Investigation of GNSS Receiver’s Accuracy Integrated on UAVs

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Key words: GNSS, Unmanned Aerial Vehicle, PPK, Testing Platform

SUMMARY

UASs (Unmanned Aerial Vehicle) find today their ever growing application for military, commercial and personal purposes. The application of UAVs for creation of surveying products like Digital Ortho Photo (DOF), 3D models, Digital Surface Models (DSM), Digital Terrain Models (DTM) etc. is related to the accuracy attainable by GNSS receivers integrated on them. Manufacturers of the UAVs usually do not provide detailed information about GNSS receiver's accuracy and reliability what in turn has a direct impact on implementation of the UAVs in surveying. Therefore, a special testing platform for assessment of the UAV GNSS receiver’s accuracy was designed at the Faculty of Geodesy and a testing procedure was developed accordingly. The platform design had to fulfill two fundamental requirements: the tested UAV GNSS receiver should move on a precisely determined trajectory (1) whose size must be significantly greater than the accuracy attainable by the GNSS receiver itself (2). The procedure implemented on designed testing platform involved two geodetic GNSS receivers Trimble R8 (Model 2): one in static and the other in PPK (Post-Processed Kinematic) observation mode enabling the determination of UAV integrated GNSS receiver’s position of controlled trajectory with cm-level accuracy. UAV GNSS receiver’s accuracy was tested on the platform in static and kinematic mode with 10 Hz frequency revealing the 1 m - level accuracy achieved by absolute positioning method. The accuracy of coordinates determined with the GNSS receiver integrated on DJI Phantom 3 Professional UAV was assessed and the results are presented in this paper. Although, the UAV GNSS receiver used within the testing procedure operated in absolute positioning mode, the presented testing platform and procedure are suitable for testing of GNSS receivers using RTK positioning method. The research activities presented herein have paved the road to the accuracy assessment procedure of other sensors integrated on UAVs like IMU (Inertial Measuring Unit).

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1. INTRODUCTION

Due to its small weight, platform stability, low power engines as well as high capacity batteries in addition to the lightweight digital cameras, the Unmanned Aerial Vehicles (UAV) find today their ever growing applications in surveying practice for data collection with the aim of the creation of final products like Digital Orthophotos, Digital Surface Models (DSM), 3D models or just a point clouds of certain spatial object. Whether for aerial survey are used fixed wing vehicles or multicopters, for the creation of mentioned products are needed powerful program tools in addition to the aerial vehicles equipped with numerous sensors like Global Navigation Satellite System (GNSS) and Inertial Navigation System (INS). Using measurements from accelerometers and gyroscopes, inertial navigation enables position and orientation monitoring of certain spatial object. Inertial Measuring Unit (IMU) is typically composed of three orthogonal accelerometers and three orthogonal gyroscopes providing information about linear accelerations and angular velocities (Woodman 2007). However, the accuracy of these data rapidly decreases over time and the initial information about position, orientation and speed are not provided. Typically, these data are provided by GNSS (today GPS/GLONASS, in the future GALILEO and BeiDou) that leads to the sensors integration with the goal of obtaining reliable information about position and orientation of aerial images. Due to their small dimensions and weight, accelerometers and gyroscopes installed on UAVs come in the form of Micro-Electro-Mechanical Systems (MEMS). The object of research activities presented in this paper was the development of testing platform used for the accuracy assessment of GNSS receivers embedded on UAVs. The accuracy of UAV's guidance during aerial survey depends on the accuracy of these data. The same apply for the accuracy of external orientation elements of aerial images. In turn, that has a direct impact on the accuracy and quality of the final aerial survey products (DSM, 3D models, Digital Orthophoto etc.)

2. TESTING OF GNSS RECEIVER ON THE UAV

GNSS receiver used for the accuracy assessment was those embedded on the UAV *DJI Phantom 3 Professional*. It is about a quadcopter which mass is 1,280 kg (battery and propellers included), maximal speed 16 m/s, equipped with GPS/GLONASS receiver, Sony EXMOR 12.4 M digital camera as well as the remote control system including appropriate software installed on the mobile device like tablet computer or smart phone (DJI 2016).

The accuracy of GNSS receiver was tested in two different ways: in static and kinematic mode. The static test was carried out on the station GFP2 with known ellipsoidal GRS80 coordinates. The station is located on the playground in the vicinity of the Faculty of Geodesy and the station has a pretty clean horizon.

2.1 Static test

The antenna of the GNSS receiver (GPS/GLONASS) embedded on the Phantom 3 Professional UAV is located on the crossing of arms with propellers (Figure 1). During the static test, the antenna of the GNSS receiver was set up above the center of station GFP2 (within few cm) where the static test took place for 10 minutes. The height difference between the bottom of the landing gear and the antenna of the GNSS receiver is approximately 20 cm.

Figure 1. Position of GNSS antenna on DJI Phantom 3 Professional (customized from (DJI 2016)).

With 1 Hz observation frequency (logging interval), during 10-minutes long test were collected 600 coordinates (φ, λ, h). The observation data were stored and downloaded in DAT format consisting of all the data recorded by sensors integrated on the UAV. Binary DAT format was converted in readable CSV format enabling subsequent data processing, analysis and interpretation. Coordinates (φ, λ, h) obtained by the GNSS receiver were transformed in the official reference system of the Republic of Croatia HTRS96/TM (Croatian Terrestrial Reference System 1996/ Transverse Mercator) leading to plane coordinates (E, N). The results of the static test determined by GPS/GLONASS receiver embedded on the UAV together with the GFP2 station are presented on the Figure 2 (position) and Figure 3 (height).

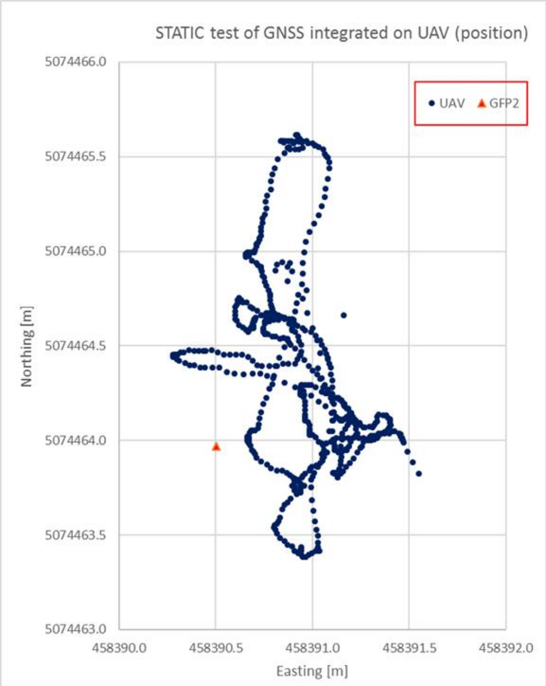

Figure 2. Results of STATIC test (posit.).

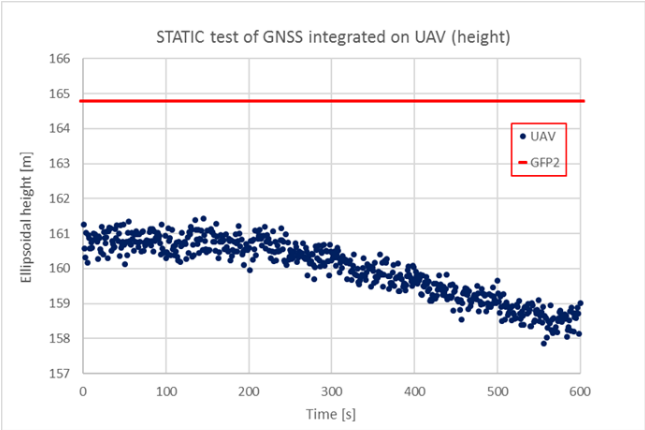

Figure 3. Results of STATIC test (height).

The average value of 600 coordinates determined with GNSS integrated on UAV was calculated and compared to the coordinated of the station GFP2 (UAV-GFP2). The comparison led to differences:

$$\Delta_E = 0{,}43 \text{ m}, \Delta_N = 0{,}39 \text{ m}, \Delta_h = -4{,}81 \text{ m}.$$

The standard deviations as the criterion for precision estimation were calculated as well giving the values:

$$\sigma_E = \pm 0{,}23 \text{ m}, \sigma_N = \pm 0{,}52 \text{ m}, \sigma_h = \pm 0{,}84 \text{ m}.$$

Due to significant fluctuations of results visible on Figure 2 and Figure 3, difference between maximal and minimal values (ranges) were calculated as follows:

$$\text{range}_E = 1{,}27 \text{ m}, \text{range}_N = 2{,}23 \text{ m}, \text{range}_h = 3{,}58 \text{ m}.$$

Considering the results (1 m-level of position accuracy) determined by absolute positioning method, it could be assumed that the GPS/GLONASS receiver, although it is not stated in specifications, uses data from *Satellite Based Augmentation System* (SBAS). In Europe, SBAS data are provided by European Geostationary Navigation Overlay System (EGNOS) which augments the performance of GPS. The corrections and information about integrity are broadcasted on L1 carrier frequency (1575,42 MHz) in order to improve the accuracy of positioning and time transfer over Europe (GSA 2015). Like other SBAS, EGNOS consists of Ground segment and Space segment composed of three geostationary satellites.

2.2 Platform for testing sensors on UAVs

In order to carry out the kinematic test, a testing platform enabling the controlled movement of the UAV was needed. By searching the available literature, no solutions for testing platform templates were found, so an appropriate testing platform had to be designed and produced from scratch. Such a testing platform should meet two basic requirements:

- the UAV has to move on rigorously controlled trajectory with enabled known position in every moment,
- the dimensions of the trajectory have to be significantly larger than the accuracy of coordinates determined by the GNSS receiver embedded on the UAV.

Bearing in mind this basic two requirements and considering the results of static test (1 m – level position accuracy) a designed testing platform consisted of vertical axis and mounted horizontal bar (wooden or metal) enabling the rotation in horizontal plane. The horizontal bar should carry the UAV in addition to the geodetic GNSS receivers for precise and reliable determination of position and orientation of the platform in every moment.

The designed testing platform was realized as 4 m long wooden board (plank) with holes drilled on its ends as well as in the middle. Using central screw, through those holes the tribrachs carrying geodetic GNSS receivers could be attached to the testing platform. The UAV could be attached (fixed) to the testing platform by binding its landing gear with tiny plastic bands.

After the construction of such a testing platform (4 m long wooden board rotating around vertical axis attached to the stable base), the methodology for coordinates determination in every moment had to be developed. The methodology was developed through three phases until a reliable and acceptable solution was found. Development phases were undertaken as follows:

1. On both ends of the testing platform (wooden board) two GNSS receivers Trimble R8 were set up and connected to the High Precision Position Service (HPPS) of CROatian POsitioning System (CROPOS). HPPS of CROPOS enables the determination of coordinates in real time with 2 cm accuracy (2D) and 4 cm accuracy (3D) (more details may be found on http://cropos.hr/servisi/vpps). After the field testing, this concept was abandoned because the HPPS of CROPOS supports coordinates determination with maximal frequency 1 Hz which is not satisfactory for kinematic test performance.
2. Two GNSS receivers Trimble R8 were set up in the middle of the horizontal bar as well as on its end collecting observations in Post-Processed Kinematic (PPK) mode with frequency 10 Hz. Observation data were processed in Trimble Business Center ver. 3.4 together with the RINEX data from approximately 150 m distant Continuously Operating Reference Station (CORS) ZAGR (GNSS antenna is located on the roof of building of the Faculty of Geodesy). RINEX data were downloaded from Geodetic Precise Positioning Service (GPPS; more details may be found on http://cropos.hr/servisi/gpps) − CROPOS GNSS REFERENCE STATION WEB SERVER (http://195.29.118.122/Map/SensorMap.aspx) with logging rate 1 second. Due to maximal observation frequency 1 Hz of the receiver on CORS ZAGR, this concept was abandoned as well.
3. Based on the experience gained through previous phases, a static observation with observation frequency 10 Hz in the middle of the horizontal bar was carried out, together with simultaneous observation in PPK mode with the frequency 10 Hz on the end of the horizontal bar. Using the

static observations collected in the middle of the horizontal bar (central GNSS receiver) and RINEX data (three station evenly distributed around the central GNSS receiver) from GPPS CROPOS, the baselines were processed and subsequently coordinates of central GNSS receiver were determined by network adjustment procedure. Furthermore, PPK observations (GNSS receiver on the end of the horizontal bar) were processed with static data (central GNSS receiver) enabling coordinate determination with frequency 10 Hz. In this way, the coordinates of GNSS receiver at the end of the horizontal bar could be calculated while the central receiver was stationary i.e. it was rotating around its vertical axis.

The feasibility of the methodology from the third development phase has enabled the performance of the kinematic test of the GNSS receiver embedded on the UAV.

2.3 Kinematic test

The kinematic test was carried out was carried out on the same playground (in the vicinity of the Faculty of Geodesy), where the test platform was set up on location with pretty clean horizon. GNSS receiver Trimble R8 (with associated TSC2 controller) was set up in the middle of the horizontal bar collecting static observations with logging interval 0.1 s i.e. observation frequency 10 Hz. On one end of the horizontal bar was set up another GNSS receiver Trimble R8 (with associated TSC2 controller) in PPK mode collecting kinematic observations with logging interval 0.1. On the opposite end of the horizontal bar was set up the DJI Phantom 3 Professional UAV which embedded GPS/GLONASS receiver. The distance between the GNSS receiver of the UAV and the central GNSS receiver was 1,855 m. The same distance was between the central GNSS receiver and the receiver set up at the end of the horizontal bar (external GNSS receiver). All three receivers were located on the same line (collinear receivers). The layout of the testing platform with geodetic GNSS receivers Trimble R8 (middle and the end of the horizontal bar) and UAV is shown on the Figure 4.

Figure 4. GNSS receivers Trimble R8 and DJI Phantom 3 Professional on the test platform.

Simultaneous observations were carried out with GNSS receivers Trimble R8 and receiver embedded on the UAV. In order to minimize additional vibrations during the kinematic test, the propellers were removed from the UAV.

Static observations collected with the central GNSS receiver were processed firstly. For the purpose of baselines processing, from GPPS CROPOS were downloaded RINEX files for the CORS ZAGR as well as for additional two Virtual Reference Stations (VRS) evenly distributed around the central GNNS receiver, at the average distance 150 m. Although, the observation with the central GNSS receiver were collected with 0.1 second logging interval, the data downloaded from GPPS CROPOS were collected with 5 logging interval. After the baselines processing and subsequent network adjustment in Trimble Business Centar (TBC) ver. 3.4, adjusted coordinated were obtained and used in further PPK data processing.

In order to achieve the fixed solution of PPK observations, sufficient data have to be collected enabling the initialization. Considering the 16-minutes long observation window, 8-minutes long observations were collected for initialization purposes while the remaining 8 minutes were used for kinematic mode (Continuous Kinematic). Although the On-The-Fly (OTF) initialization method of double frequency measurements was used with the goal of 1-cm accuracy level achievement, Trimble Ltd. recommends to perform the L1/L2 OTF initialization method with observations collected for 8 minutes if there are visible 6 satellites or more (Trimble 2009).

By importing of observation data files (T01 files) collected at the central GNSS receiver (static mode) as well at the external GNSS receiver in TBC ver. 3.4, the data processing was started and performed leading to the fixed baselines solutions between these two receivers. According to the specifications of the GNSS receiver Trimble R8 Model 2, the PPK method provides the accuracies as follows: ±10 mm + 1 ppm RMS (horizontally) and ±20 mm + 1 ppm RMS (vertically) (Trimble 2006).

Graphical representation of the circular trajectory observed by the PPK method is shown on the Figure 5. More than 4800 baselines (each one determined every 0.1 second) provided a set of points forming the circular trajectory with the approximate radius 1,855 m.

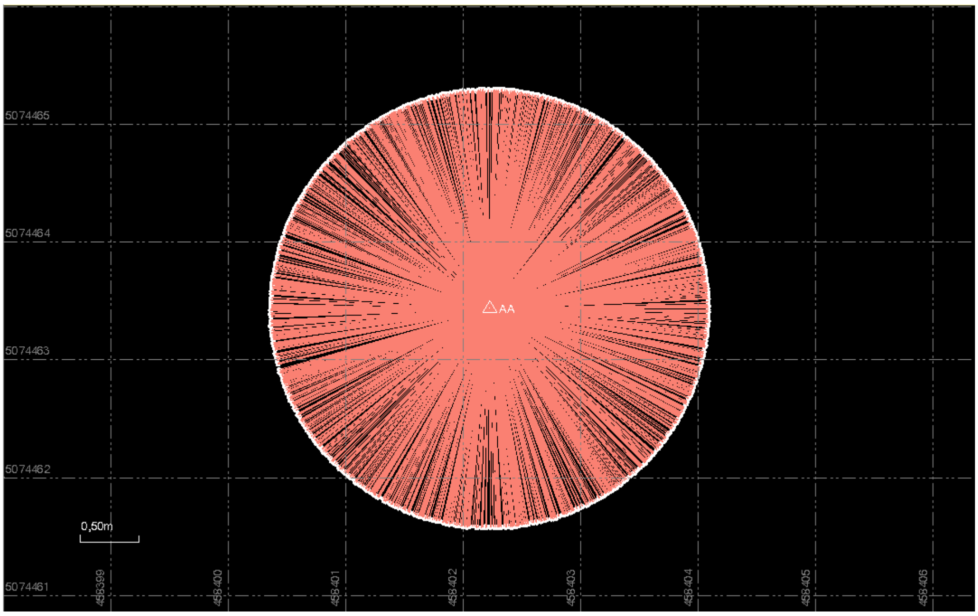

Figure 5. Circular trajectory of the GNSS receiver set up at the end of the testing platform (external GNSS receiver); central GNSS receiver is labeled with AA.

During the 16-minutes long test, but after the 8-minutes long (static) observation period needed for the initialization, the platform was spinning (rotating) twice. The observation frequency 10 Hz provided the solution for coordinates of the moving receiver every 0.1 seconds. Once the coordinates of the moving as well the stationary GNSS receivers were known, the calculation of the grid azimuths from the stationary to the moving receiver was straightforward. The time differences of two consecutive grid azimuths led to the determination of angular velocity of rotating testing platform. Furthermore, because of the fixed distance between the stationary and moving GNSS receiver (r = 1,855 m) the linear speed of the external GNSS receiver could be determined accordingly. The angular velocity of the testing platform is shown on the Figure 6.

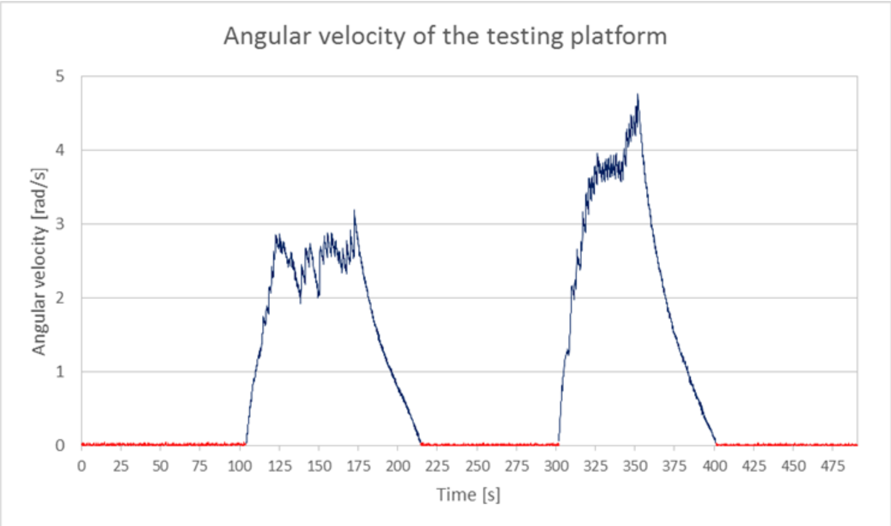

Figure 6. Angular velocity of the testing platform during kinematic test.

On the Figure 6 are quite clear visible intervals when the platform was moving (spinning) or it was stationary. Maximal angular velocity was 4,77 rad/s (273,18°/s) which correspond to the maximal linear velocity of the external GNSS receiver 8,84 m/s. From the idle status the platform started to spin (rotate) manually, during spinning the torque was maintained or even increased manually too. In the absence of torque and due to the friction and air drag, the platform was slowing down forming the smooth exponential curve.

The horizontal accuracy achievable by the PPK method is 5 cm + 5 ppm (conservative approach) for single frequency receivers. However, when dual frequency receivers are used, for baselines up to 10 km the horizontal accuracy of PPK is estimated to 2 cm (Hofmann-Wellenhof *et al*. 2008).

The horizontal accuracy estimation of the PPK method was based on the differences between the real trajectory and the theoretical one (circular trajectory with radius r = 1,855 m). The deviations were calculated as errors (Theoretical value – Practical value) with the following statistical parameters: min (-0,021 m), max (0,014 m), range (0,035 m) and average (-0,006 m). Absolute values of deviations are presented on the Figure 7, showing that 2-cm horizontal accuracy was achieved.

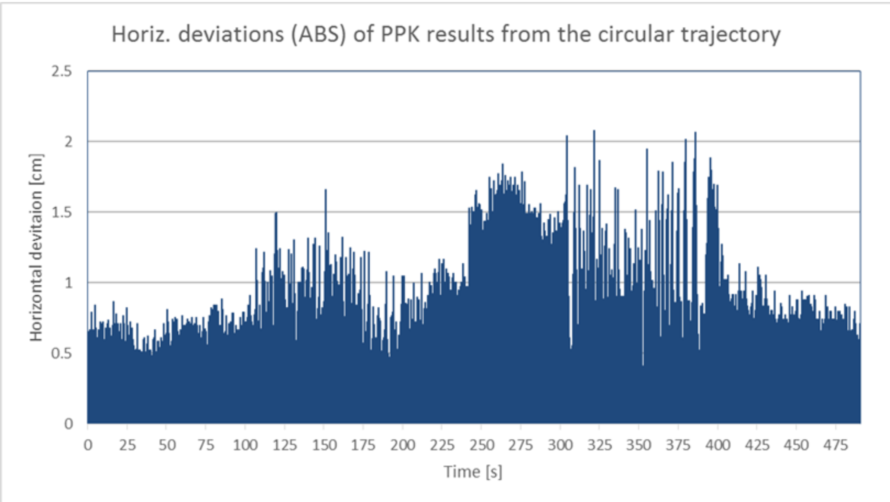

Figure 7. Horizontal deviations (absolute values) of PPK results from the theoretical circular trajectory.

As for every 0.1 seconds during the performance of the kinematic test are known the coordinates of both geodetic GNSS receivers Trimble R8 (central and external receiver), it is possible calculate the reference ('real') coordinates of the GNSS receiver embedded on the UAV.

The comparison of reference coordinate values with those obtained by the GNSS receiver on the UAV was possible after the time synchronization which was enabled by UTC time tags. Horizontal deviations (absolute values) were calculated with the following statistical parameters: min (0,020 m), max (4,402 m) and average (1,221 m) confirming the 1 m - level accuracy achieved by static test. Absolute values of the horizontal deviations are shown on the Figure 8: maximal deviations took place during the testing platform in movement. There is a high correlation between the Figure

8 and Figure 6 regarding the amplitude of deviations and time of their occurrence (‘hills’ centered around 150th and 350th second).

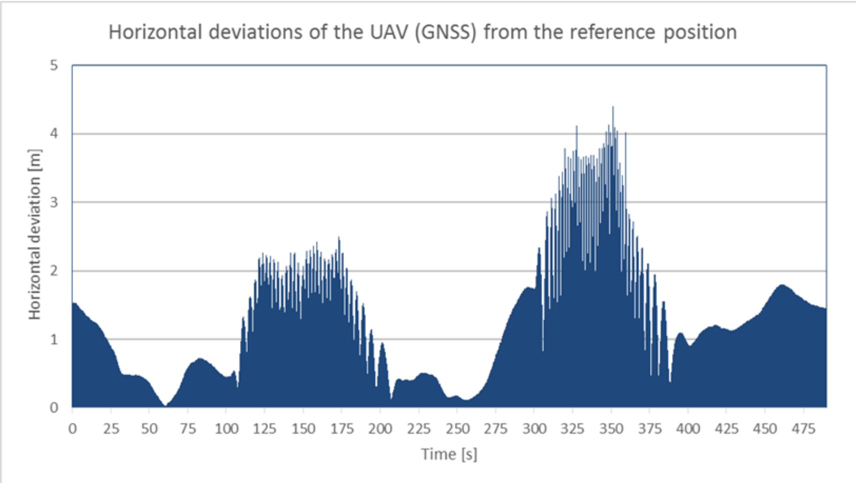

Figure 8. Horizontal deviations of UAV (GNSS) results from the reference positions.

Horizontal deviations represent the absolute values of deviations without information about their direction. Therefore, the horizontal deviations were decomposed in radial and tangential components using vector scalar product as was in details described in graduation thesis entitled “Unmanned Aerial Vehicle INS/GNSS sensor performance testing” (Grzunov 2016). The analysis has provided the following statistical parameters of radial components (min: -1,793 m; max: 4,075 m; average: 0,203 m) and tangential components (min: 0,000 m; max: 3,199 m; average: 0,762 m) of the horizontal deviations. As was expected, maximal values of deviation components occurred during the testing platform in movement.

All points (coordinates) determined with the central GNSS receiver (point marked with red triangle), the second (external) GNSS receiver placed at the end of the testing platform (PPK observations, forming tick red circular trajectory) and the GNSS receiver embedded on the UAV are shown on the figure 9 (altogether there are shown more than 9200 points).

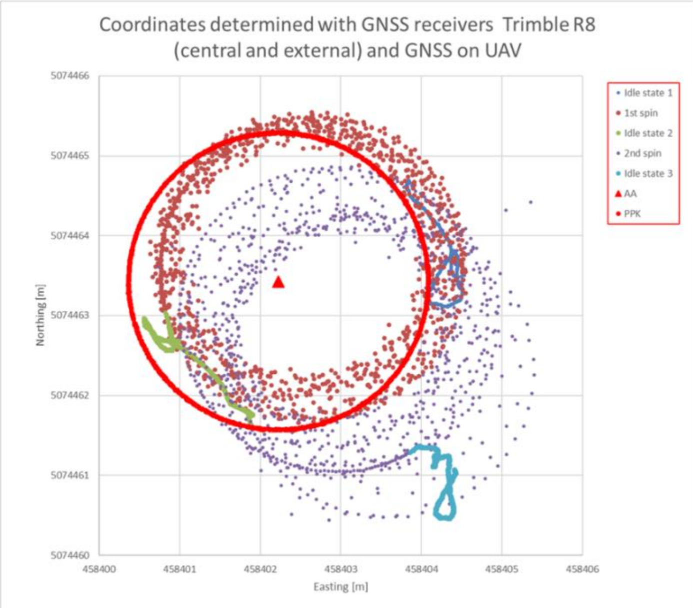

Figure 9. All coordinates determined during the kinematic test (GNSS receivers Trimble R8 (central and external) and GNSS on UAV).

However, since the platform was spinning two times during the kinematic test performance, it is interesting to display separately the points determined during the first spin (max angular velocity 3,191 rad/s) as well as during the second spin (max angular velocity 4,768 rad/s). The fist spin is shown on the Figure 10 and the second one is shown on the Figure 11.

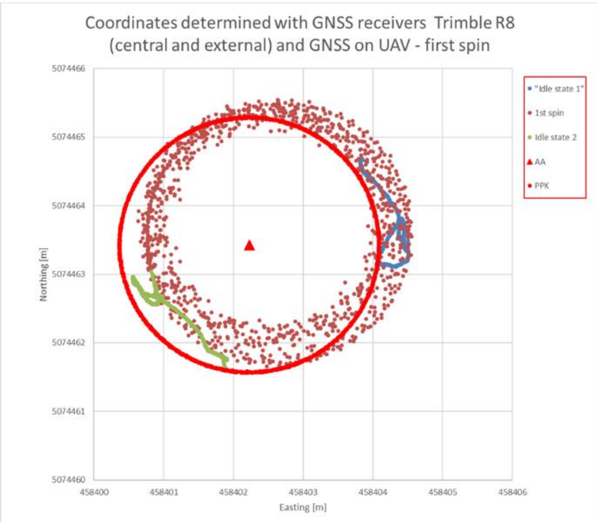

Figure 10. Points determined during the 1st spin.

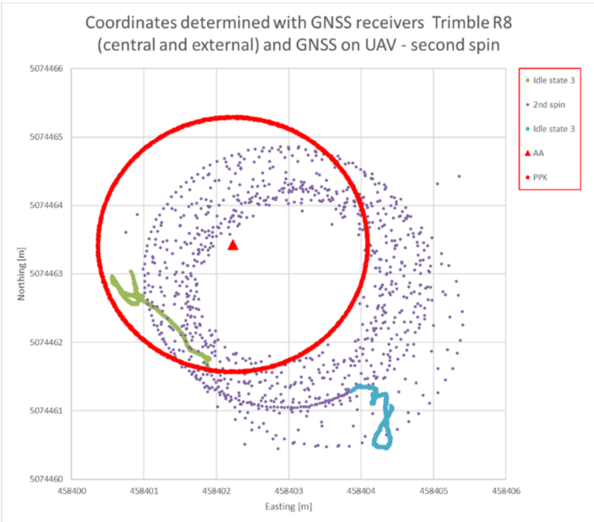

Figure 11. Points determined during the 2nd spin.

Although there was no significant difference in duration of the first and second testing platform spin (first spin lasted for 108 s, second spin lasted for 98 s) as well as no significant change in satellite constellation (GPS+GLONASS) (time difference between the start of the first and second spin was 4 minutes and 17 seconds) during the kinematic test performance, the points during the second spin showed larger scatter. The summary of the results obtained through kinematic test is given in the Table 1.

Table 1. Summary of results obtained during the kinematic test on testing platform.

UAV state	Num. of points	Lin. speed [m/s] (average)	Lin. speed [m/s] (max)	Hor. Deviation [m] (average)
Idle state 1st	1039	0,02	0,16	0,65
1st spin	1080	3,51	5,92	1,39
Idle state 2nd	892	0,02	0,32	0,65
2nd spin	980	4,55	8,84	2,02
Idle state 3rd	909	0,02	0,20	1,37

Although during the idle state of the testing platform it was stationary indeed, results from the Table 1 do not confirm this, what is the consequence of the PPK method accuracy. Larger horizontal deviations that occurred during the movement i.e. decreased accuracy of GPS/GLOASS receiver integrated on UAVs during the movement are possible reasons why during the aerial survey (camera shooting) on preplanned points of the trajectory the UAV stops. Stopping the UAV during the image shooting has multiple advantages: the vibrations are reduced, stability is increased and the determination of coordinates is improved.

3. CONCLUSION

The goal of this paper was to present the development and assessment of the testing platform which has, in the form of controlled trajectory, enabled the testing of the GNSS receivers integrated on the UAVs in idle state (static test) as well as in the movement state (kinematic test). The need for testing of GNSS receivers on the UAVs is significant since the manufacturers (i.e. equipment providers) provide poor information about receiver's specifications. The static test results of the GNSS receiver embedded on the DJI Phantom 3 Professional have shown that the horizontal position is on 1 m-level accuracy (it is more realistic to consider 2 m accuracy level), the vertical accuracy is about 5 m, while the horizontal accuracy in kinematic conditions goes down to 4 m (in average 2 m). Although it is not stated in UAV product specifications, the results of static test indicate that GNSS receiver integrated on UAV uses SBAS data corrections like EGNOS in Europe. Considering the positioning accuracies achievable by DJI Phantom 3 Professional UAV, it becomes clear why the aerial survey for the purpose of final product generation (Digital Orthophoto, DSM, 3D model etc.) must rely on Ground Control Points (GCP). The increase of accuracy could be realized by application of the Real Time Kinematic (RTK) positioning method providing cm-level accuracy. Even such receivers are subject and suitable for testing on the presented testing platform in static and kinematic mode. Further improvements of the testing platform are expected as the results of planned activities within upcoming tests.

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