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Application of the SBAS/EGNOS positioning method to determine UAV coordinates

Abstract: The article presents the results of research on determining the UAV (Unmanned Aerial Vehicle) position using the SBAS (Satellite Based Augmentation System) positioning method for the EGNOS (European Geostationary Navigation Overlay Service) support system. The experiment used a single-frequency AsteRx-m2 UAS receiver, which recorded GPS (Global Positioning System) satellite observations and EGNOS corrections. The test flight was performed in 2020 near Warsaw. Navigational calculations for determining the position of the UAV during the flight were made in the gLAB v.5.5.1 software. Based on the performed calculations, the following were determined: BSP coordinates in the ellipsoidal system BLh, mean errors of BSP coordinates, and values of DOP (Dilution of Precision) geometric coefficients. In addition, during the calculations, it was found that the mean error values of the determined BSP coordinates do not exceed 3.6 m, and the maximum value of the geometric coefficient GDOP (Geometric DOP) is less than 3.5.

Keywords: SBAS, EGNOS, BSP, mean errors, DOP

Introduction

In the 21st century, there was a rapid development of unmanned platforms, for which the GNSS satellite receiver became the basic navigation equipment. This applies to both the construction and implementation of single-frequency and dual-frequency GNSS satellite receivers. In the case of single-frequency GNSS (Global Navigation Satellite System) receivers, the basic positioning method is the SPP (Single Point Positioning) method, in which we use C/A code observations on the L1 frequency and a navigation message in a given GNSS satellite system [5]. The disadvantage of this method is the low positioning accuracy, although it is the most common and used in aviation applications. Therefore, improved navigational solutions are sought to improve UAV position determination using single-frequency GNSS receivers. One of the ways to improve the UAV position determines to use the SBAS positioning method [1]. As part of the SBAS positioning method, we use differential corrections specified for a given GNSS navigation system. Developing the concept of differential corrections, we mean corrections to the GNSS satellite coordinates, corrections to the GNSS satellite clock error, ionospheric correction in the form of VTEC (Vertical TEC) parameters, and tropospheric correction calculated from the RTCA-MOPS model (Radio Technical Commission for Aeronautics - Minimum Operational Performance Standards) and SBAS quick fixes. SBAS corrections to the satellite position and GNSS satellite clock error are referred to as long-term SBAS corrections and the ionospheric and tropospheric corrections as atmospheric corrections [7].

In Europe, the SBAS augmentation system is the EGNOS geostationary system. The EGNOS system consists of a space segment (3 satellites), a ground segment (stations: RIMS (Ranging and Integrity Monitoring Stations), NLES (Navigation Land Earth Stations) and MCC (Mission Control Centers)), a user segment (satellite receivers). The EGNOS system is currently developing differential corrections for the GPS navigation system. In the future, EGNOS will be compatible and interoperable with Galileo (European Navigation Satellite System) [2, 8].

The main purpose of the work is to show the results of research on the determination of UAV coordinates as part of an example flight. For this purpose, GPS code observations, GPS navigation messages, and EGNOS corrections were used. The new gLAB v.5.5.1 software package with the SBAS positioning module was used in the calculations. The whole work is divided into 5 chapters, i.e. 1. Introduction, 2. Research method, 3. Research test, 4. Research results and discussion, 5. Conclusions. At the end of the work, a compact bibliography was added.

Research method

Chapter 2 shows the algorithms for determining the BSP position and the values of the mean errors of the determined coordinates. The basic observation equation for the SBAS/EGNOS positioning method takes the form noted below [6]:

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

where:

l - code measurement, i.e. pseudo-distance in the GPS system,

d - geometric distance between the satellite and the receiver takes into account the position of the GPS satellite (X_s, Y_s, Z_s), takes into account long-term corrections of the EGNOS orbit,

$d = \sqrt{(X - X_S)^2 + (Y - Y_S)^2 + (Z - Z_S)^2}$,

(X, Y, Z) - receiver antenna coordinates searched parameters,

dtr - receiver clock error, unknown parameter,

dts - satellite clock error, calculated from the GPS navigation message and EGNOS long-term corrections,

c - speed of light,

Ion - ionospheric correction, calculated based on the SBAS/EGNOS ionosphere model,

Trop - tropospheric correction, calculated based on the RTCA-MOPS model for SBAS augmentation systems,

TGD - hardware delay, calculated on the basis of GPS navigation message,

Rel - relativistic correction, calculated on the basis of the GPS navigation message

Mp - multipath effect for GPS code observations,

PRC - EGNOS quick fixes.

From equation (1) the parameters are determined as unknown, i.e. the 3 components of the position (X, Y, Z) and the receiver clock error dtr. The unknown parameters are determined by the method of least squares in a stochastic process [4]:

$$\begin{cases} Qx = N^{-1} \cdot L \\ v = A \cdot Qx - dl \\ m0_{post} = \sqrt{\frac{[pvv]}{n-k}} \\ C_{Qx} = m0_{post}^2 \cdot N^{-1} \\ m_{Qx} = diag\left(\sqrt{C_{Qx}}\right) \end{cases} \tag{2}$$

where:
Q_x – vector of determined parameters,
$N – A^T \cdot p \cdot A$ – matrix of the system of normal equations,
A – matrix of coefficients,
p – weight matrix,
$p = \frac{1}{m0_{post}^2 \cdot ml^2}$,
$m0_{post}$ – mean unit error a posteriori,
ml – matrix with pseudorange mean errors,
$ml^2 = \left(\frac{ml_{ClA}}{\sin(El)}\right)^2 + m_{SBAS}^2$,
El – elevation angle,
$ml_{C/A}$ – standard deviation of code measurements in the GPS system,
m_{SBAS} – SBAS/EGNOS correction model error,
$L = A^T \cdot p \cdot dl$,
dl – free words vector,
n – number of observations,
k – number of determined parameters,
v – patch vector,
C_{Qx} – the variance-covariance matrix containing the values of the mean errors of the determined parameters,
m_{Qx} – mean errors of determined parameters, related to the ECEF geocentric system.

Due to the fact that in air navigation the UAV position is expressed using ellipsoidal coordinates BLh (geodetic latitude B, geodetic longitude L, ellipsoidal height h), equation (3) presents a model of transformation of XYZ to BLh coordinates [9]:

$$\begin{bmatrix} B \\ L \\ h \end{bmatrix} = \begin{bmatrix} \arctan\left(\frac{Z}{\rho} + \frac{\delta_1 \cdot tgB_{i-1}}{\sqrt{\delta_2 \cdot tg^2 B_{i-1}}}\right) \\ \arctan\left(\frac{Y}{X}\right) \\ \frac{\rho}{cosB} - R \end{bmatrix} \tag{3}$$

where:
(a, b) – the major and minor semi-axes of the ellipsoid,
e – first eccentricity, $e = \sqrt{\frac{a^2-b^2}{a^2}}$,
R – the radius of curvature of the ellipsoid's first vertical, $R = \frac{1}{\sqrt{1-e^2 \cdot sin^2 B}}$,
$\rho = \sqrt{X^2 + Y^2}$,
$\delta_1 = \frac{a \cdot e}{\rho \cdot \sqrt{1-e^2}}$,
$\delta_2 = \frac{1}{1-e^2}$,
$i - 1$ – previous iteration,
(B, L, h) – ellipsoidal coordinates of the aircraft,
B – geodetic latitude,
L – geodetic length,

h – ellipsoidal height.

In addition, the values of the mean errors m_{Qx} calculated for the geocentric XYZ coordinates can also be expressed in the ellipsoidal system BLh [4, 9]:

$$\begin{bmatrix} mB \\ mL \\ mh \end{bmatrix} = \begin{bmatrix} \sqrt{m_{BLh}(1,1)} \\ \sqrt{m_{BLh}(2,2)} \\ \sqrt{m_{BLh}(3,3)} \end{bmatrix} \tag{4}$$

where:

m_{BLh}- the variance-covariance matrix of determined parameters in the ellipsoidal system BLh,

$m_{BLh} = R \cdot C_{Qx} \cdot R^T$,

R - transition matrix from the XYZ geocentric system to the BLh geodetic system,

mB - mean error of geodetic latitude determination B,

mL - mean error of determining the geodetic length L,

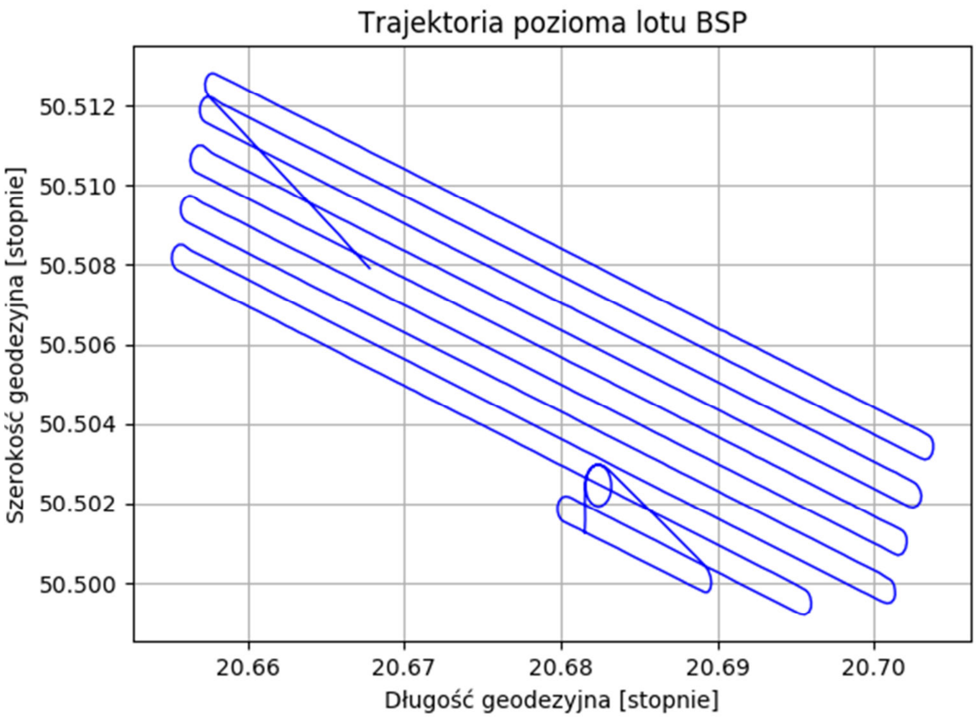
mh - mean error of determining the ellipsoidal height h.

Research test

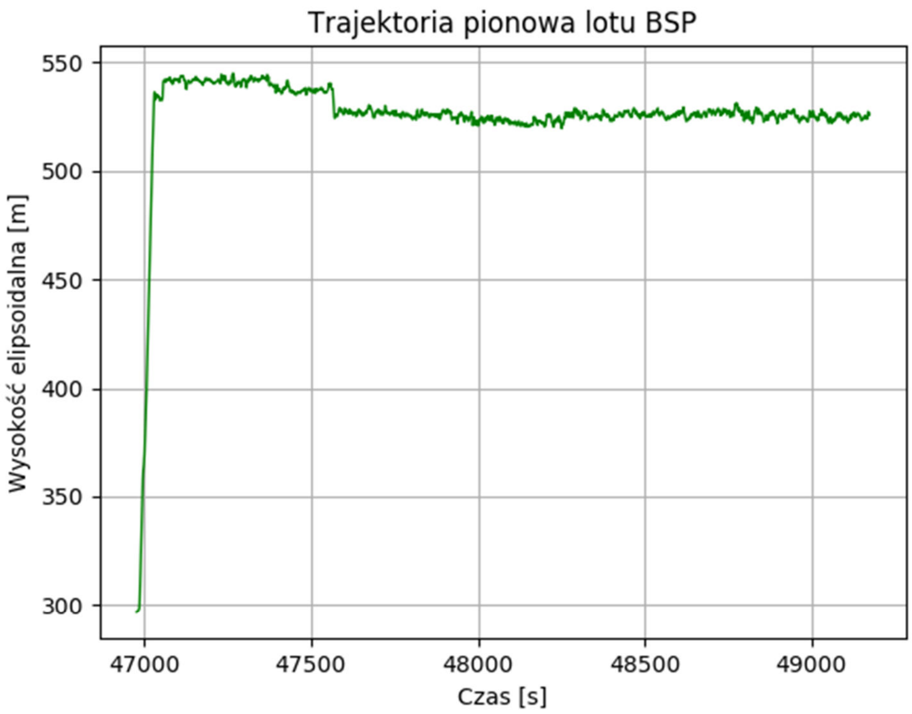
The research test for work was divided into 2 stages. The first stage concerned the test flight of the UAV platform, on which a GPS satellite receiver was mounted. The test flight took place in April 2020 near Warsaw, Poland. A single-frequency AsteRx-m2 UAS receiver was mounted on board the BSP platform, which recorded raw GPS satellite observations and corrections from the EGNOS augmentation system from the S123 satellite. The flight lasted from 13:02:55 to 13:39:35 according to GPST (GPS Time). Figure **1** shows a sketch of the UAV's horizontal flight trajectory, and Figure **2** shows a sketch of its vertical flight trajectory. The flight altitude did not exceed 550 m.

The second stage of the experiment concerned the performance of navigational calculations and numerical analyzes of the obtained test results. At this stage, calculations were made in the gLAB v.5.5.1 software in the SBAS positioning module [3]. During the calculation, the SBAS positioning module was configured as follows:

- observation data: RINEX observation file in 2.11 format,
- orbital data source and satellite clock: GPS navigation message + EGNOS corrections,
- source of SBAS corrections: EGNOS corrections in EMS format,
- calculation interval: 1 s,
- observation cutoff mask: 5o,
- positioning mode: kinematic,
- method of determining unknown parameters: forward Kalman filtering,
- type of GPS observations: L1-C/A code observations,
- ionosphere model: SBAS/EGNOS model,
- troposphere model: RTCA-MOPS model for the EGNOS system,
- coordinate system: WGS-84 system.



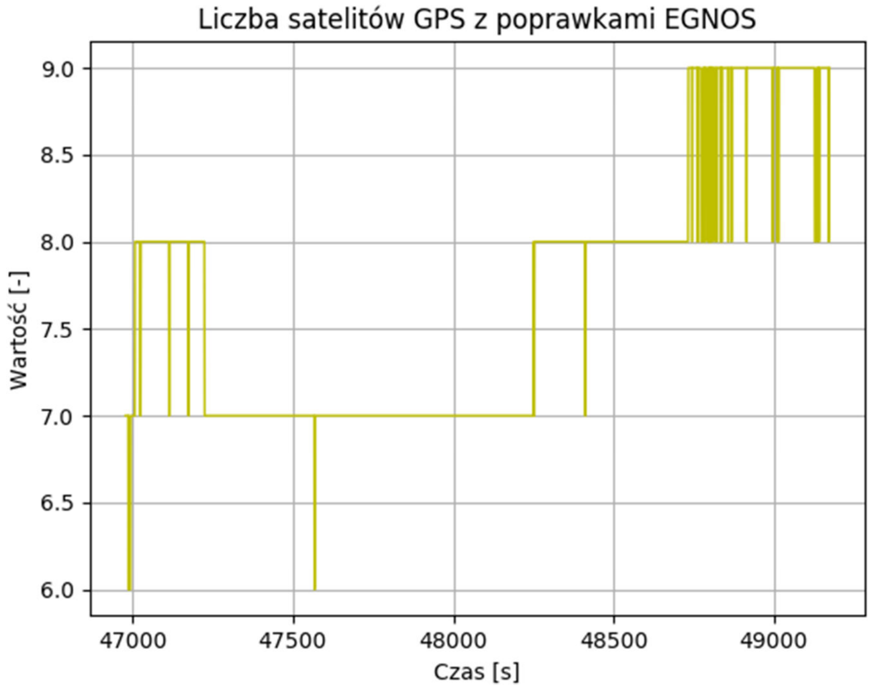
1. UAV horizontal flight trajectory
Source: [own elaboration]



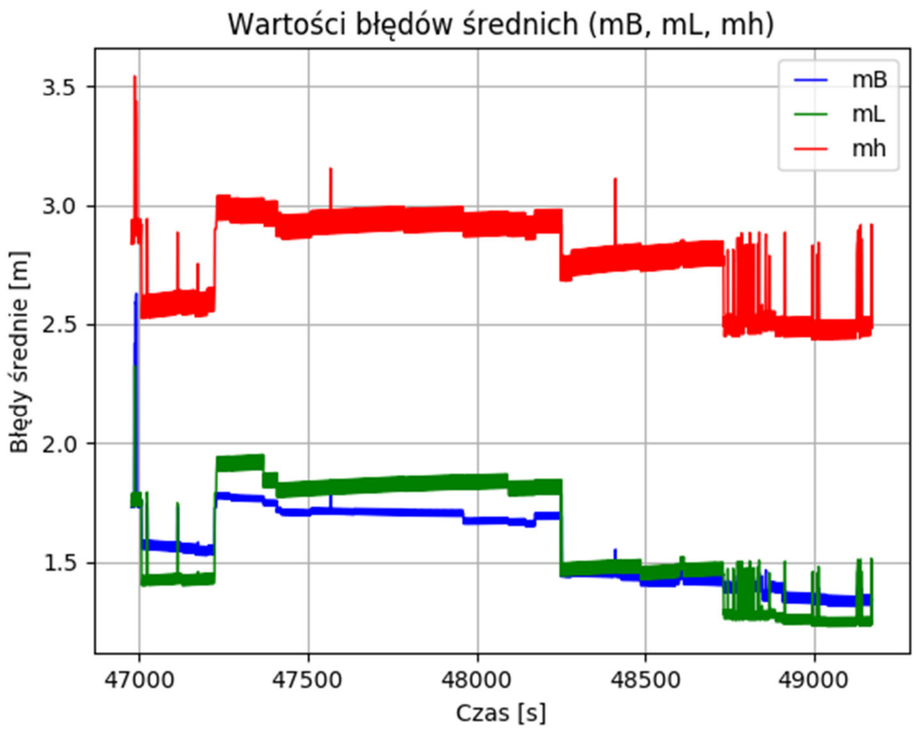
2. UAV vertical flight trajectory
Source: [own elaboration]

Research results and discussion

The presentation of the research results began with determining the number of GPS satellites for which EGNOS corrections were determined. Figure **3** shows the number of GPS satellites for the BSP position navigation solution. It should be noted that the results shown in Figure **3** refer to GPS satellites for which the gLAB program calculated corrections from the EGNOS system. The number of GPS satellites during the flight ranged from 6 to 9. The smallest number of GPS satellites was visible in the initial phase of the flight and ranged from 6 to 8. The largest number of GPS satellites was visible in the final phase of the flight and ranged from 8 to 9.

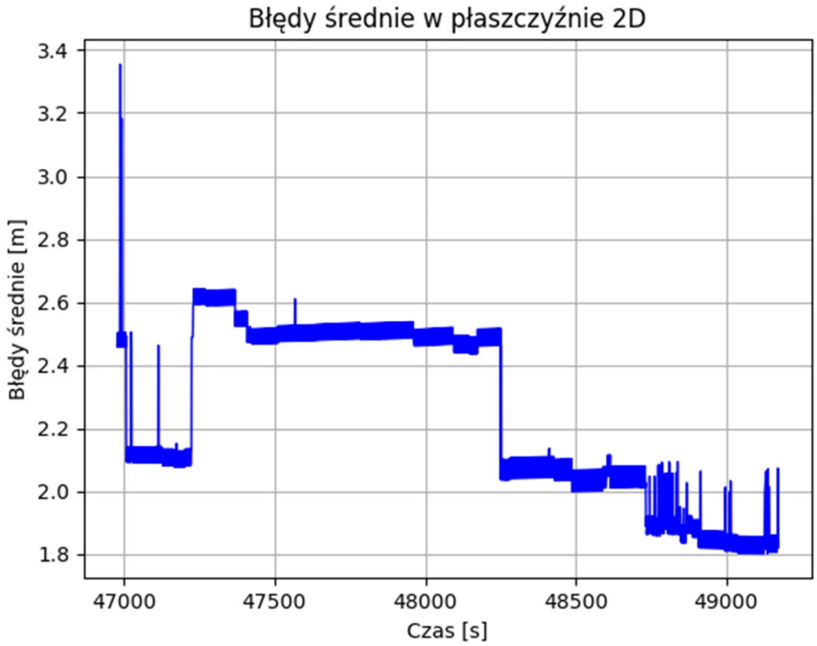


3. Number of GPS satellites for which EGNOS corrections have been developed
Source: [own elaboration]

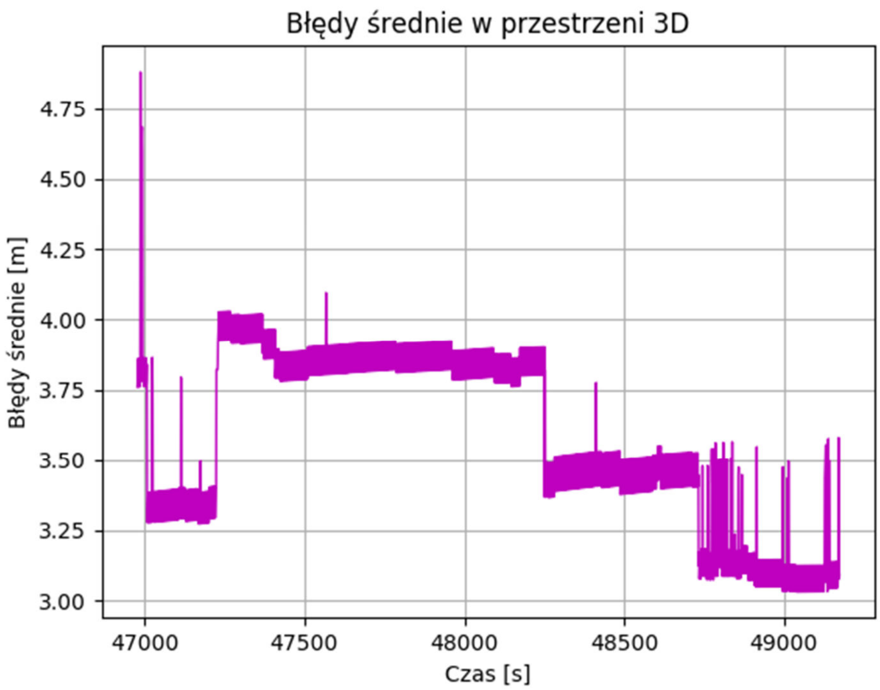


4. Mean errors of UAV position determination from the SBAS/EGNOS solution
Source: [own elaboration]

Figure **4** shows the results of mean errors in determining the BSP position, following formula (4). In particular, the results of calculating the parameters (mB, mL, mh) are shown. The mean values of the determination of the B component of the UAV position range from 1.3 m to 2.7 m. The mean values of the determination of the L component of the UAV position range from 1.2 m to 2.3 m. BSP ranges from 2.5 m to 3.6 m. As can be seen, the ellipsoidal height is determined with the most significant mean error. In turn, the horizontal coordinates B and L are best determined.



5. The resultant value of mean errors in determining the UAV position for the 2D plane
Source: [own elaboration]



6. The resultant value of mean errors in determining the UAV position for 3D space
Source: [own elaboration]

Figure **5** shows the results of the resultant mean errors in determining the BSP position for the 2D plane, calculated in accordance with the formula (5) [9]:

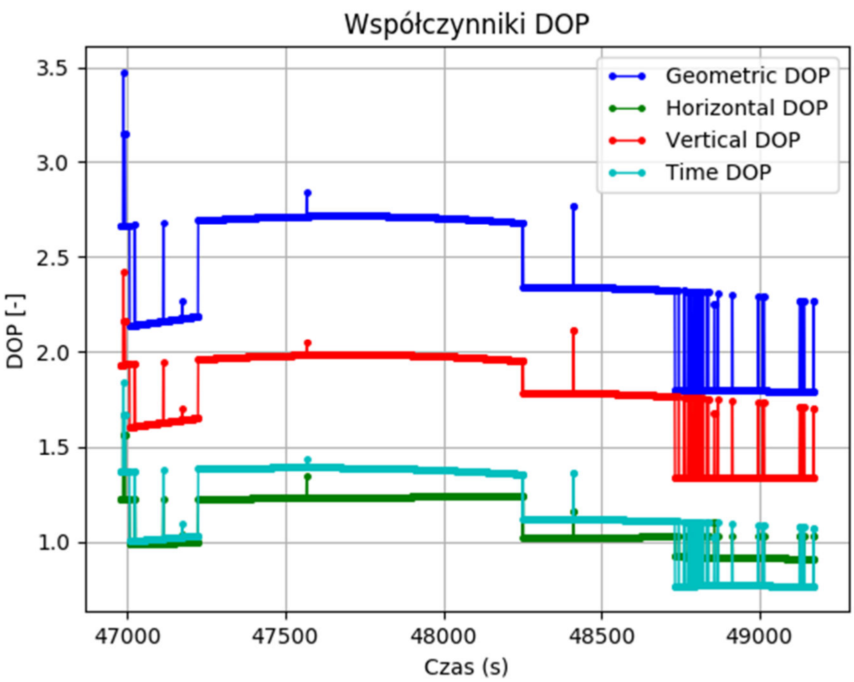
$$DR = \sqrt{mB^2 + mL^2} \tag{5}$$

Values of the resultant mean errors in the 2D plane depend mainly on the parameters (mB, mL). Values of the resultant mean errors in determining the UAV position in the horizontal 2D plane range from 1.8 m to 3.3 m. The worst results of the DR parameter are noticeable in the initial phase of the flight. In turn, the best results of the DR parameter are visible in the final phase, which is influenced by the number of GPS satellites in the BSP position navigation solution.

Figure **6** shows the results of the resultant mean errors in determining the BSP position for 3D space, calculated under the formula (6) [9]:

$$DS = \sqrt{mB^2 + mL^2 + mh^2} \tag{6}$$

The values of the resultant mean errors in the 2D plane depend mainly on the parameters (mB, mL, mh). The values of the resultant mean errors in determining the UAV position in 3D space range from 3.1 m to 4.8 m. The worst results of the DS parameter are noticeable in the initial phase of the flight when the number of GPS satellites is from 6 to 8. The best results of the DS parameter are visible in the final phase, which is influenced by the number of GPS satellites in the BSP position navigation solution.



7. Geometric DOP coefficients for the designated BSP position
Source: [own elaboration]

Figure **7** shows the results of the DOP (Dilution of Precision) geometric coefficients, calculated according to the formula (6) [10]:

$$\begin{cases} HDOP = \sqrt{N^{-1}(1,1) + N^{-1}(2,2)} \\ VDOP = \sqrt{N^{-1}(3,3)} \\ TDOP = \sqrt{N^{-1}(4,4)} \\ GDOP = \sqrt{N^{-1}(1,1) + N^{-1}(2,2) + N^{-1}(3,3) + N^{-1}(4,4)} \end{cases} \tag{7}$$

During the study, the following DOP coefficients were determined: GDOP (Geometric DOP), HDOP (Horizontal DOP), VDOP (Vertical DOP), and TDOP (Time DOP). The DOP values are 1.8 to 3.5 for GDOP, 0.9 to 1.5 for HDOP, 1.3 to 2.4 for VDOP, and 0.7 to 1.8 for TDOP, respectively. It should be noted that the highest values of DOP coefficients are in the initial phase of the UAV flight when the number of GPS satellites is from 6 to 8. In turn, in the final phase of the UAV flight, the DOP coefficients are less than 2.4.

Summary

This paper presents the results of research on determining the UAV position using the SBAS/EGNOS method. The study used GPS data and EGNOS corrections recorded by the AsteRx-m2 UAS single-frequency receiver mounted on the unmanned UAV platform. The test flight took place in April 2020 near Warsaw, Poland, from 13:02:55 to 13:39:35 GPST. Navigational calculations for the research were made in the gLAB v.5.5.1 program. In particular, the work determined UAV flight coordinates, mean errors of UAV position coordinate determination, the number of GPS satellites with available EGNOS corrections, and geometric DOP coefficients. During the calculations, it was found that the mean error values of the determined BSP coordinates do not exceed 3.6 m, and the maximum value of the geometric coefficient GDOP is less than 3.5.

Source materials

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