm] in the north, while at the height the solution shows an RMS error of 12.00 [cm].

It should be noted that the modified solution achieves a better solution than the solution obtained from the default solution, where it provides the RMS error values 1.70 [cm] in the east, 2.40 [cm] in the north and 3.00 [cm] in height.

Fig. 2. Solution of the PPP concept of a SAPOS station with a satellite clock for 0384 station [sampling frequency 5s], presenting a solution of the PPP concept for pseudorandom code signals [duration 5s].

Fig. 3. Solution of the PPP concept of a SAPOS station with a satellite clock for 0384 station [sampling frequency 5s], presenting a solution of the PPP concept for pseudorandom code signals [duration 30s-default].

Fig. 4. Solution of the PPP concept of a SAPOS station with a satellite clock for 0384 station [sampling frequency 5s], presenting a solution of the PPP concept for pseudorandom code signals [duration 30s-modified].

The above figures (Figs. 2-4) show based on the simulator printout estimated errors of PPP station 0384

for all solutions. The left part shows the error graph over time, the vertical axis refers to the error [m], and the horizontal axis shows the weekly time of the GPS system [29], [30], [31], [32]. The right side shows the east-north and east-height error graphs. The purpose of these plots is to show the density of errors for the estimated information contained within the preamble.

A more fluent solution was obtained from satellite clocks 5 [s], as shown in Figure 1, compared to the clock obtained from satellite clocks 30 [s]. This means that in this case a smaller range of errors is obtained. In detail, figure 2 shows the kinematic errors of PPP station 0384 default solution for pseudorandom code signals [duration 30s].

On the basis of Fig. 2 it can be concluded that the largest coordinates have the coordinates of the height. Two leaps in height are shown in dashed lines. In turn, figure 3 shows errors for the modified solution. It can be observed that a significant improvement was achieved compared to the default solution.

6 Summary and final conclusions

In order to determine the kinematic accuracy of the PPP concept solution, various aspects were explored: (1) The influence of the satellite clock interval, (2) The influence of the tropospheric zenith delay model TZD (*Troposphere Zenith Delay*) and (3) Implementation of the height limit for measurements.

Satellite clock intervals play an important role in estimating the accuracy of the kinematic solution of the PPP concept. Two satellite clocks provided by the CODE center were used in the kinematic processing of the PPP concept. These clocks have a range of 30 [s] and 5 [s] respectively.

In the case of static CORS stations, the general results of the satellite clocks of pseudo-random signals [duration 5s] show the average RMS value of 1.30 [cm], 1.70 [cm] and 3.35 [cm] respectively for the east, north and height. Compared to the modified pseudo-random code signal solution [duration 30s], the solution of pseudo-random code signals [duration 5s] achieves a better solution of about 25 [%] in the east, 40 [%] in the north and 12 [%] in height.

In addition, the resolution of pseudo-random code signals [duration 5s] shows an improvement of 70 [%] higher than that obtained from the default solution of pseudo-random code signals [duration 30s].

The second group has data for fast sampling 1 [s]. Similarly to the first group, this group has a data set consisting of four CORS stations. Due to the large interpolation interval between the satellite clocks of pseudorandom code signals [duration 30s] and the sampling frequency of observations of 5 [s], a huge number of observational data is eliminated. Therefore, the solution contains only a modified solution from pseudo-random code signals [duration 30s].

In addition, the satellite clock for pseudo-random code signals was also checked [duration 5s]. The four CORS stations consistently have an average RMS value of 2.43 [cm], 2.15 [cm] and 6.10 [cm] respectively for

the east, north and height directions.

In comparison to the modified solution of pseudo-random code signals [duration 30s], pseudo-random code signals [duration 5s], approx. 10 [%] improvement in accuracy is achieved.

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