AVIATION AND SECURITY ISSUES NO. 4(2/2023)
ISSN 2720-197X / eISSN 2956-3380

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DOI: 10.55676/asi.v4i2.76

ACCURACY ANALYSIS OF EGNOS POSITIONING IN FLIGHT TEST IN AIR TRANSPORT

ANALIZA DOKŁADNOŚCI POZYCJONOWANIA EGNOS W EKSPERYMENCIE LOTNICZYM W TRANSPORCIE

Abstract

The purpose of this publication is to determine the accuracy of EGNOS positioning in aviation using correction data from the PRN120 and PRN124 geostationary satellites. The paper compiles GPS satellite data with EGNOS corrections to determine the position of aircraft and to determine positioning accuracy. The study used research material from an airborne experiment carried out in Mielec. GNSS data were elaborated in post-processing mode in the RKTLIB software, and numerical analyses were performed in Microsoft Excel. The average accuracy of EGNOS positioning using data from the PRN120 satellite for B, L, h coordinates was 0.9 m, 0.2 m and 0.3 m, respectively. In contrast, the average accuracy of EGNOS positioning using data from the PRN124 satellite is also similarly 0.9 m, 0.2 m and 0.3 m for BLh coordinates. It was observed that the positioning accuracy at a given measurement epoch is dependent on the number of GPS satellites observed. Furthermore, in the study, the accuracy of EGNOS positioning using corrections from the PRN120 and PRN124 satellites was compared with the certification requirements of the International Civil Aviation Organisation.

Keywords: SBAS, EGNOS, accuracy, aircraft position

Streszczenie

Celem niniejszej publikacji jest określenie dokładności pozycjonowania EGNOS w lotnictwie przy użyciu danych korekcyjnych z satelitów geostacjonarnych PRN120 i PRN124. W artykule zastosowano system GPS z poprawkami EGNOS w celu określenia pozycji statku powietrznego i określenia dokładności pozycjonowania statku powietrznego. W badaniu wykorzystano dane z eksperymentu lotniczego przeprowadzonego w Mielcu. Dane GNSS zostały opracowane w trybie post-processingu w oprogramowaniu RKTLIB, a analizy numeryczne wykonano w programie Microsoft Excel. Średnia dokładność pozycjonowania EGNOS z wykorzystaniem danych z satelity PRN120 dla współrzędnych B, L, h wyniosła 0,9 m, 0,2 m i 0,3 m. Natomiast średnia dokładność pozycjonowania EGNOS przy użyciu danych z satelity PRN124 również wynosi 0,9 m, 0,2 m i 0,3 m dla współrzędnych BLh. Zaobserwowano, że dokładność pozycjonowania w danej epoce pomiarowej zależy od liczby obserwowanych satelitów GPS. Ponadto w badaniu dokładność pozycjonowania EGNOS z wykorzystaniem poprawek z satelitów PRN120 i PRN124 została porównana z wymaganiami certyfikacyjnymi Organizacji Międzynarodowego Lotnictwa Cywilnego.

Słowa kluczowe: SBAS, EGNOS, dokładność, pozycja statku powietrznego

Artykuł wpłynął do redakcji: 30.09.2023 / Zatwierdzono do publikacji: 30.12.2023

1. INTRODUCTION

Aviation in the 21st century is undergoing a revolution comparable to that brought about by the creation of the first airports, aeronautical charts and radio navigation systems. The development of space flight and satellite technology resulted in the launch of the first Soviet satellite, Sputnik-1, into orbit in 1957. Although so simple in its design, it created entirely new perspectives for mankind in the development and application of technology. Shortly thereafter, the 'space race' between the USSR and the United States began, resulting in solutions that are still necessary today. One of the consequences of the technological struggle between these two powers is the GNSS (Global Navigation Satellite Systems) that is widely used today[1].

GNSS systems are constellations of satellites that transmit navigation signals to receivers located on Earth. Based on the time difference of the signal waveform, the receivers determine a pseudo-distance, which makes it possible to determine position in 4D space[2]. By definition, GNSS Global Navigation Systems should have worldwide coverage. Today, the systems in use are the European Galileo, the American NAVSTAR GPS, the Russian GLONASS and the Chinese BeiDou[3]. The use of these systems is almost unlimited, and their popularity can be evidenced by the fact that almost every electronic device currently manufactured such as laptops and telephones provide support for at least one of these positioning systems. It is estimated that there are currently more than 7 billion devices using GNSS global positioning systems.

GNSS has found wide application in aviation. Knowing the exact position of the aircraft is a fundamental parameter in guaranteeing the safe execution of operations. While GNSS fulfils its role as a guidance system in the en-route flight of an aircraft, its performance in the approach phase of landing remains a separate issue. The use of GNSS global positioning systems in the most critical phase of flight, which is landing, must meet the requirements of the International Civil Aviation Organisation (ICAO). To enhance performance and meet the requirements GNSS is supported by three types of augmentation systems[4]:

1. SBAS (Satellite Based Augmentation System),
2. ABAS (Aircraft Based Augmentation System),
3. GBAS (Ground Bases Augmentation System).

According to ICAO Document 9750, GNSS is supposed to be a key solution for improving the quality of communication, navigation, surveillance and air traffic management. Therefore, each ICAO Member State should study navigation satellite systems and implement solutions to improve their positioning quality[5].

1 https://igs.org/mgex/constellations/ [access: 14.08.2023].
2 E. Osada, Geodezja, Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2001, p. 237–241.
3 https://www.gsa.europa.eu/european-gnss/what-gnss [access: 14.08.2023].
4 H. Jafernik, K. Krasuski, J. Michta, Assessment of suitability of radionavigation devices used in air, "Sci. J. Sil. Univ. Technology. Ser. Transport", 2016, 90, p. 99–112.
5 A. Ciećko, M. Grzegorzewski, J. Ćwiklak, S. Oszczak, H. Jafernik, Air navigation in eastern Poland based on EGNOS, In Proceedings of the Aviation Technology, Integration, and Operations Conference (ATIO 2013), Los Angeles, CA, USA, 12-14 August 2013; Red Hook: Curran, NY, USA, 2013, Volume 1, p. 603–613.

DOI: 10.55676/asi.v4i2.76

This work focuses on SBAS, which is based on the use of additional data transmitted by geostationary satellites. In Europe, SBAS support is provided by EGNOS, the European Geostationary Navigation Overlay Service[6]. Its establishment is due to the European Commission, the European Space Agency and EUROCONTROL. The system increases the accuracy and integrity of an aircraft's position by applying corrections to GPS observations. The EGNOS system is designed to cover Europe and enable precise and safe approaches to European airports.

The aim of this study is to determine the most important of the four GNSS positioning quality parameters, which is the positioning accuracy of the system. The other three parameters are integrity, continuity and availability. The accuracy assessment will be based on data obtained from the flight test. The paper uses data from an airborne test conducted on 7 September 2011 in Mielec, Poland. The experiment involved flying a Piper PA-34-200T aircraft along a closed route and measuring GPS navigation signals received with a Topcon HiperPro on-board receiver. The RTK-OTF differential technique[7] was used to assess the accuracy of EGNOS positioning. For this purpose, a local reference station was installed at Mielec airport to collect GPS phase observations. The collected data were processed and analysed in post-processing mode. The entire work is divided into 7 chapters and a literature list is added at the end.

2. SCIENTIFIC KNOWLEDGDE ANALYSIS

The first tests of the EGNOS system in Poland were carried out in 2003 as part of the "BRDA" and "ODRA" research projects. The test was carried out using the TS-11 Iskra aircraft. At that time, it was shown that horizontal positioning with the use of EGNOS was very precise and gave similar results to autonomous positioning. The accuracy of vertical position determination was also satisfactory, but did not meet the ICAO requirements needed for APV approaches and landings. Position errors in altitude determination ranged from 1 to 18 metres[8]. Further research tests were conducted in 2007 in the "LIWIEC" flight experiment. In 2010 and 2011, tests were conducted in south-eastern Poland in Dęblin, Chełm and Mielec[9]. The EGNOS solution was then compared with the flight reference position from the RTK-OTF technique[10]. The RTK-OTF method is similar to differential DGPS measurements and requires two receivers recording phase measurements at the same time. The RTK-OTF method uses phase observations at L1 and L2 frequencies in GPS system[11]. Therefore, two Thales Mobile

6 C. Specht, J. Pawelski, L. Smolarek, M. Specht, P. Dąbrowski, Assessment of the Positioning Accuracy of DGPS and EGNOS Systems in the Bay of Gdansk Using Maritime Dynamic Measurements, "Journal of Navigation", 2019, 72, p. 575–587.

7 D. Próchniewicz, J. Walo, Quality Indicator for Ionospheric Biases Interpolation in the Network RTK, "Reports Geodesy", 2012, 92, p. 7–21.

8 M. Grzegorzewski, Navigating an aircraft by means of a position potential in three dimensional space, "Annual of Navigation", 2005, 9, p. 1–111.

9 M. Grzegorzewski, A. Świątek, A. Ciećko, S. Oszczak, J. Ćwiklak, Study of EGNOS safety of life service during the period of solar maximum activity, "Artificial Satellites", 2012, 47, p. 137–145.

10 K. Krasuski, M. Lalak, P. Gołda, M. Mrozik, J. Kozuba, Analysis of the precision of determination of aircraft coordinates using EGNOS+SDCM solution, "Archives of Transport", 2023, 67(3), pp. 105–117.

11 R.B. Langley, RTK GPS, „GPS WORLD", 1998, September, p. 70–76.

Mapper and Javad Alpha receivers were mounted on board of the aircraft in Chełm experiment. GNSS reference stations were located along the flight path. The processing of the flight data showed that the reference position error in the horizontal plane was less than 0.05 m and in the vertical plane 0.1 m from the RTK-OTF solution. On the other hand, the accuracy of the EGNOS solution for the B ellipsoidal coordinate was between -3 m and +0.1 m, for the L coordinate it was between -1.1 m to +0.1 m, and for the ellipsoidal height coordinate h from -1.2 m to +2.9 m.

On 18 March 2013, the European Commission implemented a new Open Service version for EGNOS, which was to be characterised by an improvement in GNSS positioning quality. Signal coverage for the area of eastern Poland was to be comparable to that in Western Europe[12]. Subsequent EGNOS test flights in Dęblin in 2013 covered the most critical phase of the flight, which is the approach to landing. During all 4 approaches, system availability was 100%. The accuracy of horizontal position determination was 1-3 m and vertical position determination was 1-5 m. The recorded isolated losses of EGNOS positioning quality were due to the way the receiver device was mounted.

Two years earlier, in 2011, the Polish Air Navigation Services Agency conducted tests in the SBAS APV landing approach procedure. At that time, the position of the aircraft in the horizontal plane LNAV and vertical plane VNAV was tested. The average positioning accuracy was 1-2 m and 1.5-2.5 m, respectively, which met the objectives of SBAS APV approaches[13].

Another flight test at Dęblin and Olsztyn Dajtki was carried out in 2016 and involved determining the protection levels - HPL and VPL related to positioning integrity during a flight test[14].

Research on the EGNOS system worldwide has taken a similar form to that in Poland. As early as 2000, the comparison of GNSS positioning quality with geostationary augmentation system to ILS CAT I approaches began. At that time, the quality of position determination was estimated to be less than 10 metres in horizontal plane and vertically with an availability of more than 95%[15]. The paper[16] proposed the use of EGNOS in testing positioning accuracy for SBAS APV-I approaches. The test results showed that the European EGNOS geostationary system meets the requirements for this type of approach.

12 https://egnos-user-support.essp-sas.eu/new_egnos_ops/sites/default/files/library/official_docs/egnos_os_sdd_in_force.pdf [access: 14.08.2023].

13 A. Fellner, H. Jafernik, Airborne measurement system during validation of EGNOS/GNSS essential parameters in landing, “Rep. Geod. Geoinf.”, 2014, 96, p. 27–37.

14 A. Ciećko, G. Grunwald, The comparison of EGNOS performance at the airports located in eastern Poland, “Tech. Sci.”, 2017, 20, p. 181–198.

15 E. Breeuwer, R. Farnworth, P. Humphreys, A. Mcgregor, P. Michel, H. Secretan, S. J. Leighton, Ashton K.J., Flying EGNOS: The GNSS-1 Testbed, “Galileo’s World Paper”, January 2000, p. 10–21.

16 J. Oliveira, C. Tiberius, Landing: Added Assistance to Pilots on Small Aircraft Provided by EGNOS, In “Proceedings of the Conference 2008 IEEE/ION Position, Location and Navigation Symposium”, Monterey, CA, USA, 5-8 May 2008, pp. 321–333.

 DOI: 10.55676/asi.v4i2.76

3. RESEARCH PROBLEM

The introduction and continued development of EGNOS has enabled a new type of landing approaches that depend solely on GNSS systems. These approaches, using the RNP APCH (Required Navigation Performance Approaches) standardisation, do not require complex airport radio navigation equipment[17]. RNP is an airspace requirement defined by 4 key parameters that determine the quality of GNSS positioning. In the present study, one of the factors influencing the certification of a landing approach, satellite positioning accuracy, was investigated. The calculated values were compared with the certification requirements of the International Civil Aviation Organisation. The aim of the study is to verify that EGNOS enables air navigation in accordance with ICAO certification, based on the positioning accuracy measurements obtained during the flight test conducted.

4. RESEARCH METHOD

The criterion for determining the quality of positioning is contained in four basic parameters of the GNSS signal. According to Annex 10 of the International Civil Aviation Organisation, the following are tested: accuracy, integrity, availability, continuity. SBAS positioning is implemented using the SPP code method (Single Point Positioning) with SBAS corrections. The basic observation equation for the application of EGNOS corrections in the algorithm of the SPP code positioning method for GPS observations takes the form according to equation no. (1)[18]:

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

where:

l – pseudorange at L1 frequency in GPS measurements,

d^* – the geometric distance between the satellite and the receiver, taking into account the Sagnac effect correction and long-term EGNOS corrections,

$d^* = \sqrt{(X - X^*{}_{GPS})^2 + (Y - Y^*{}_{GPS})^2 + (Z - Z^*{}_{GPS})^2}$,

X, Y, Z – aircraft coordinates determined from the SPP method,

$X^*{}_{GPS}$, $Y^*{}_{GPS}$, $Z^*{}_{GPS}$ – coordinates of GPS satellites in the XYZ geocentric system, taking EGNOS corrections into account,

c – the speed of light,

dtr – receiver clock correction, a parameter determined together with the aircraft coordinates,

[17] A. Fellner, R. Fellner, E. Piechoczek, Pre-flight validation of RNAV GNSS approach procedures for EPKT in “EGNOS APV Mielec project”, “Sci. J. Sil. Univ. Technol. Series Transp.”, 2016, 90, p. 37–46.

[18] J. Kozuba, K. Krasuski, J. Ćwiklak, H. Jafernik, Aircraft position determination in SBAS system in air transport, In “Proceedings of the 17th International Conference Engineering for Rural Development”, Jelgava, Latvia, 23-25 May 2018; pp. 788–794.

dtr^* – correction of the satellite's clock bias, determined on the basis of a second--degree polynomial from the GPS navigation message and using the long-term corrections of the EGNOS system,

Ion^* – ionospheric correction, determined from the GRID regular grid model using polynomial interpolation of the VTEC parameter,

$Trop^*$ – tropospheric correction determined from the RTCA-MOPS troposphere model,

Rel – the relativistic effect, determined from the data from the navigation message,

PRC – EGNOS fast corrections,

TGD – group delay for sending a code measurement for GPS satellites based on data from a navigation message,

Mp – the effect of multiple GPS code observations.

A practical application of the SPP algorithm was implemented for the Topcon HiperPro receiver, which was used to collect GPS measurement data. SBAS satellite-assisted systems make use of the corrections included in equation no. (1) so that the positioning accuracy is higher than when using raw GPS measurements alone.

Accuracy is the difference between the position determined using EGNOS and the actual position of the aircraft determined using the RTK-OTF differential technique. We can calculate this parameter for each of the BLh ellipsoidal coordinates (B – latitude, L – longitude, h – ellipsoidal height) in a manner consistent with equation no. (2)[19]:

$$\begin{cases} \Delta B = (B_1 - B_{R1}) \\ \Delta B = (B_2 - B_{R2}) \\ \vdots \\ \Delta B = (B_N - B_{RN}) \end{cases}$$

$$\begin{cases} \Delta L = (L_1 - L_{R1}) \cdot \cos(\frac{(B_1 + B_{R1})}{2}) \\ \Delta L = (L_2 - L_{R2}) \cdot \cos(\frac{(B_2 + B_{R2})}{2}) \\ \vdots \\ \Delta L = (L_N - L_{RN}) \cdot \cos(\frac{(B_N + B_{RN})}{2}) \end{cases}$$

$$\begin{cases} \Delta h = h_1 - h_{R1} \\ \Delta h = h_2 - h_{R2} \\ \vdots \\ \Delta h = h_N - h_{RN} \end{cases} \tag{2}$$

19 K. Krasuski, The research of accuracy of aircraft position using SPP code method. PhD Thesis, Warsaw University of Technology, Warsaw, Poland, 2019, pp. 1–106.

 DOI: 10.55676/asi.v4i2.76

where:

ΔB – the positioning accuracy along the geodetic latitude B, expressed in metres,

B_N – measurement of the n-th geodetic latitude B of the aircraft using a GPS+EGNOS solution,

B_{RN} – measurement of the n-th latitude of an aircraft using an RTK-OTF solution,

ΔL – the positioning accuracy along the geodetic longitude L, expressed in metres,

L_N – measurement of the aircraft's n-th longitude using a GPS+EGNOS solution,

L_{RN} – measurement of the n-th longitude of an aircraft using an RTK-OTF solution,

Δh – accuracy of ellipsoidal height positioning, expressed in metres,

h_N – measurement of the aircraft's n-th ellipsoidal height by means of a GPS+EGNOS solution,

h_{RN} – measurement of the n-th ellipsoidal height of the aircraft by means of an RTK-OTF solution.

5. RESEARCH EXPERIMENT

The test flight took place along a closed route from Mielec airport, ICAO code EPML. The test was conducted on 7th September 2011[20]. The GNSS satellite measurements were collected from a Topcon HiperPro GPS receiver, which was installed on a Piper Seneca PA34-200T aircraft. The receiver recorded GPS positioning with an interval of 1 second. The EGNOS satellite augmentation data came from the European Space Agency's free web service[21]. The received measurement files and downloaded data enable post-processing with raw GPS measurements and EGNOS corrections.

EGNOS corrections having the extension ".ems" were imported into the RTKLIB software[22]. The acquired EGNOS corrections were used in the calculations in RTKLIB software. The compilation of the GNSS data started by importing the files "s120.ems" and "s124.ems" from the EGNOS satellites S120 and S124. The extension ".ems" stands for EGNOS Message Server, which contains the differential corrections transmitted by the SBAS geostationary satellites. An example of the contents of the ".ems" file is shown in Figure 1.

[20] H. Jafernik, The test programme concerning aircraft positioning and traffic monitoring-Part II, "Sci. J. Sil. Univ. Technol. Ser. Transp.", 2016, 93, p. 41–48.

[21] http://www.egnos-pro.esa.int/ems/index.html [access: 14.08.2023].

[22] http://rtklib.com/ [access: 14.08.2023].

```
120 11 09 07 12 00 00 18 C6494C000000000000400001F00003F80003FC0003FE0001FF0001FFBAE2F800
120 11 09 07 12 00 01 2 5309001800001FFF4000000000003FC0003FB80000297BBBBBB9F97A7C648B80
120 11 09 07 12 00 02 3 9A0E0000000000000000000002800000000000000003BBBBBA39BBBBB0DFBE00
120 11 09 07 12 00 03 24 C66004FFC3FD400000000155BBB8A03A80210CFDBFC0D13F9F00480009E41D40
120 11 09 07 12 00 04 17 534400000000000000000F822EBACB978000000000000000000000A90FAA78C0
120 11 09 07 12 00 05 2 9A0A001800001FFF0000000000003FC4003FB80000297BBBBBB9F97A4D979440
120 11 09 07 12 00 06 3 C60C000000000000000000002C000000000000000003BBBBBA39BBBBAE4330C0
120 11 09 07 12 00 07 24 536004FFC3FD400000000155BBB880397BFAFA0100010700000001C0995F380
120 11 09 07 12 00 08 12 9A30000C280000007129D03FA0103DA4EA3CE8000000000000000001C2DD780
120 11 09 07 12 00 09 2 C608001800001FFF0000000000003FC8003FB80000297BBBBBB9F97A64526280
120 11 09 07 12 00 10 3 530D000000000000000000002C000000000000000003BBBBBA39BBBB96E9B080
120 11 09 07 12 00 11 24 9A6004FFC3FD400000000155BBB8902C12000000022C37D210E78023E013340
120 11 09 07 12 00 12 26 C66A57FDFFEFFF7FFBFFDE0000000000000000000000000000000000AA45180
120 11 09 07 12 00 13 2 5309001800001FFF0000000000003FC8003FB80000217BBBBBB9F97A67AB4700
120 11 09 07 12 00 14 3 9A0E000000000000000000002C003FFC000000000003BBBBBA39BBBBA7A67680
120 11 09 07 12 00 15 24 C66004FFC3FD400000000155BBB8A028841FFB0540B25CBFFFF00FFA2B4E0440
```

Fig. 1. Format of EGNOS corrections in extension ".ems"

Source: own study.

The first step in processing the GPS+EGNOS satellite data is to import them into RTKLIB accordingly. The data were imported according to the scheme shown in Figure 2.

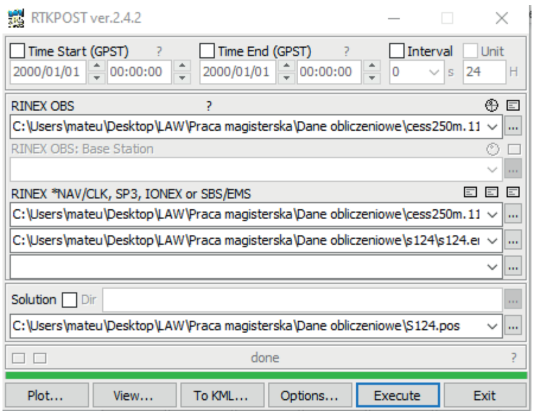

Fig. 2. Import of raw GPS+EGNOS data into RTKLIB

Source: own study.

In the field "RINEX OBS", RINEX observations were imported with the extension ".11o". RINEX data stands for Receiver Independent Exchange Format and represents raw data from a GPS navigation system that can be post-processed. The RINEX data format is a universal data exchange format for all satellite receivers[23]. The field "RINEX *NAV/CLK, SP3, IONEX or SBS/EMS" is used to import RINEX navigation data and EMS corrections from a specific SBAS satellite. Figure 2 shows the import from the geostationary satellite S124. The "Solution" function is used to define the storage path of the processed data. The saving of the final calculation results is done in ".pos" format.

[23] https://www.igs.org/data/#daily_data [access: 14.08.2023].

DOI: 10.55676/asi.v4i2.76

Selecting the 'Options' window takes the user to the settings area to be adjusted to the selected GNSS positioning method. The desired settings, i.e. the GPS solution with SBAS corrections, are illustrated in Fig. 3. The observation elevation angle was set to 5°, which meets the requirements for APV SBAS approaches[24]. The ionosphere and troposphere corrections were set to 'SBAS' mode. The ephemeris and clock error of the satellite were set to the 'Broadcast+SBAS' calculation mode. At the bottom of the interface, the navigation systems, in this case GPS and SBAS, were selected. It is important to adjust the format of the resulting positioning in ellipsoidal coordinates (B, L, h). The setting is done in the "Output" interface and is illustrated in Fig. 4. The desired field is called „Lat/Lon/Height".

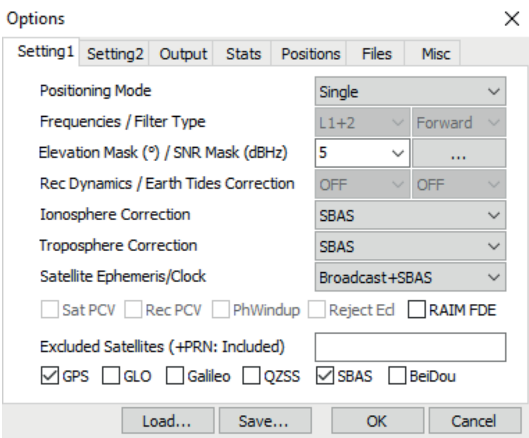

Fig. 3. The RTKLIB settings field

Source: own study.

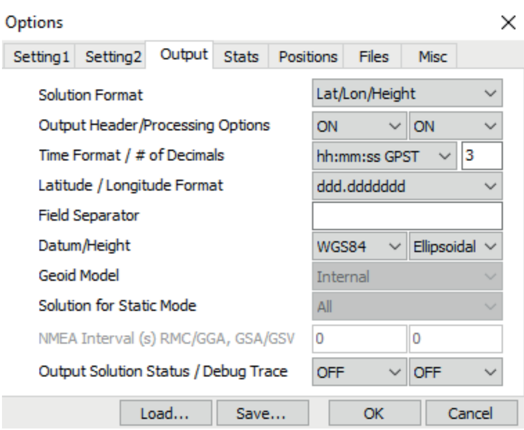

Fig. 4. The "Output" format setting field of RTKLIB

Source: own study.

[24] www.ulc.gov.pl/pl/prawo/prawo-mi%C4%99dzynarodowe/206-konwencje [access: 14.08.2023].

The programme prepared in this way can be used to accurately determine the position of the aircraft using GPS and EGNOS in post-positioning mode. The result is two reports, "S120.pos" and "S124.pos", which represent the coordinate performance for the GPS+EGNOS solution using corrections from the S120 and S124 satellites, respectively. The final calculation reports are shown in Figure 5.

```
% program   : RTKPOST ver.2.4.2
% inp file  : C:\Users\mateu\Desktop\LAW\Praca magisterska\Dane obliczeniowe\cess250m.11o
% inp file  : C:\Users\mateu\Desktop\LAW\Praca magisterska\Dane obliczeniowe\cess250m.11n
% inp file  : C:\Users\mateu\Desktop\LAW\Praca magisterska\Dane obliczeniowe\s120\s120.ems
% obs start : 2011/09/07 12:47:38.0 GPST (week1652 305258.0s)
% obs end   : 2011/09/07 14:05:43.0 GPST (week1652 309943.0s)
% pos mode  : single
% elev mask : 5.0 deg
% ionos opt : sbas
% tropo opt : sbas
% ephemeris : broadcast+sbas
% navi sys  : gps sbas
%
% (lat/lon/height=WGS84/ellipsoidal,Q=1:fix,2:float,3:sbas,4:dgps,5:single,6:ppp,ns=# of satellites)
%  GPST                  latitude(deg) longitude(deg)  height(m)   Q  ns   sdn(m)   sde(m)   sdu(m)  sdne(m)  sdeu(m)  sdun(m) age(s)  ratio
2011/09/07 12:47:38.000   50.326744190   21.450513824   207.1732   3   6   1.6537   1.0516   2.3750  -0.6891   1.1106  -1.2617   0.00    0.0
2011/09/07 12:47:39.000   50.326734582   21.450509074   208.2916   3   6   1.6496   1.0560   2.3798  -0.7055   1.1370  -1.2504   0.00    0.0
2011/09/07 12:47:40.000   50.326732153   21.450507292   208.3325   3   6   1.6668   1.0683   2.4087  -0.7150   1.1529  -1.2658   0.00    0.0
2011/09/07 12:47:41.000   50.326727531   21.450505402   209.2779   3   6   1.6677   1.0804   2.4387  -0.7384   1.1671  -1.2976   0.00    0.0
2011/09/07 12:47:42.000   50.326729974   21.450504628   208.5534   3   6   1.6533   1.0518   2.3753  -0.6896   1.1108  -1.2612   0.00    0.0
2011/09/07 12:47:43.000   50.326734073   21.450507587   208.1259   3   6   1.6492   1.0561   2.3801  -0.7060   1.1371  -1.2499   0.00    0.0
2011/09/07 12:47:44.000   50.326771821   21.450501472   203.6703   3   8   1.0219   1.0237   1.9141  -0.5111   0.9851   0.5097   0.00    0.0
2011/09/07 12:47:45.000   50.326770729   21.450500582   203.5707   3   8   1.0197   1.0337   1.9247  -0.5277   0.9891   0.4808   0.00    0.0
2011/09/07 12:47:46.000   50.326768884   21.450507340   203.5160   3   8   1.0220   1.0135   1.8831  -0.5146   0.9619   0.4869   0.00    0.0
2011/09/07 12:47:47.000   50.326768851   21.450509883   203.3252   3   8   1.0135   1.0127   1.8930  -0.5074   0.9733   0.5038   0.00    0.0
2011/09/07 12:47:48.000   50.326770735   21.450508785   203.0965   3   8   1.0219   1.0238   1.9142  -0.5111   0.9849   0.5109   0.00    0.0
2011/09/07 12:47:49.000   50.326771818   21.450504954   202.6555   3   8   1.0197   1.0337   1.9248  -0.5277   0.9889   0.4822   0.00    0.0
2011/09/07 12:47:50.000   50.326770399   21.450507042   203.0966   3   8   1.0220   1.0135   1.8833  -0.5146   0.9617   0.4881   0.00    0.0
2011/09/07 12:47:51.000   50.326769374   21.450507080   203.1494   3   8   1.0135   1.0128   1.8932  -0.5074   0.9731   0.5050   0.00    0.0
2011/09/07 12:47:52.000   50.326768303   21.450506057   202.7585   3   8   1.0219   1.0238   1.9143  -0.5112   0.9846   0.5121   0.00    0.0
```

```
% program   : RTKPOST ver.2.4.2
% inp file  : C:\Users\mateu\Desktop\LAW\Praca magisterska\Dane obliczeniowe\cess250m.11o
% inp file  : C:\Users\mateu\Desktop\LAW\Praca magisterska\Dane obliczeniowe\cess250m.11n
% inp file  : C:\Users\mateu\Desktop\LAW\Praca magisterska\Dane obliczeniowe\s124\s124.ems
% obs start : 2011/09/07 12:47:38.0 GPST (week1652 305258.0s)
% obs end   : 2011/09/07 14:05:43.0 GPST (week1652 309943.0s)
% pos mode  : single
% elev mask : 5.0 deg
% ionos opt : sbas
% tropo opt : sbas
% ephemeris : broadcast+sbas
% navi sys  : gps sbas
%
% (lat/lon/height=WGS84/ellipsoidal,Q=1:fix,2:float,3:sbas,4:dgps,5:single,6:ppp,ns=# of satellites)
%  GPST                  latitude(deg) longitude(deg)  height(m)   Q  ns   sdn(m)   sde(m)   sdu(m)  sdne(m)  sdeu(m)  sdun(m) age(s)  ratio
2011/09/07 12:47:38.000   50.326743474   21.450514298   207.4840   3   6   1.6527   1.0493   2.3656  -0.6880   1.1206  -1.2408   0.00    0.0
2011/09/07 12:47:39.000   50.326734461   21.450509601   208.5910   3   6   1.6507   1.0579   2.3876  -0.7066   1.1289  -1.2680   0.00    0.0
2011/09/07 12:47:40.000   50.326732158   21.450507828   208.6285   3   6   1.6681   1.0706   2.4179  -0.7164   1.1432  -1.2866   0.00    0.0
2011/09/07 12:47:41.000   50.326727426   21.450506320   209.4829   3   6   1.6664   1.0785   2.4310  -0.7370   1.1750  -1.2801   0.00    0.0
2011/09/07 12:47:42.000   50.326729793   21.450505538   208.7599   3   6   1.6522   1.0494   2.3659  -0.6885   1.1207  -1.2403   0.00    0.0
2011/09/07 12:47:43.000   50.326734729   21.450508566   208.3152   3   6   1.6503   1.0580   2.3879  -0.7071   1.1290  -1.2674   0.00    0.0
2011/09/07 12:47:44.000   50.326771178   21.450502767   203.9164   3   8   1.0439   1.0300   1.9134  -0.5119   0.9771   0.4679   0.00    0.0
2011/09/07 12:47:45.000   50.326770588   21.450504971   203.7505   3   8   1.0184   1.0525   1.9277  -0.5288   0.9871   0.5054   0.00    0.0
2011/09/07 12:47:46.000   50.326768879   21.450510488   203.5406   3   8   1.0203   1.0304   1.8868  -0.5135   0.9600   0.5147   0.00    0.0
2011/09/07 12:47:47.000   50.326768071   21.450512890   203.2957   3   8   1.0174   1.0378   1.8922  -0.5278   0.9615   0.4865   0.00    0.0
2011/09/07 12:47:48.000   50.326769865   21.450511822   203.0629   3   8   1.0263   1.0494   1.9129  -0.5333   0.9724   0.4895   0.00    0.0
2011/09/07 12:47:49.000   50.326771291   21.450507204   202.5805   3   8   1.0185   1.0525   1.9278  -0.5288   0.9869   0.5067   0.00    0.0
2011/09/07 12:47:50.000   50.326769828   21.450508760   203.1106   3   8   1.0203   1.0305   1.8869  -0.5135   0.9598   0.5159   0.00    0.0
2011/09/07 12:47:51.000   50.326768470   21.450509154   203.1700   3   8   1.0174   1.0379   1.8923  -0.5277   0.9613   0.4877   0.00    0.0
2011/09/07 12:47:52.000   50.326767337   21.450508481   202.7805   3   8   1.0263   1.0495   1.9130  -0.5333   0.9722   0.4908   0.00    0.0
```

Fig. 5. Final calculation reports from RTKLIB
Source: own study.

The RTKLIB programme allows the determination of horizontal and vertical flight trajectories in its environment and allows the import of the resulting measurement data into the Google Earth environment. Figures 6 and 7 show the results of converting the data from the ".pos" format to the ".kml" format, which enabled the flight trajectory to be imaged in Google Earth[25].

25 https://www.google.pl/intl/pl/earth/ [access: 14.08.2023].

 DOI: 10.55676/asi.v4i2.76

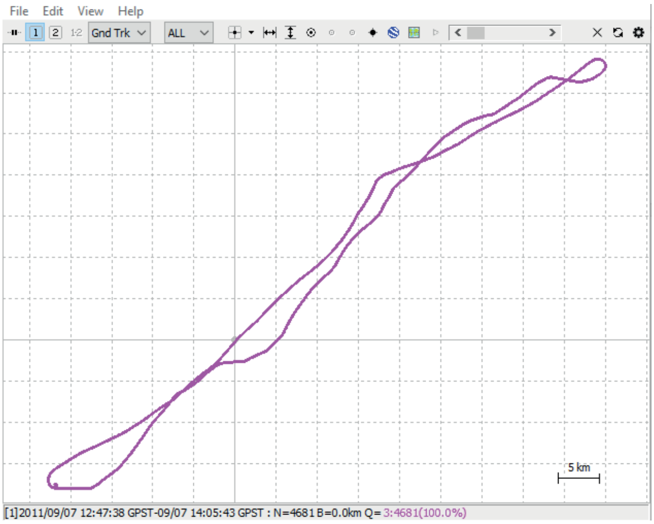

Fig. 6. Flight trajectory obtained from the RTKLIB programme
Source: own study.

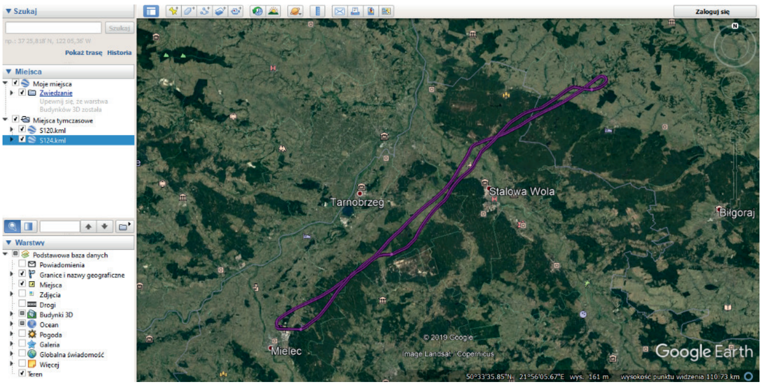

Fig. 7. Flight trajectory in the Google Earth environment
Source: own study.

The next step is to convert the files from ".pos" format to ".xlsx" format supported by Microsoft Office. This will make it possible to apply mathematical formulas to calculate the positioning accuracy of GPS+EGNOS with reference to the differential RTK-OTF technique. The RTK-OTF solution used data from the "Base" station, which was a local physical reference station located near the runway of the Mielec airport. Data from the "Base" reference station was used to determine the flight reference position of the Piper Seneca PA34-200T aircraft within the RTK-OTF solution.

6. RESEARCH RESULTS AND DISCUSSION

As part of this work, a series of computer calculations were performed to find out the accuracy of positioning using EGNOS. The EGNOS data from two satellites was used in test, so the calculations made are separately for satellite S120, S124 and the average of the measurements from both satellites. The test time was 4476 seconds, which translates into 1 hour 14 minutes and 36 seconds according to GPST time.

In the first step, the GPS+EGNOS positioning accuracy was determined using corrections from the S120 satellite. The results of the navigation calculations are shown in Fig. 8.

The positioning accuracy did not go beyond -2.5 m to +2.5 m for each of the BLh ellipsoidal coordinates during almost the entire test period. The amplitude of the accuracy values for the B coordinate is -5.1 m to +2.6 m. The average accuracy for the B coordinate is +0.9 m. For the L coordinate, the amplitude of the accuracy values ranges from -5.3 m to +4.4 m. The average accuracy of the navigation solution of the L coordinate is +0.2 m. Calculations of the positioning accuracy of the h coordinate showed an amplitude ranging from -2.0 m to +9.7 m. The average accuracy of the navigation solution of the h coordinate is +0.3 m. The lowest accuracy of the EGNOS navigation solution was observed between 12:47:49 and 12:55:54. This corresponds to the lower number of GPS satellites available, as illustrated later in the paper in Figure 11. The positioning accuracy is closely dependent on the number of GPS satellites observed and tracked.

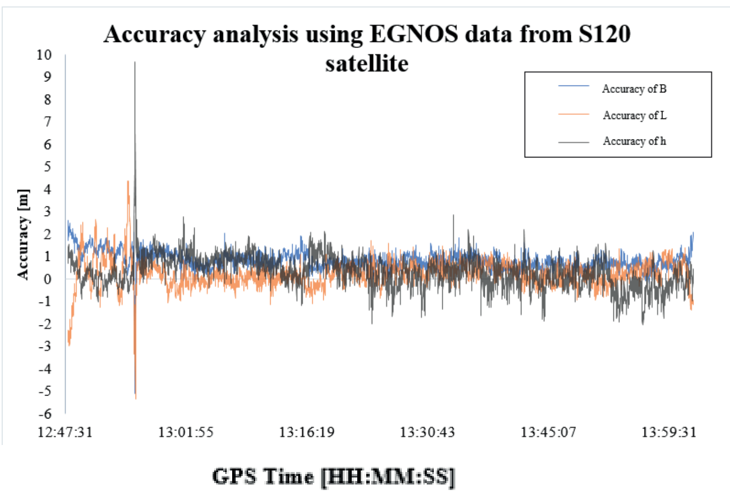

Fig. 8. Accuracy positioning using EGNOS data from S120 satellite
Source: own study.

 DOI: 10.55676/asi.v4i2.76

An analogous series of calculations for 4476 seconds was performed for the EGNOS S124 satellite. The accuracy was calculated from equation (1) and the result of the calculation is shown in Fig. 9. The amplitude of the accuracy of the B coordinate was determined, which ranged from -5.0 m to +2.6 m. The average accuracy value along the B axis is +0.9 m. For the L-coordinate, the accuracy spread is -5.5 m to +4.5 m. The average accuracy value for the L coordinate was calculated to be +0.2 m. Figure 9 also shows the accuracy for the h coordinate, which ranged from -1.9 m to +9.6 m. The average accuracy of the GPS+EGNOS navigation solution for the altitude coordinate is +0.3 m. As with the S120 satellite, the lowest positioning accuracy was observed in the time interval from 12:47:49 to 12:55:54. Beyond this, an accuracy of between -2.0 m and 2.5 m was observed for most of the test time. Of note is the period from 13:18:24 to 13:22:20, which shows a degradation in the determination of the accuracy of the h-component.

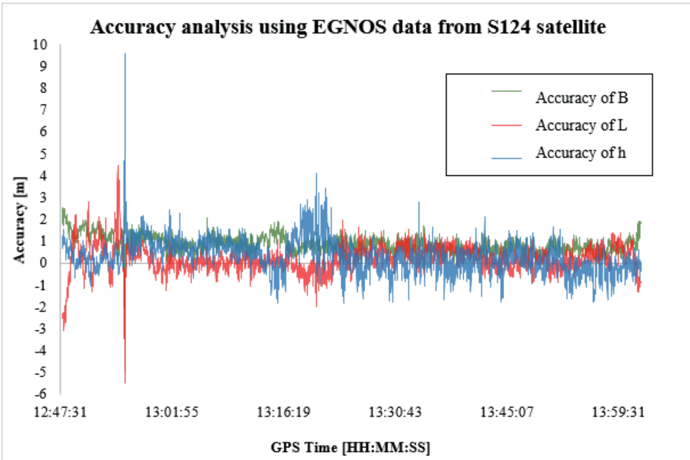

Fig. 9. Accuracy positioning using EGNOS data from S124 satellite
Source: own study.

The average positioning accuracy was then calculated using data from the S120 and S124 satellites. Formula (3) was used for this purpose:

$$\begin{cases} \Delta B_m = \frac{\Delta B_{S120}+\Delta B_{S124}}{2} \\ \Delta L_m = \frac{\Delta L_{S120}+\Delta L_{S124}}{2} \\ \Delta h_m = \frac{\Delta h_{S120}+\Delta h_{S124}}{2} \end{cases} \tag{3}$$

where:

$(\Delta B_m, \Delta L_m, \Delta h_m)$ – average accuracy of EGNOS positioning,

$(\Delta B_{S120}, \Delta L_{S120}, \Delta h_{S120})$ – EGNOS positioning accuracy using data from the S120 satellite, calculated from equation (2),

(ΔB_{S124}, ΔL_{S124}, Δh_{S124}) – EGNOS positioning accuracy using data from the S124 satellite, calculated from equation (2).

Figure 10 shows the results of the average EGNOS positioning accuracy according to equation (3). The average positioning accuracy along the B axis was 0.9 m, along the L axis 0.2, and along the h axis 0.3 m. The positioning amplitude for the B ellipsoid coordinate ranges from -5.0 m to 2.6 m, for the L coordinate it is from -5.4 m to 4.4 m, and for the h coordinate it was from -1.9 m to 9.6 m. Of note is the degradation in positioning accuracy over the period 12:55:00 to 12:56:00.

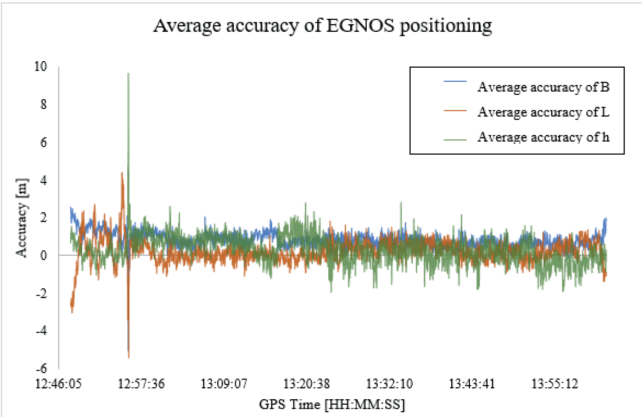

Fig. 10. Average accuracy of EGNOS positioning
Source: own study.

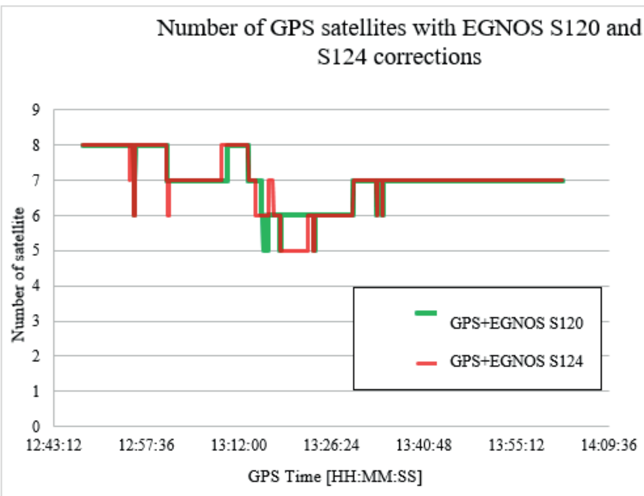

Fig. 11. Number of GPS satellite with EGNOS S120 and S124 corrections
Source: own study.

DOI: 10.55676/asi.v4i2.76

In order to assess whether the EGNOS positioning accuracy was affected by the number of GPS satellites observed, Figure 11 was drawn up with the number of GPS satellites tracked for which EGNOS corrections were determined. During the time period 12:55:00 to 12:56:00, a decrease in the number of observed GPS satellites was observed from 8 to 6. This coincided with a degradation in EGNOS positioning accuracy. It follows that the number of observed satellites is closely related to the accuracy of positioning. Another time period with a lower number of GPS satellites is the period between 13:16:00 and 13:23:45. A degradation in positioning accuracy along the h-axis was observed then, when the number of GPS satellites tracked was equal to 5.

A comparison was then made between the average accuracy of EGNOS positioning and the certification requirements of the International Civil Aviation Organisation[26]. The results of the comparison are shown in Table 1. The EGNOS solution from the S120 satellite meets the requirements of the SBAS APV-I procedure for the entire test period. In contrast, the EGNOS solution from the S124 satellite meets the more stringent requirements of the SBAS APV-II procedure, except for the period 12:55:51, which corresponds to a momentary degradation in positioning accuracy resulting from the loss of the observed GPS satellites. This degradation is temporary and only lasts for 1 measurement epoch, so it does not affect the final assessment of EGNOS positioning quality. It can therefore be said that the results of the EGNOS positioning accuracy tests meet the certification requirements of the SBAS APV-I and SBAS APV-II procedure.

Table 1. Average EGNOS positioning accuracy results obtained and ICAO certification requirements

Requirements/Solution	Horizontal accuracy [m]	Vertical accuracy [m]
SBAS APV I	16	20
SBAS APV II	16	8
Average accuracy from the EGNOS S120 solution	0.5	0.3
Average accuracy from the EGNOS S124 solution	0.5	0.3
Average accuracy from the EGNOS S120 and S124 solution	0.5	0.3

Source: own study.

7. CONCLUSIONS

The main objective of the study was to determine the accuracy of EGNOS positioning in aviation. In this study, measurement data from the GPS navigation system and the EGNOS S120 and S124 geostationary satellites were processed. The data were processed in post-processing mode in the RKTLIB environment. The downloaded data were converted to the ".xlsx" extension, which enabled their further analysis with Microsoft Excel software. Using the resulting measurements, the EGNOS positioning

[26] www.ulc.gov.pl/pl/prawo/prawo-mi%C4%99dzynarodowe/206-konwencje, [access: 14.08.2023].

accuracy was calculated. The average accuracy of EGNOS positioning using data from the S120 satellite for the B, L, h coordinates is 0.9 m, 0.2 m and 0.3 m, respectively. In contrast, the average accuracy of EGNOS positioning using data from the S124 satellite is also similarly 0.9 m, 0.2 m and 0.3 m for BLh coordinates. It was observed that the positioning accuracy in a given measurement epoch is dependent on the number of GPS satellites observed. This is particularly important during the critical phase of flight, which is the approach and landing. The accuracy of EGNOS positioning using corrections from the S120 and S124 satellites was compared with the certification requirements of the International Civil Aviation Organisation. The measurements meet the certification requirements of SBAS APV-I and SBAS APV-II approaches.

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