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METHODOLOGY TO IMPROVE THE ACCURACY OF DETERMINING THE POSITION OF UAVS EQUIPPED WITH SINGLE-FREQUENCY RECEIVERS FOR THE PURPOSES OF GATHERING DATA ON AVIATION OBSTACLES

Summary. Low-altitude photogrammetric studies are often applied in detection of aviation obstacles. The low altitude of the Unmanned Aerial Vehicle (UAV) flight guarantees high spatial resolution (X, Y) of the obtained data. At the same time, due to high temporal resolution, UAVs have become an appropriate tool for gathering data about such obstacles. In order to ensure the required accuracy of orientation of the photogrammetric block, Ground Control Points (GCPs) are measured. The recently introduced UAV positioning solutions that are based on Post-Processing Kinematic (PPK) and Real Time Kinematic (RTK) are known to effectively reduce, or, according to other sources, even completely eliminate the necessity to conduct GCP measurements. However, the RTK method involves multiple limitations that result from the need to ensure continuous communication between the reference station and the rover receiver. The main challenge lies in

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achieving accurate orientation of the block without the need to conduct time-consuming ground measurements that are connected to signalling and measuring the GCPs. Such solution is required if the SPP code method is applied to designation the position of the UAV. The paper presents a research experiment aimed at improving the accuracy of the determination of the coordinates of UAV for the SPP method, in real time. The algorithm of the SPP method was improved with the use of IGS products.

Keywords: IGS, GPS, UAV, photogrammetry, aviation obstacle, accuracy analysis, SBAS

1. INTRODUCTION

In recent years, we have been witnessing a dynamic growth in the use of low altitude photogrammetric studies in remote sensing [13, 40], in Geographic Information Systems (GIS) [2, 9] or aviation [10]. The potential of these miniature aerial vehicles that has also been noticed by the aviation sector is used, among others, in ensuring safety in the airspace [14]. The main area of focus in the fields of photogrammetry, remote sensing and geographic information is currently the monitoring of aviation obstacles, including the detection of such obstacles in the vicinity of airports.

The 21st century has become a symbol of the development of various branches of the industry. This leads to the dramatic growth of investment areas. As a result, we are witnessing rapidly emerging new objects (various types of structures, etc.) not only in large agglomerations, but also in less urbanised areas and in the neighbourhood of airports. From the point of view of aviation safety, such objects situated near the airport may constitute a potential threat for the operations of aerial vessels, and thus become aviation obstacles. Their presence requires developing flight procedures based on the height of the aviation obstacle. Accurate and reliable data about such obstacles, in particular about their location or dimensions, such as height, are essential for planning safe take-off and landing paths for aircrafts. Existing guidelines for aviation obstacle data collection methods strictly define the accuracy of data collection. Despite the regulation of this issue, methods are still evolving to achieve the highest possible degree of automation [14]. The detection of small obstacles and those of elongated shapes is becoming a major challenge [14]. If such an object is captured, it is necessary for the scale of the image to be larger than in traditional exploratory flights. This is possible with a lower flight altitude by using a UAV. The techniques employed for the detection of aviation obstacles used so far were based on Airborne Laser Scanning (ALS). However, in such cases, one cannot exclude the possibility of omitting an obstacle [14], and the object detection was controlled using ordinary geodetic measurements. As a result, the process was time-consuming and strenuous, not to mention ineffective, especially in representing large-surface areas. In order to maintain the safety of air operations, it is necessary that the data about obstacles should be updated regularly, whenever necessary. Unfortunately, ALS data does not guarantee high temporal resolution of obtaining data. The latest guidelines [14] for obtaining obstacle data recommend using data obtained from lower altitudes of flight, which may be achieved by using UAVs. They allow obtaining imagery in a scale which is significantly larger than that obtained from traditional photogrammetric flights. In addition, the UAV altitude will allow for much higher spatial accuracy (X, Y, Z) of aviation obstacle data. The accuracy of obtaining data from UAV is influenced by several factors. Among them, one may distinguish the method and accuracy of positioning of the Unmanned Aerial Vehicle [36] and the accuracy of adjustment of the photogrammetric block [30, 15, 4]. Until recently, the processing of data obtained from a photogrammetric flight required conducting a measurement of the control points (GCP) to perform an absolute orientation of the model. This resulted in an extended duration of the process of measurement as well as data processing. Currently, the development of the UAV technology, among others, in photogrammetric applications, resulted in the possibility to use numerical algorithms that improve the positioning of the platform in real time, while the necessary navigation analyses may be conducted in post-processing mode. As a consequence, this may lead to the complete elimination of the need to conduct measurements of ground control points (GCP). For more than ten years, the main device used to detect the position of the UAV has been the GNSS (Global Navigation Satellite System) satellite receiver with the functions of tracking, monitoring, and recording the observations and navigation data. GNSS receivers provide the 3 main navigation parameters of a UAV: position, velocity, and time [23]. From the point of view of photogrammetric applications, the navigation data of the UAV enable the determination of elements of exterior orientation, first of all linear ones, i.e. the centres of the projection of each photograph [15]. In this case, it is necessary to know the eccentric of the position shift of the GNSS receiver antenna and of the camera at the moment of exposure. While the value of the eccentric is provided by the manufacturer on the name plate of the unmanned platform, the position of the antenna of the GNSS receiver mounted on the platform still has to be determined. In low-cost on-board GNSS receivers, the coordinates of the UAV is designated in near-real time with the use of the SPP (Single Point Positioning) method [29]. This method is based on the application of single-frequency receivers mounted on the UAV platform [37]. Even though this method is the most commonly used, it is characterised by low positioning accuracy, reaching even up to 10 m [5, 11]. Another currently used solution is an RTK system integrated with the aerial vessel, which can allow the number of GCPs to be reduced or eliminated altogether. However, the RTK method involves multiple limitations that result from the need to ensure continuous communication between the base station and the mobile receiver. It should be noted that a UAV equipped with GPS does not require the data from GNSS reference station, which might significantly improve the efficiency of the process of collecting data on aviation obstacles. Previous studies [33] revealed the possibility to obtain a high accuracy by UAVs equipped with GPS receivers.

The authors of this study took an attempt to improve the determination of the accuracy of the positioning of UAVs for the SPP method. With this aim, IGS products were used to improve the algorithm of the SPP method.

1.1. Related works

In recent years, many studies have been conducted on the application of the single point positioning method to determine the position of aerial vehicles [22]. Publications discussing the accuracy of the SPP method in positioning Unmanned Aerial Vehicles [37] and the attempts to improve this accuracy are also becoming more common. The need to enhance the accuracy of positioning UAVs resulted in the development of numerical algorithms that improve the positioning of UAVs in terms of code observations for the SPP method [39] and thus, the adjustment of the determination of the linear elements of exterior orientation.

In the study by Santerre et al. [29], the Chinese satellite system BeiDou was used and compared to the American GPS system and the Russian GLONASS systems. In fact, the BeiDou system consists of 14 satellites that provide complete coverage of the whole Asia and Pacific area. Positioning with use of the SPP method was conducted in Changsha in the Hunan Province of China, in order to demonstrate the benefits of the use of the combined pseudodistance solutions from these 3 satellite navigation systems, in particular in covered locations. The results demonstrated an improvement in accuracy by 20% for the horizontal coordinates and by 50% for the vertical coordinates. The combination of the GPS/GLONASS/BeiDou solutions resulted in an accuracy of approx. 5 m.

Other methods of enhancing the accuracy of the single point positioning method were presented in the study by Angrisano et al. [3]. The tests were conducted with the use of UAVs in the area of an urban agglomeration, with tall structures such as skyscraper buildings. The navigation algorithm for positioning the UAV was based on the weighted average model. The conducted experiments resulted in an accuracy of approx. 10 m, which was achieved in a difficult, urban area.

Furthermore, Forlani et al. [15] presented the results of a research experiment that consisted in assessing the improvement of the orientation accuracy of a photogrammetric block with use of various numbers of GCP. Apart from that, the authors compared alternative positioning methods (including the SPP method) in order to determine the position of the UAV platform. The photogrammetric flight was performed with the Dji Phantom 4 RTK platform on the test military training ground in the Italian Alps. The conducted research demonstrated that determining the coordinates of a UAV platform with the use of the SPP code method allows obtaining a spatial accuracy of several meters when independent ground control points are used in the whole test area.

Kai-Wei Chiang et al. [7] developed a fast and inexpensive system for gathering spatial information in near-real time. The authors pointed out that fast collection of information had become a new trend in remote sensing applications. During the studies, a platform for obtaining spatial information based on UAV, without the need to measure ground control points, was developed. The UAV-based platform shown has a Direct Georeferencing (DG) module [6], which includes an integrated Inertial Navigation System (INS)/ Global Positioning System (GPS). The initially results of the analysis of positioning accuracy in the DG mode revealed that the accuracy of horizontal positioning was approx. 5 m at the flight attitude of 300 m above ground. The positioning accuracy for the vertical component was lower than 10 m.

The research conducted by Himanshu Sharma et al. [34] demonstrated a significant increase in positioning accuracy over the standard SPP solution, after the application of the Kalman filter. H.R. Hosseinpoor et al. [20] developed an algorithm that enables to estimate the geolocation of the target based on the video images captured by a UAV with RTK GPS module. These results were compared to the positioning accuracy obtained with use of the GPS solution for the SPP code method instead of RTK. The research results revealed that the accuracy improved by several tens of centimetres without the necessity to perform measurements of ground control points.

In order to facilitate certain types of applications, e.g., environmental detection or monitoring disasters, it is essential to develop an effective system for acquiring spatial information in near-real time. Speed and ease in gathering spatial information has become the most important goal in land mapping technology. Meng-Lun Tsai et al. [7] presented a platform that was developed to obtain spatial information based on UAV. Additionally, the results of the assessment of data collection accuracy were provided. The presented platform based on UAV is equipped with a DG module, including an integrated INS/GPS system, a digital camera, as well as other general UAV modules in which all the necessary calibration procedures were implemented. During the research project, test flights were conducted in order to verify the positioning accuracy in the direct georeferencing mode, without using ground control points. The preliminary results of the positioning accuracy in direct geo-referencing mode without the use of GCP demonstrated that the accuracy of horizontal positioning was lower than 20 meters, while the vertical positioning accuracy (z) was lower than 50 m at the flight altitude of 600 meters above ground. The authors pointed out that the obtained accuracy results may be useful in monitoring disasters, where it is vital to obtain spatial information fast, in near-real time.

The literature review revealed a recurring problem of low positioning accuracy of unmanned aerial vehicles when the SPP code method was used. In the conducted research, the authors of the present study took an attempt to enhance the accuracy of positioning the UAV for the purposes of collecting data about aviation obstacles. In order to achieve it, the algorithm of the SPP code method was modified by adding IGS products to determine the position of the UAV.

1.2. Research purpose

In this paper, a research question was posed: whether the modification of the algorithm of the absolute positioning method SPP by adding IGS products will enable to enhance the accuracy of the positioning of UAVs for the purposes of collecting data about aviation obstacles? IGS products are understood as precise ephemerides in the EPH format, precise clocks in the CLK format, the IONEX ionosphere map format, the DCB instrumental error format, and the format of the antenna phase center of the satellite/receiver ANTEX.

The main objective of the research was to develop a methodology to enhance the accuracy of the positioning of UAVs that are equipped with single-frequency receivers and the accuracy of photogrammetric products for the purposes of collecting data about aviation obstacles without measuring the ground control points.

The paper consists of: section 2 where the research method is described; section 3 presents the experimental materials and results; section 4 is a description of the results obtained and section 5 provides a summary.

2. METHODS

This chapter provides a description and presentation of the observation equation for the SPP positioning method with use of GPS navigation data and the observation equation in the modified algorithm of the SPP positioning method with IGS products, i.e.: the precise ephemerides EPH, precise clocks CLK, the IONEX format, DCB format, and ANTEX format. The block diagram of the process of improving the accuracy of determining the position of the UAV for the purposes of collecting data about obstacles is presented in the illustration below (Fig. 1). It presents two methods of determining the position of the UAV: with the SPP method and with the SPP + IGS method. For these two methods, the photogrammetric block of images was adjusted without measuring the ground control points. Then, based on the obtained results, the accuracy of positioning of the UAV and the adjustment of the block of images were analysed.

In this study, two research methods were used to designation the position of the UAV. These were: the classic navigation algorithm for the code-based SPP method using the GPS navigation data and the modified algorithm of the SPP method with the added products of the IGS geodesic service. The fundamental observation equation for the SPP method using GPS navigation data takes the form presented below [18, 31]:

$$l = d + c(dtr - dts) + Ion + Trop + Rel + TGD + Mp \tag{1}$$

where:
l – code observations;

d – geometric distance between the satellite and the receiver;
$d = \sqrt{(X - X_{GPS})^2 + (Y - Y_{GPS})^2 + (Z - Z_{GPS})^2}$;
(X, Y, Z) – unknown coordinates of the UAV;
$(X_{GPS}, Y_{GPS}, Z_{GPS})$ – coordinates of the GPS satellites;
c – light speed;
dtr – unknown bias of the receiver clock;
dts – correction of the receiver clock;
Ion – ionospheric correction;
$Trop$ – tropospheric delay;
Rel – relativistic effect;
TGD – group delay in GPS system;
Mp – multipath effect.

The positioning algorithm in equation (1) is a classical solution of the position in the SPP method. The position of the UAV in the geocentric frame XYZ are determined from equation (1) in form of parameters (X, Y, Z).

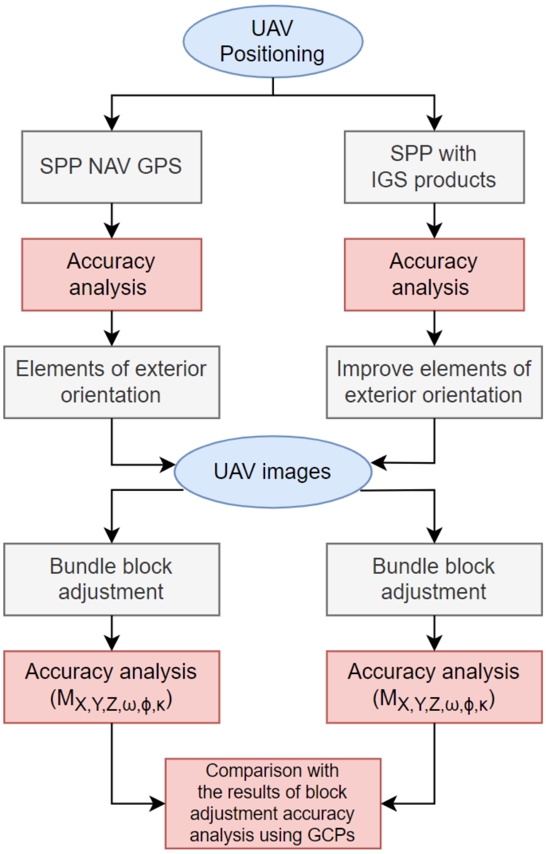

Fig. 1. The scheme of improving the accuracy of UAV position

On the other hand, the basic observation equation in the modified algorithm of the SPP method with use of the IGS products takes the following form [17, 24]:

$$l = d' + c(dtr - dts') + Ion' + Trop + \mathrm{Rel} + SDCB'_{P1} + RDCB'_{P1} + Mp \qquad (2)$$

where:
l – code observations;
d – geometric distance between the satellite and the receiver, include the phase center offset from ANTEX format;
$d' = \sqrt{(X - X'_{GPS})^2 + (Y - Y'_{GPS})^2 + (Z - Z'_{GPS})^2}$;
(X, Y, Z) – unknown coordinates of the UAV;
$(X'_{GPS}, Y'_{GPS}, Z'_{GPS})$ – coordinates of GPS satellites, the coordinates are determined with the use of Lagrange's polynomial from the precise ephemeris EPH obtained from the IGS geodesic services;
c – light speed;
dtr – unknown bias of the receiver clock;
dts' – bias of the receiver clock, determined based on the CLK format from the IGS geodesic services;
Ion' – ionosphere delay, which is interpolated from the GRID in the IONEX format obtained from the IGS geodesic services;
$Trop$ – tropospheric delay, calculated based on the determinist model of tropospheric delay;
Rel – relativistic effect;
$SDCB'_{P1}$ – hardware delay for the $SDCB_{P1}$ satellite, based on the DCB product from the IGS geodesic services;
$RDCB'_{P1}$ – hardware delay for the $SDCB_{P1}$ receiver, determined in the linear combination Geometry-Free or based on the DCB product from the IGS geodesic services;
Mp – multipath effect.

The algorithm in equation (2) is a modified solution of positioning in the code-based SPP method, where IGS products were applied, i.e.: the EPH format, CLK format, IONEX format, DCB format, and the ANTEX format. Similarly, as with equation (1), algorithm (2) enables the designation of the coordinates of the UAV. When comparing the observation equations (1) and (2), attention should be paid to different models of systematic errors. Thus, if the position of the GPS satellite on the orbit is determined from equation (1), Kepler's model of the orbit is applied, while equation (2) uses the Lagrange polynomial model. Apart from that, the coordinates of GPS satellites that are determined from the Lagrange polynomial take into account the correction of the phase centre offset of the satellite antenna based on the ANTEX format. The accuracy of positioning from the Kepler model of the orbit is 1 m, while with the Lagrange polynomial it is 0.10 m. Additionally, the error of the satellite clock in the Kepler orbit model is determined with use of a 2nd degree polynomial, and the accuracy of this solution is 5 ns (approx. 0.15 m). In addition, in equation (2), the error of the GPS satellite clock is determined from the CLK format, and its accuracy is higher than 3 ns (approx. 0.1 m [21]). As for the model of the ionosphere, the Klobuchar model applied in equation (1) reduces ionospheric delay by approx. 50-60%, while the ionosphere model from the IONEX format reduces it by approx. 80-90% respectively. As far as hardware delay is concerned, the TGD parameter is used in equation (1), while equation (2) is based on DCB instrumental errors [18]. The comparison of equations (1) and (2) reveals that the application of different types of systematic errors will influence the final designation of the coordinates of the UAV in the stochastic process, as well as the accuracy of positioning of the UAV. The results of the research are presented in Section 3.

3. MATERIALS AND EXPERIMENTAL RESULTS

3.1. Study area

The research experiment was performed near the Radom-Sadków airport (Fig. 2). The Radom-Sadków airport is located near the city centre of Radom. The area surrounding the airport is covered by aviation obstacle data collection zones. In the nearest vicinity of the airport, zone 2a – in the runway strip and zone 2b that is directly connected to zone 2a and covers the take-off sector (Fig. 2).

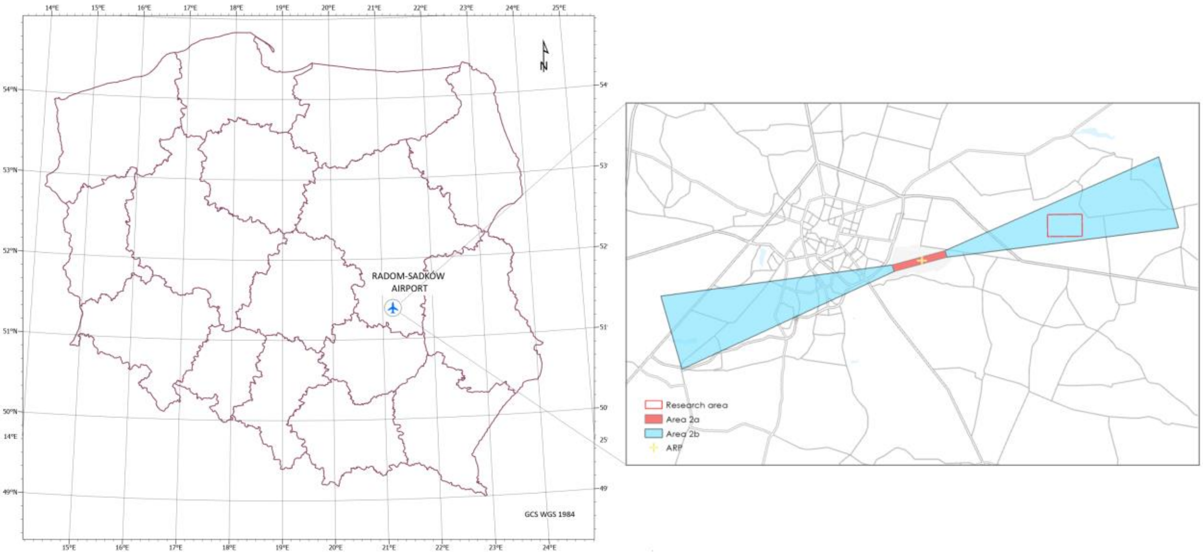

Fig. 2. Location of the research area

The zones of collecting data about aviation obstacles are planes in which data about aviation obstacles are collected. Such data are necessary in the widely understood process of ensuring safety in airspace, from designing flight operations procedures to developing aeronautical charts.

In the research area near the Radom-Sadków airport, data were acquired using the VTOL WingtraOne system. The platform was equipped with a single-frequency GPS receiver, recording data at 10 Hz. The flight was conducted over two test areas in June 2021. Atmospheric conditions during the raids were good. The test block consisted of 35 series, which constituted 850 images (Fig. 2), acquired from a height of 250 m above the ground surface. The flight was conducted in an east-west direction, with transverse and longitudinal coverage of 75%. The main parameters of the test block in the conducted experiment are presented in the table below (Tab. 1).

Tab. 1

Parameters of the test block

Set of coordinates	PUWG 2000/7
Image saving format	JPEG
Number of series	35
Sensor	Sony RX1R II camera

Lens focal length [mm]	35 mm
Average longitudinal/ transverse coverage [%]	75/75
Flight altitude [m]	250
Theoretic pixel size [m]	0.04

For the purposes of conducting the study and verifying the correctness of the applied mathematical algorithms (1) and (2), navigation calculations were performed in the RTKLIB v. 2.4.3 software [28], and then in the language environment Scilab v.6.1.1. [32]. The RTKLIB was used to designation the position of the UAV based on the mathematical equations (1) and (2). For equation (1), the calculations in RTKLIB software were configured as follows [27]:

- source of observation data: format RINEX 2.11,
- source of navigation data: RINEX navigation 2.11,
- observations used: code-based observations L1-C/A from the AsteRx-m2 UAS receiver,
- calculation interval: 1 second,
- set of coordinates: WGS-84, geocentric coordinates XYZ,
- positioning method: SPP,
- source of ephemeral data: GPS navigation message,
- source of data about satellite clock error: GPS navigation message,
- ionosphere model: Klobuchar model from the GPS navigation message,
- elevation mask: 5^{o},
- troposphere model: Saastamoinen model,
- hardware delay: TGD parameter,
- navigation system: GPS system,
- reference time: GPS Time.

Moreover, for equation (2), the configuration of the computations in the RTKLIB programme was set as follows [27]:

- source of observation data: format RINEX 2.11,
- source of navigation data: RINEX navigation 2.11,
- observations used: code-based observations L1-C/A from the AsteRx-m2 UAS receiver,
- calculation interval: 1 second,
- set of coordinates: WGS-84, geocentric coordinates XYZ,
- positioning method: SPP,
- source of ephemeral data: EPH format and ANTEX format,
- source of data about satellite clock error: CLK format,
- ionosphere model: IONEX format,
- elevation mask: 5o,
- troposphere model: Saastamoinen model,
- hardware delay: DCB format,
- navigation system: GPS system,
- reference time: GPS Time.

The RTKLIB software was also used to determine the reference position of the UAV flight with use of the RTK-OTF positioning method. The following scheme of configuration of the input parameters for the determination of the reference position of flight was applied [27]:
- positioning type: MOVING BASE,
- source of GNSS navigation data: GPS board message,
- source of GNSS observation data from the on-board receiver: kinematic GPS observations in the RINEX 2.12 format from the AsteRx-m2 UAS receiver,
- source of GNSS observation data from reference station: static GPS observations in RINEX 2.12 format,
- method of determining the coordinates of the GPS satellite: based on the parameters of Kepler's orbit,
- elevation mask: 5°,
- ionosphere model: Klobuchar model from the GPS navigation message,
- troposphere model: Saastamoinen model,
- model of orbit and clocks: board ephemeris,
- calculation interval of the measurement epoch: 1 second,
- set of coordinates: WGS-84,
- final format of coordinates: geocentric coordinates XYZ,
- navigation system: GPS,
- reference time: GPS Time.

After the navigation calculations were performed in the RTKLIB software, the authors developed a script in the Scilab programming language to determine the accuracy of the positioning of UAV for the SPP method using equation (1) and for the SPP method with IGS products from equation (2).

3.2. Experimental results

The research experiment consisted in a flight of an unmanned aerial vehicle. Then, based on the obtained data, the accuracy of UAV positioning and the accuracy of the adjustment of the block of images from the UAV were analysed.

3.2.1. Analysis of UAV positioning accuracy

In the framework of the conducted research, the UAV positioning accuracies were determined for equations (1) and (2). Firstly, position errors were determined, i.e., the coordinates of the UAV calculated from equations (1) and (2) were compared to the reference position of the flight from RTK-OTF solution [38]. To achieve it, position errors were calculated as follows:

$$dX = \begin{cases} X_{SPP} - X_{RTK} \\ X_{IGS} - X_{RTK} \end{cases} \tag{3}$$

$$dY = \begin{cases} Y_{SPP} - Y_{RTK} \\ Y_{IGS} - Y_{RTK} \end{cases} \tag{4}$$

$$dZ = \begin{cases} Z_{SPP} - Z_{RTK} \\ Z_{IGS} - Z_{RTK} \end{cases} \tag{5}$$

Where:
(dX, dY, dZ) – position errors,
$(X_{SPP}, Y_{SPP}, Z_{SPP})$ – coordinates of the UAV from equation (1),
$(X_{IGS}, Y_{IGS}, Z_{IGS})$ – coordinates of the UAV from equation (2),
$(X_{RTK}, Y_{RTK}, Z_{RTK})$ – reference coordinates of the UAV flight from the RTK-OTF solution.

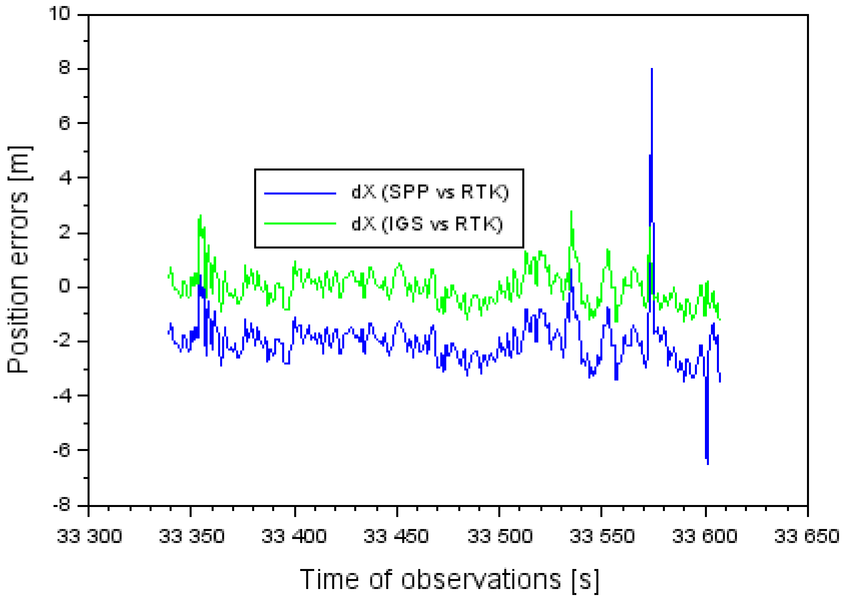

Fig. 3. The position errors for X coordinate

Figure 3 presents the results of position errors for X coordinate for a representative flight of the UAV in Radom. The values of position errors along the X axis for the comparison of the coordinates from equation (1) and the RTK-OTF technique is between -6.5 m to +8.1 m, with the average value of -2.1 m. On the other hand, position errors for equation (2) for the comparison of the coordinates from equation (2) and the RTK-OTF technique ranged from -1.3 m to +2.8 m, with the average value of -0.1 m. The comparison allows us to state that the application of the IGS products in the SPP method resulted in improving the accuracy of determining the position of the UAV along the X axis by approx. 95% in comparison to the classical SPP solution for equation (1).

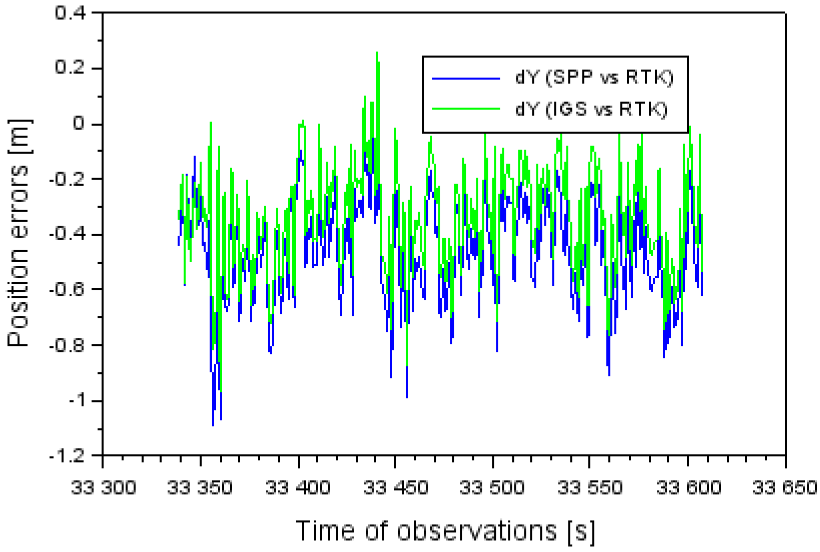

Fig. 4. The position errors for Y coordinate

Figure 4 presents the results of position errors for Y coordinate based on equation (4). The values of position errors along the Y axis for the comparison of the coordinates from equation (1) and the RTK-OTF technique range from -1.1 m to +0.2 m, with the average value of -0.5 m. On the other hand, position errors for equation (2) for the comparison of the coordinates from equation (2) and the RTK-OTF technique ranged from -1.0 m to +0.3 m, with the average value of -0.3 m. The comparison allows us to state that the application of the IGS products in the SPP method resulted in improving the accuracy of determining the position of the UAV along the Y axis by 40% in comparison to the classical SPP solution for equation (1).

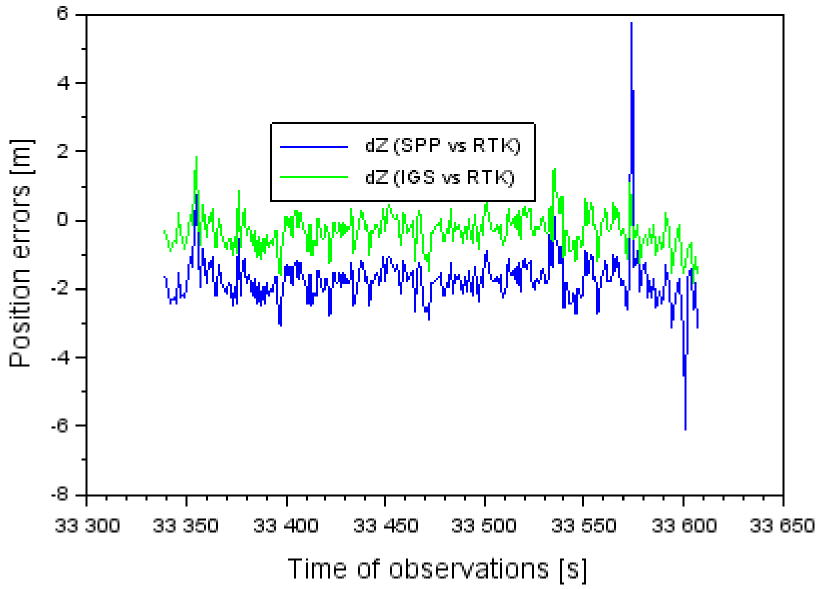

Fig. 5. The position errors for Z coordinate

Figure 5 presents the results of position errors for Z coordinate based on equation (5). The values of position errors along the Z axis for the comparison of the coordinates from equation (1) and the RTK-OTF technique is between -6.1 m to +5.8 m, with the average value of -1.7 m. On the other hand, position errors for equation (2) for the comparison of the coordinates from equation (2) and the RTK-OTF technique ranged from -1.8 m to +1.8 m, with the average value of -0.3 m. The comparison allows us to state that the application of the IGS products in the SPP method resulted in improving the accuracy of determining the position of the UAV along the Z axis by over 80% in comparison to the classical SPP solution for equation (1).

As far as collecting data about aviation obstacles by UAVs is concerned, a particularly important element is the designation of the resultant accuracy of the platform in 3D space. Then it is necessary to use it as the basis for calculating the accuracy of UAV position in 3D space, as presented below:

$$dS = \begin{cases} \sqrt{dX_{SPP}^2 + dY_{SPP}^2 + dZ_{SPP}^2} \\ \sqrt{dX_{RTK}^2 + dY_{RTK}^2 + dZ_{RTK}^2} \end{cases} \tag{6}$$

where:
dS – the resultant accuracy of the designation of the position of the UAV.

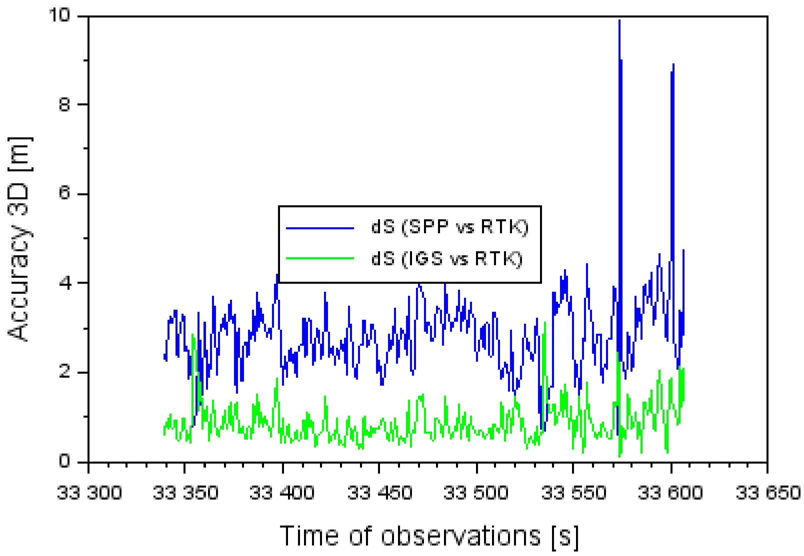

Fig. 6. The resultant accuracy of UAV in 3D space

Figure 6 shows the results of the determination of parameter dS for the position of UAV. Here, for the comparison of the coordinates from equation (1) and the RTK-OTF technique, the values of the dS factor range from 0.6 m to 9.9 m, with the average value of 2.8 m. On the other hand, for the comparison of the coordinates from equation (1) and the RTK-OTF technique, the values of the dS factor are between 0.1 m to 3.2 m, with the average value of 0.9 m. The comparison of the obtained results of the dS parameter allows us to claim that the application of the IGS products in the SPP method enabled to reduce the dS parameter by approx. 67% in comparison to the classic SPP navigation solution.

3.2.2. Block adjustment accuracy analysis

The image data obtained during the flight were processed in the UASMaster software. The block of images obtained at a low altitude was adjusted based on the adjustment algorithm using the independent bundle method. Then, the exterior orientation of the images was defined and approximate elements of exterior orientation were introduced for each image. The linking points were generated automatically using a digital image correlation strategy based on the least squares method. The block was adjusted without measuring the control points, for two variants of the UAV positioning method. The first variant was based on UAV positioning with use of the single point positioning method, while the second one was based on UAV positioning with use of the code-based SPP method modified to include the EPH format, CLK format, IONEX format, DCB format, and the ANTEX format. For the purposes of accuracy analysis, the results obtained from the block adjustment were then compared to the results of block adjustment using GCPs. To do so, additionally, measurements of 14 signalled ground control points were conducted in the test area with use of the RTK method in the GPS system. The accuracy of determination of the coordinates of ground control points (X, Y, Z) was 0.03 m.

After the block adjustment in the first variant of UAV positioning, the errors were calculated for the linear and angular elements of exterior orientation. The accuracy of determining the coordinates of the centres of projections X_0, Y_0, Z_0 amounted to 3.16 m to 7.22 m. The angular elements of exterior orientation ω, φ, κ were determined with an accuracy of 0.211° to 0.256°. For the second variant of UAV positioning, the accuracy of the liner elements X_0, Y_0, Z_0 ranged from 1.98 m to 3.22 m, while the accuracy of the angular elements ω, φ, κ ranged from 0.172° to 0.215°. As a result of block adjustment with use of ground control points, the following accuracy values were obtained: for linear elements X_0, Y_0, Z_0 from 0.13 m to 0.17 m, and for angular elements ω, φ, κ from 0.061° to 0.078°. The results of block adjustment for specific variants are presented in the table below (Tab. 2).

Tab. 2

Summary of blocks adjustment

Description	Variant 1: without GCPs (SPP positioning)	Variant 2: without GCPs (SPP positioning + IGS)	With GCPs
MX_0 [m]	3.16	2.31	0.14
MY_0 [m]	4.08	3.22	0.13
MZ_0 [m]	7.22	1.98	0.17
Mω [°]	0.243	0.215	0.061
Mφ [°]	0.211	0.172	0.068
Mκ [°]	0.256	0.194	0.078

Based on the obtained results, it was found that the application of the classical SPP method extended to include IGS products led to an improved accuracy of the adjustment of a block of photographs. The accuracy of the determination of the linear elements of exterior orientation increased, on average, by 58%, while the accuracy of the angular elements increased, on average, by 18%. The proposed modification of the absolute positioning algorithm SPP by adding IGS products allowed us to obtain the accuracy results of block adjustment that were very similar to those obtained when the block was adjusted based on the measured ground control points.

4. DISCUSSION

Due to the fact that there are two important aspects of the conducted accuracy analysis, this section has been divided into two subsections. In the first part, the accuracy results of the proposed method of positioning UAV are analysed. Part two discusses the results from the adjustment of a block of images after applying the suggested positioning method.

4.1. UAV positioning

This part of the discussion addresses three topics: 1) the reproducibility of the proposed research method, 2) the comparison of the obtained test results with the SPP solution with EGNOS corrections, and 3) the comparison of the obtained results to the knowledge state analysis.

As far as the reproducibility of the proposed research method is concerned, the results of the accuracy of positioning of UAV from another test flight, from the period from 11:22:15 (40935 s) to 12:06:03 (43563 s) according to GPS Time (GPST) were presented. This flight also took place in Radom, on the same measurement day. Figures 7-9 present the results of the accuracy of the UAV position determination along the XYZ axes of coordinates. Figure 7 shows that the application of the IGS products in the SPP method resulted in improving the accuracy of determining the coordinates of the UAV along the X axis by 96% in comparison to the classical SPP navigation solution. Furthermore, Figure 8 shows that the application of the IGS products in the SPP method resulted in improving the accuracy of determining the position of the UAV along the Y axis by 31% in comparison to the classical SPP navigation solution. Finally, Figure 9 confirms that the application of the IGS products in the SPP method resulted in improving the accuracy of determining the position of the UAV along the Z axis by 86% in comparison to the classical SPP navigation solution. The obtained experimental results demonstrated that it is justified to include IGS products in the code-based SPP method. Moreover, the comparison of the test results presented in Fig. 3-5 and Fig. 7-9 reveals the repeatability of the calculation process in form of the reduction in position errors when IGS products were used in the navigation solution for the positioning of the UAV.

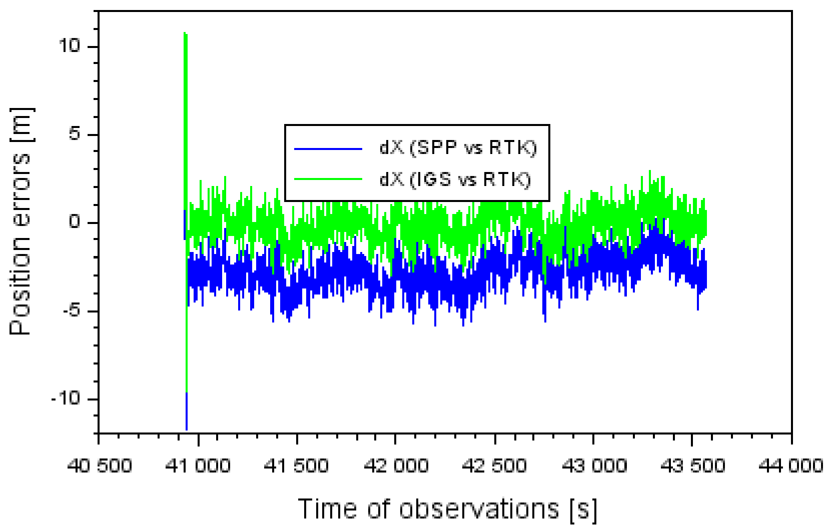

Fig. 7. The position errors for X coordinate in the 2nd test flight

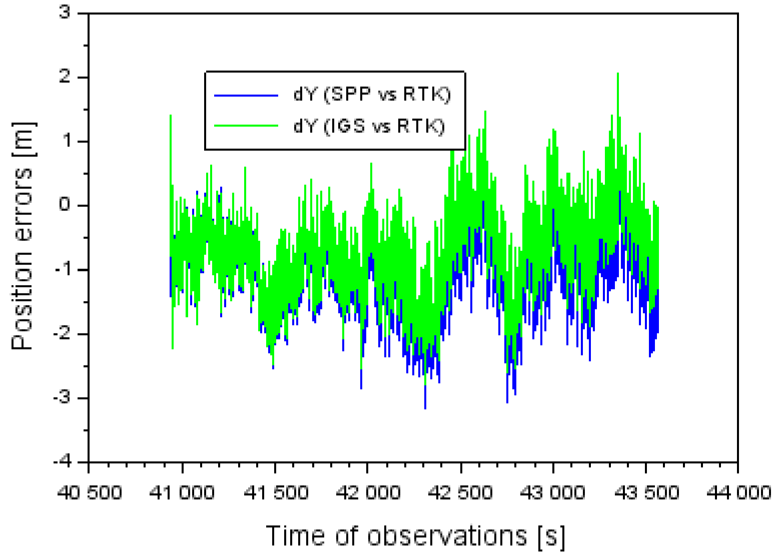

Fig. 8. The position errors for Y coordinate in the 2nd test flight

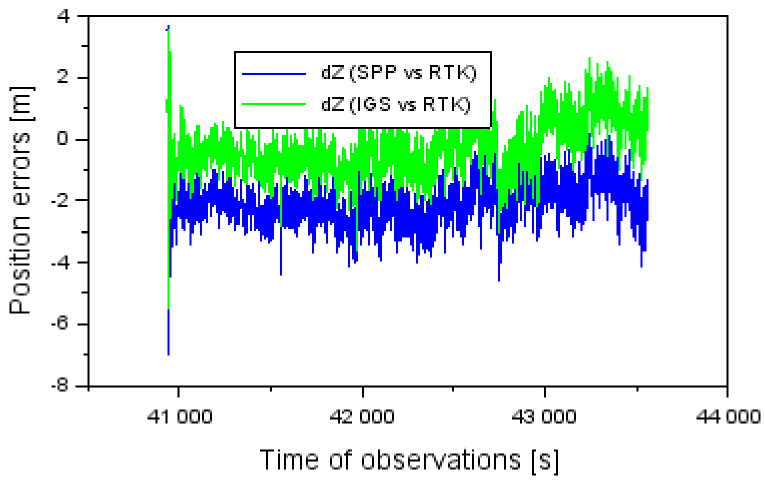

Fig. 9. The position errors for Z coordinate in the 2nd test flight

Additionally, Figure 10 shows the results of the *dS* parameter for test flight 2 with use of the UAV platform. Similarly, as in Figure 6, the accuracy of the positioning of UAV also improved by approx. 60% after the application of IGS products.

The second part of the discussion compares the obtained test results with another research method by comparing the results from the SPP solution with use of the IGS products to the SPP solution with EGNOS corrections [8]. The results of this comparison are presented in Figure 11. For the purposes of comparison, the accuracy results of *dS* term in 3D space from test flight 2 were also compared. The results for the *dS* term for the SPP solution with IGS products were also presented above, in Figure 10. They were, respectively, from 0.1 m to 11.2 m, while the results of the *dS* term from the SPP solution with EGNOS correction ranged from 0.1 m to 15.2 m. Thus, the application of IGS products enabled to improve the accuracy of UAV positioning by approximately 3÷4% in comparison to the application of EGNOS corrections.

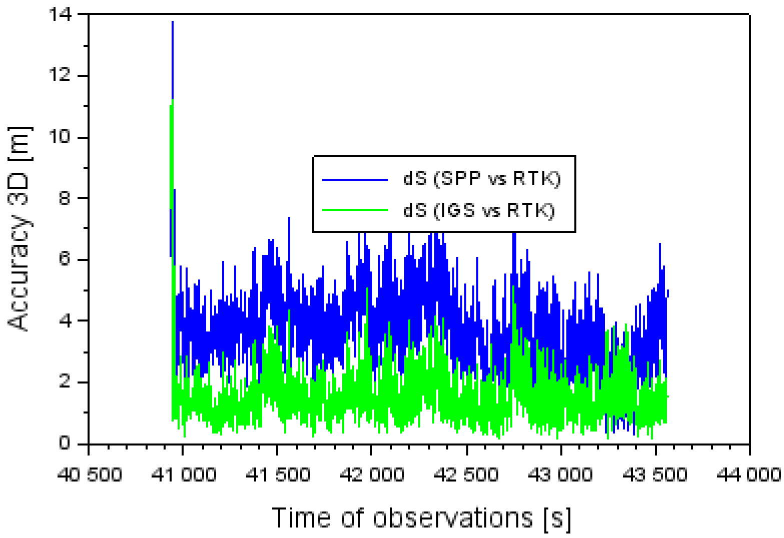

Fig. 10. The resultant accuracy of UAV in 3D space in the 2nd test flight

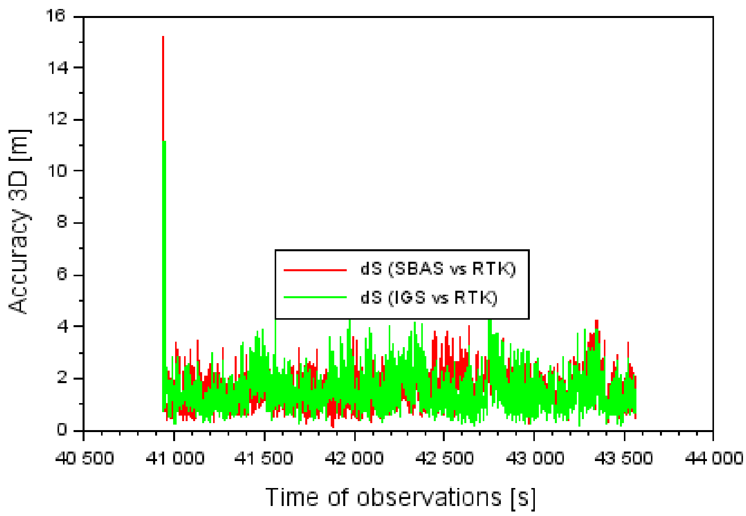

Fig. 11. Comparison of resultant accuracy *dS* using IGS products and EGNOS corrections in 2nd test flight

The last element of this part of the discussion is the comparison of the obtained results to the knowledge state analysis. The results of the research experiment presented in the work by Himanshu Sharma et al. [34] showed an improvement in the accuracy of the positioning of an UAV with the use of the SPP method extended by adding the Kalman filter. The obtained results demonstrated that the accuracy of UAV positioning improved by several tens of centimetres in comparison to the classical SPP method. The study by Angrisano et al. [3] presented an improvement in the accuracy of the absolute method of UAV positioning by applying a positioning algorithm that was based on the weighted average model. As a result, although the tests were conducted in an urban area that is difficult to measure, horizontal accuracy below 10 m was achieved. The attempts at improving the accuracy of positioning with use of the SPP method that were discussed in previous publications demonstrated that it is possible and realistic to obtain satisfactory results. However, the methodology of enhancing the accuracy of determining the position of UAV proposed here, which consists in modifying the algorithm of the SPP method by including products of the IGS geodesic services, shows an improvement in the accuracy by as much as 95% along the X axis, by 40% along the Y axis, and by 80% along the Z axis.

4.2. UAV block adjustment

Evaluation of the effectiveness of the proposed method for increasing the accuracy of UAV position determination was carried out on the basis of a research experiment of adjustment of a block of images in two variants of the positioning method. The application of the classical navigation solution for the code-based SPP method with use of GPS navigation data allowed us to obtain the following accuracy values of the exterior orientation elements: from 3.16 m to 7.22 m for linear elements and from 0.211° to 0.256° for angular elements. The determination of the UAV coordinates with use of the algorithm of the SPP method modified by adding the products of IGS geodesic services resulted in improving the accuracy of the adjustment of the block of images by 58%, on average, for linear exterior orientation elements, and by 18%, on average, for the angular elements. The reliability of the results of the conducted accuracy analysis was compared to the accuracy of adjustment of the block of images where ground control points were used for the internal orientation of the model. The methodology presented in this paper to increase the accuracy of UAV positioning allowed to achieve block adjustment accuracy without the use of photogrammetric matrix points at a level higher than 3.22 m. Previous publications on the determination of the position of unmanned aerial vehicles for single-frequency GPS receivers usually pointed to the necessity to establish and measure a photogrammetric grid in the test area in order to improve the accuracy of the generated photogrammetric points [25, 16, 12]. Particular attention was paid to the influence of the number and distribution of ground control points in the whole test area [26, 19, 35, 33, 1]. As the research results are often quite ambiguous about this issue, the topic of the accuracy of UAV positioning and the accuracy of the generated photogrammetric products continues to evolve. In his studies, Shahbazi et al. [33] presented the possibility to obtain a high level of accuracy of the adjustment of the block obtained from a UAV equipped with a GPS receiver. Moreover, the RTK system that is also currently used is integrated with unmanned aerial vehicle and may contribute to reducing the number of GCPs or eliminating them completely, allows achieving an accuracy of UAV positioning on the level of only several centimetres.

5. CONCLUSION

This paper shows the results of the experiments and analyses concerning the determination of the position of an UAV. The main objective of the research was to develop a methodology to improve the accuracy of UAV positioning based on modifying the algorithm of the SPP method by adding products of the IGS geodesic services. The second objective was to improve the accuracy of photogrammetric products for aviation obstacles data collection without the need to conduct measurements of ground control points. The tests were conducted with the use of two methods. The first of them presented a classic navigation solution for the code-based SPP method with use of GPS navigation data. The second method employed the algorithm of the SPP method that was modified to include IGS products (i.e. precision ephemeris, precision clock, the IONEX format, the DCB format, and the ANTEX format). The conducted analyses revealed that the use of the modification of the absolute positioning SPP method by adding IGS products allowed to improve the accuracy of determining the position of an UAV in order to obtain data about aviation obstacles by 95% along the X axis, by 40% along the Y axis, and by 80% along the Z axis.

The designation of the position of an UAV with use of the algorithm of the SPP method modified by adding the products of IGS geodesic services resulted in improving the accuracy of the adjustment of the block of images by 58%, on average, for linear exterior orientation elements, and by 18%, on average, for the angular elements. Applying the modification of the Single Point Positioning method by adding IGS products will enable to obtain the accuracy of collecting data about aviation obstacles that is required by the European standards [14] – for the X, Y coordinates on the level of 5 m, and for the Z coordinate on the level up to 3 m.

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References

1. Agüera-Vega Francisco, Fernando Carvajal-Ramírez, Patricio Martínez-Carricondo. 2017. „Assessment of photogrammetric mapping accuracy based on variation ground control points number using unmanned aerial vehicle”. *Measurement* 98: 221-227. DOI: https://doi.org/10.1016/j.measurement.2016.12.002.
2. Almawas Mohammad, Azmi Mastura. 2022. „A review on use of GIS technology for mapping and modelling urban floods”. *Journal of Hunan University (Natural Sciences)* 49(02).
3. Angrisano Antonio, Silvio Del Pizzo, Salvatore Gaglione, Salvatore Troisi, Mario Vultaggio, 2018. „Using local redundancy to improve GNSS absolute positioning in harsh scenario”. *Acta Imeko* 7(2): 16-23. DOI: https://doi.org/10.21014/acta_imeko.v7i2.538.
4. Arévalo-Verjel Alba Nely, José Luis Lerma, Juan F. Prieto, José Fernández. 2022. „Estimation of the Block Adjustment Error in UAV Photogrammetric Flights in Flat Areas”. *Remote Sensing* 14: 2877. DOI: https://doi.org/10.3390/rs14122877.
5. Ashraf Shahrukh, Priyanka Aggarwal, Praveen Damacharla, Hong Wang, Ahmad Y. Javaid, Vijay Devabhaktuni. 2018. „A low-cost solution for unmanned aerial vehicle navigation in a global positioning system–denied environment”. *International Journal of Distributed Sensor Networks* 14(6): 1-17. DOI: https://doi.org/10.1177/1550147718781750.
6. Butowtt Jerzy, Roumuald Kaczyński. 2010. *Fotogrametria*. Warsaw: Military University of Technology. [In Polish: *Photogrammetry*.]. ISBN: 9788361486398.
7. Chiang Kai-Wei, Meng-Lun Tsai, Chien-Hsun Chu. 2012. „The development of an UAV borne direct georeferenced photogrammetric platform for ground control point free applications”. *Sensors* 12(7): 9161-9180. DOI: https://doi.org/10.3390/s120709161.
8. Ciećko Adam, Mieczysław Bakuła, Grzegorze Grunwald, Janusz Ćwiklak. 2020. „Examination of Multi-Receiver GPS/EGNOS Positioning with Kalman Filtering and Validation Based on CORS Stations”. *Sensors* 20(9): 2732. DOI: https://doi.org/10.3390/s20092732.
9. Colpaert Alfred. 2022. „Satellite and UAV Platforms”. *Remote Sensing for Geographic Information Systems, Sensors* 22: 4564. DOI: https://doi.org/10.3390/s22124564.

10. Congress Surya Sarat Chandra, Anand J Puppala, Clayton Treybig, Charles F Gurganus, Jim Halley. 2022. „Application of Unmanned Aerial Vehicles for Monitoring Airport Asset Surfaces”. *Transportation Research Record*: 03611981221115729. DOI: https:doi.org/10.1177/03611981221115729
11. Daakir Mehdi, Marc Pierrot-Deseilligny, Pierre Bosser, Francis Pichard, Christian Thom, Yohann Rabot, Olivier Martin. 2017. „Lightweight UAV with on-board photogrammetry and single-frequency GPS positioning for metrology applications”. *ISPRS J. Photogramm. Remote Sens.* 127: 115-126. DOI: https://doi.org/10.1016/j.isprsjprs.2016.12.007
12. DeWitt Bon, Paul Wolf. 2000. *Elements of Photogrammetry (with Applications in GIS).* 3rd ed. New York, USA: McGraw-Hill Higher Education. ISBN: 0-07-292454-3.
13. Eling Christian, Markus Wieland, Christophe Hess, Lasse Klingbeil, Heiner Kuhlmann, 2015. „Development and evaluation of a UAV based mapping system for remote sensing and surveying applications”. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL-1/W4: 233-239. DOI: https://doi.org.10.5194/isprsarchives-XL-1-W4-233-2015.
14. Eurocontrol. 2021. *Terrain and Obstacle Data Manual*. 3rd ed. Eurocontrol: Brussels, Belgium.
15. Forlani Gianfranco, Fabrizio Diotri, Umberto Morra Di Cella, Riccardo Roncella. 2020. „UAV block georeferencing and control by on-board gnss data”. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences* 43: 9-16. DOI: htpps://doi.org/10.5194/isprs-archives-XLIII-B2-2020-9-2020.
16. Fryer John, Harvey Mitchell, Jim Chandler. 2007. *Applications of 3D measurement from images*. Dunbeath, UK: Whittles. ISBN: 978-1-904445-63-0.
17. Gao Y., 2008. „GNSS biases, their effect and calibration”. In *IGS Workshop*: 24. Natoional Geographic Survey. 2-6 June, Miami Beach, USA.
18. Ge Yulong, Feng Zhou, Baoqi Sun, Shengli Wang, Bo Shi. 2017. „The Impact of Satellite Time Group Delay and Inter-Frequency Differential Code Bias Corrections on Multi-GNSS Combined Positioning”. *Sensors* 17(3): 602. DOI: https://doi.org/10.3390/s17030602.
19. Harwin Steve, Arco Lucieer. 2012. „Assessing the accuracy of georeferenced point clouds produced via multi-view stereopsis from Unmanned Aerial Vehicle (UAV) imagery”. *Remote Sens*. 4: 1573-1599. DOI: https://doi.org.10.3390/rs4061573.
20. Hosseinpoor Ahmad Reza, Farhad Samadzadegan, F. Dadras Javan. 2016. „Pricise target geolocation and tracking based on UAV video imagery”. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences* XLI-B6: 243-249. DOI: https://doi.org/10.5194/isprs-archives-XLI-B6-243-2016.
21. IGS. „Products”. Available at: https://igs.org/products/#about.
22. Kaniewski Piotr. 2006. „Aircraft Positioning with INS/GNSS Integrated System. *Molecular and Quantum Acoustics* 27: 149-168. ISSN: 1731-8505.
23. Kaniewski Piotr, Rafal Gil, Stanisław Konatowski, 2016. „Algorithms of position and velocity estimation in GPS receivers”. *Annual of Navigation* 23: 53-68. DOI: https://doi.org/10.1515/aon-2016-0004.
24. Le Anh Quan, Christian Tiberius. 2007 „Single-frequency precise point positioning with optimal filtering”. *GPS Solutions* 11(1): 61-69. DOI: https://doi.org/10.1007/s10291-006-0033-9.
25. Luhmann Thomas, Stuart Robson, 2011. *Close Range Photogrammetry: Principles, Methods and Applications*. Cdr ed. Dunbeath, UK: Whittles. ISBN: 978-1-84995-057-2.

26. Mancini Francesco, Marco Dubbini, Mario Gattelli, Francesco Stecchi, Stefano Fabbri, Giovanni Gabbianelli. 2013. „Using Unmanned Aerial Vehicles (UAV) for High-Resolution Reconstruction of Topography: The Structure from Motion Approach on Coastal Environments”. *Remote Sens.* 5: 6880-6898. DOI: https://doi.org.10.3390/rs5126880.
27. RTKLIB: An Open Source Program. „RTKLIB ver. 2.4.2 Manual, Package for GNSS Positioning”. Available at: http://www.rtklib.com/prog/manual_2.4.2.pdf.
28. RTKLIB Website. „ RTKLIB: An Open Source Program Package for GNSS Positioning”. Available at: http://rtklib.com/.
29. Santerre Rock, Lin Pan, Changsheng Cai, Jianjun Zhu. 2014. „Single Point Positioning Using GPS, GLONASS and BeiDou Satellites”. *Positioning* 5: 107-114. DOI: https://doi.org.10.4236/pos.2014.54013.
30. 30. Sanz-Ablanedo Enoc, Jim H. Chandler, José Ramón Rodríguez-Pérez, Celestino Ordóñez. 2018. „Accuracy of unmanned aerial vehicle (UAV) and SfM photogrammetry survey as a function of the number and location of ground control points used”. *Remote Sensing* 10(10):1606. DOI: https://doi.org/10.3390/rs10101606.
31. Schaer S., 1999. „Mapping and predicting the Earth’s ionosphere using Global Positioning System”. *PhD thesis*. Berne: University of Berne.
32. Scilab Website. Available at: https://www.scilab.org/.
33. Shahbazi Mozhdeh, Gunho Sohn, Jérôme Théau, Patrick Menard. 2015. „Development and evaluation of a UAV-photogrammetry system for precise 3D environmental modeling”. *Sensors* 15: 27493-27524. DOI: https://doi.org/10.3390/s151127493.
34. Sharma Himanshu, Andreas Schütz, Thomas Pany. 2018. „Preliminary analysis of the RTK positioning using Android GNSS Raw Measurements and Application Feasibility for the Trajectory mapping using UAV’s”. In: *The 31st International Technical Meeting of the Satellite Division of The Institute of Navigation* (ION GNSS+ 2018): 432-444. The Institute of Navigation, Manassas. 24-28 September 2018, Miami, Florida, USA. ISBN: 0-936406-10-0.
35. Tahar Khairul Nizam. 2013. „An evaluation on different number of ground control points in unmanned aerial vehicle photogrammetric block”. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci*. 40: 93-98. DOI: https://doi.org/10.5194/isprsarchives-XL-2-W2-93-2013.
36. Tahar Khairul Nizam, Suryani Kamarudin. 2016. „UAV onboard GPS in positioning determination”. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences* 41: 1037-1042. DOI: https://doi.org/ 10.5194/isprs-archives-XLI-B1-1037-2016.
37. Taro, S., Y. Takahashi, Y. Amano. 2016. „Precise UAV Position and Attitude Estimation by Multiple GNSS Receivers for 3D Mapping”. In: *The 29th International Technical Meeting of the Satellite Division of The Institute of Navigation* (ION GNSS+ 2016): 1455-1464. The Institute of Navigation, Manassas.12-16 September, Portland, Oregon. ISBN: 0-936406-12-7
38. Ueno M., T. Nimura, T. Fujiwara, K. Nonaka. 1997. „Evaluation of RTK-OTF positioning system for free running manoeuvrability test of a model ship”. In: *Oceans '97. MTS/IEEE Conference Proceedings* 2: 1120-1125. DOI: 10.1109/OCEANS.1997.624149.
39. Wang Shizhuang, Xingqun Zhan, Yawei Zhai, Cheng Chi, Jiawen Shen. 2021. „Highly reliable relative navigation for multi-UAV formation flight in urban environments”. *Chin. J. Aeronaut.* 34(7): 257-270. DOI: https://doi.org/10.1016/j.cja.2020.05.022.

40. Wierzbicki Damian, Michał Kędzierski, Anna Sekrecka. 2019. „A Method for Dehazing Images Obtained from Low Altitudes during High-Pressure Fronts". *Remote Sensing* 12(1): 25. DOI: https://doi.org.10.3390/rs12010025.

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