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ACCURACY ANALYSIS OF AIRCRAFT POSITIONING USING NAVIGATIONAL DATA FROM AVIA-W RADAR

ANALIZA DOKŁADNOŚCI POZYCJONOWANIA STATKU POWIETRZNEGO NA PODSTAWIE DANYCH NAWIGACYJNYCH Z RADARU AVIA-W

Abstract

The paper presents an analysis of the accuracy of determination of parameters of the position of aircraft using data from the AVIA-W radar. In the first place, the authors determined the position of the aircraft as well as the range and azimuth parameters by the AVIA-W radar, located in Dęblin. This was followed by a determination of the absolute position error of the aircraft and the determination of the range and azimuth measurement error by the AVIA-W radar. The research test was carried out using a Diamond DA40 NG aircraft on which a GPS satellite receiver was mounted in order to determine the flight reference position. In addition, the range and azimuth measurements for the aircraft were acquired from the AVIA-W radar. Navigational calculations were conducted for polar and rectangular planar coordinates. Based on the performed research, the azimuth error was found to be –1.4°, while the radar range measurement error was equal to –0.04 km. The conducted research is experimental in its character. In the future it will be repeated and extended to the GCA-2000 radar, which is also located at Dęblin military airfield.

Keywords: radar, GPS, accuracy, aircraft position, azimuth, range

Streszczenie

W pracy przedstawiono analizę dokładności wyznaczenia parametrów pozycji statku powietrznego z użyciem danych z radaru AVIA-W. W pierwszej kolejności dokonano wyznaczenia pozycji statku powietrznego oraz określenia parametru zasięgu i azymutu przez radar AVIA-W, zlokalizowany w Dęblinie. Następnie dokonano wyznaczenia błędu absolutnego pozycji statku powietrznego oraz określenia błędu pomiaru zasięgu i azymutu przez radar AVIA-W. Test badawczy przeprowadzono z użyciem samolotu Diamond DA40 NG, na pokładzie którego zamontowano odbiornik satelitarny GPS w celu wyznaczenia pozycji odniesienia lotu. Dodatkowo z radaru AVIA-W pozyskano pomiary zasięgu i azymutu do statku powietrznego. Obliczenia nawigacyjne zrealizowano dla współrzędnych biegunowych i prostokątnych płaskich. Na podstawie wykonanych badań stwierdzono, że błąd azymutu wynosi –1,4°, z kolei błąd pomiaru zasięgu radaru wynosi –0,04 km. Przeprowadzone badania mają charakter eksperymentalny i w przyszłości zostaną powtórzone i rozszerzone o radar GCA-2000, który także znajduje się na lotnisku wojskowym Dęblin.

Słowa kluczowe: radar, GPS, dokładność, pozycja statku powietrznego, azymut, zasięg

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1. INTRODUCTION

An airfield area control radar is a device used to detect and determine the position of airborne objects. Nowadays, it is hard to imagine maintaining a smooth, orderly and safe flow of air traffic without the provision of a radar-based air traffic control service, of which a radar is an essential tool. An airfield area control radar is a device whose application is also crucial from the perspective of national defence, as it enables a regular observation of a designated area of space as well as a quick recognition of enemy air forces[1].

The use of radars to detect and determine the position of objects using electromagnetic waves is described in the field of radio engineering referred to as radiolocation. The term radar itself is derived from an English acronym for "radio detection and ranging" and it stands for "detection and ranging by radio waves"[2]. This device uses a focused beam of electromagnetic radiation to detect and determine the position of objects that are capable of reflecting electromagnetic waves[3]. It is used to conduct continuous radar reconnaissance and provide radar information on the airspace situation in an airfield area[4].

In modern aviation, continuous monitoring and tracking of aircraft during flight operations is a key element. In practice, navigation radars installed at airfields are used to continuously monitor changes in aircraft position. The navigational radar readings are referenced to a polar coordinate system or a spherical coordinate system. In the case of a polar coordinate system, the authors refer to a two-dimensional coordinate system. In such a system, the basic parameters measured are range (R) and azimuth (B). In the case of a spherical coordinate system, the author refers to a three-dimensional coordinate system. In such a system, the basic measured parameters are range (R), azimuth (B) and elevation (ε)[5].

2. SCIENTIFIC KNOWLEDGE ANALYSIS

The research themes concerning determination of aircraft position using radar data have been widely addressed in the available scientific literature. The research work has been carried out both in Poland and internationally. In the case of the research conducted in Poland, the main themes concern:

1 Z. Czekała, *Parada radarów*, Bellona, Warszawa 1999, p. 1–456.

2 A. Goś, *Charakterystyka porównawcza radarów AVIA i GCA2000*, [in:] *Wybrane aspekty zabezpieczenia nawigacji lotniczej*, ed. J. Ćwiklak, "Współczesna Nawigacja", T. I, LAW, Dęblin 2019, p. 161–174.

3 A. Truskowski, *Detecting aircraft made in stealth technology*, "Scientific journal of Polish Naval Academy" 2014, vol. 4(199), DOI: 10.5604/0860889X.1139635, p. 83–102.

4 https://www.defence24.pl/polskie-wojsko-chce-wymienic-radary-kontroli-rejonu-lotniska [access: 17.05.2023].

5 Z. Tao, L. Chunxia, L. Quanhua, C. Xinliang, *Tracking with nonlinear measurement model by coordinate rotation transformation*, "Science China Technological Sciences" 2014, vol. 57, DOI: 10.1007/s11431-014-5694-y, p. 2396.

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- determining the aircraft position by means of a long-range radar[6];
- tests of modern radiolocation equipment carried out by the Air Force Institute of Technology with regard to aircraft precision positioning[7];
- determination of the precise trajectory of an aircraft by a radar in the “BRDA” flight experiment[8];
- application of methods for aircraft discrimination by radar equipment during a flight test[9];
- analysis, evaluation and review of selected air traffic management systems in Poland[10];
- detection and tracking of small and high speed moving ballistic objects by radar equipment[11];
- application of the multilateration technique in airspace management in Poland[12];
- analysis of the effectiveness of radar interference for the aircraft self-defence system[13];
- representation of radar metrics for the aircraft self-defence systems database[14],
- development of a method for testing the azimuthal and distance discriminability of radiolocation stations[15];
- testing of equal types of radars manufactured in Poland, including navigation applications[16];

6 M. Brzozowski, M. Myszka, Z. Lewandowski, A. Modrzewski, *Wykorzystanie metod precyzyjnego wyznaczania pozycji obiektów powietrznych za pomocą GPS do badań radaru dalekiego zasięgu RST-12M*, “Problemy Techniki Uzbrojenia” 2007, vol. 36(101), p. 53–62.

7 M. Brzozowski, M. Pakowski, M. Myszka, M. Michalczewski, U. Winiarska, *The research of modern radar equipment conducted in the Air Force Institute of Technology by the application of military aircrafts*, “Aviation Advances & Maintenance” 2017, vol. 1(40), DOI: 10.1515/afit-2017-0002, p. 27–65.

8 M. Grzegorzewski, *Navigating an aircraft by means of a position potentialin three dimensional space*, “Annual of Navigation” 2005, vol. 9, p. 1–111.

9 M. Brzozowski, Z. Lewandowski, *Metoda określania rozróżnialności obiektów powietrznych przez urządzenia radiolokacyjne z wykorzystaniem lotów samolotów z zamontowanymi na pokładzie odbiornikami i rejestratorami pozycji*, “Problemy Techniki Uzbrojenia” 2009, vol. 38(112), p. 105–115.

10 M. Siergiejczyk, K. Krzykowska, *Analiza i ocena wybranych systemów dozorowania w ruchu lotniczym*, “TTS Technika Transportu Szynowego” 2013, vol. 20(10), p. 1825–1834.

11 M. Brzozowski, M. Pakowski, M. Nowakowski, M. Myszka, M. Michalczewski, *Radiolocation Devices for Detection and Tracking Small High-Speed Ballistic Objects – Features, Applications, and Methods of Tests*, “Sensors” 2019, vol. 19, DOI: 10.3390/s19245362, p. 5362.

12 M. Siergiejczyk, J. Siłkowska, *Analiza możliwości wykorzystania techniki multilateracji w dozorowaniu przestrzeni powietrznej*, “Prace Naukowe Politechniki Warszawskiej. Transport” 2014, vol. 102, p. 119–133.

13 J. Matuszewski, J. Dudczyk, *Analiza skuteczności zakłóceń radiolokacyjnych systemu samoobrony statku powietrznego*, “Elektronika: Konstrukcje, Technologie, Zastosowania” 2015, vol. 56(10), DOI: 10.15199/13.2015.10.17, p. 83–88.

14 J. Matuszewski, *Metryka radaru dla potrzeb bazy danych samolotowych systemów samoobrony*, „Przegląd Elektrotechniczny” 2015, vol. 91(3), DOI:10.15199/48.2015.03.18, p. 77–80.

15 M. Brzozowski, M. Myszka, Z. Lewandowski, *Metoda badania rozróżnialności azymutalnej i odległościowej stacji radiolokacyjnych*, „Problemy Techniki Uzbrojenia” 2004, vol. 33(92), p. 49–56.

16 M. Pakowski, M. Brzozowski, M. Michalczewski, M. Myszka, *Methods for Testing Military Radars Produced in Poland*, „Proceedings of the 2018 5th IEEE International Workshop on Metrology for AeroSpace (MetroAeroSpace)”, DOI: 10.1109/MetroAeroSpace.2018.8453542, p. 322–327.

- testing the accuracy of azimuth and range measurement by radar equipment during a flight test[17].

Worldwide, navigation applications of radars have addressed issues in the area:
- determining the basic navigational, technical and operational parameters of the radar for aircraft detection[18];
- determination of the precise flight altitude of the aircraft by a radar[19];
- development of aircraft separation monitoring for Tokyo International Airport in Japan[20];
- development of a collision avoidance system for aircraft including radar data control[21];
- specifying the accuracy of the determination of the aircraft's airspeed by a radar[22];
- integration of radar and GPS satellite data for the aircraft precision approach procedure[23];
- comparison of radar and GPS satellite data for aircraft positioning[24];
- tracking the movement of UAVs by a meteorological radar[25];
- using the telephone in order to determine the position of aircraft with reference to navigational radar data[26];
- using radars in air traffic management, including approach and landing phases[27];
- aircraft position prediction using radar data for fuzzy models[28];

17 M. Pakowski, M. Brzozowski, M. Nowakowski, M. Myszka, M. Michalczewski, *Research on radar angular and range resolution with the use of a system assisting the pilots in maintenance of flight parameters*, "Proceedings of the 2019 IEEE 5th International Workshop on Metrology for AeroSpace (MetroAeroSpace)", DOI: 10.1109/MetroAeroSpace.2019.8869694.

18 S.H.M. Al Sadoon, B.H. Elias, *Radar theoretical study: minimum detection range and maximum signal to noise ratio (SNR) equation by using MATLAB simulation program*, "American Journal of Modern Physics" 2013, vol. 2(4), DOI: 10.11648/j.ajmp.20130204.20, p. 234–241.

19 W. Semke, N. Allen, A. Tabassum, M. Mccrink, M. Moallemi, K. Snyder, E. Arnold, D. Stott, M.G. Wing, *Analysis of Radar and ADS-B Influences on Aircraft Detect and Avoid (DAA) Systems*, "Aerospace" 2017, vol. 4, DOI: 10.3390/aerospace4030049, p. 49.

20 K. Sekine, F. Kato, K. Kageyama, E. Itoh, *Data-Driven Simulation for Evaluating the Impact of Lower Arrival Aircraft Separation on Available Airspace and Runway Capacity at Tokyo International Airport*, "Aerospace" 2021, vol. 8, DOI: 10.3390/aerospace8060165, p. 165.

21 M. Džunda, P. Dzurovčin, L. Melníková, *Anti-Collision System for Small Civil Aircraft*, "Applied Sciences" 2022, vol. 12, DOI: 10.3390/app12031648, p. 1648.

22 J. Maas, R. Van Gent, J. Hoekstra, *A portable primary radar for general aviation*, "PLoS ONE" 2020, vol. 15(10), DOI: 10.1371/journal.pone.0239892, p. 1–32.

23 N. Nabaa, G. Clary, J. Cross, D. Howard, R. Thayer, *Integration of DGPS and Precision Tracking Radar for Aircraft Precision Approach*, "Proceedings of the 57th Annual Meeting of The Institute of Navigation (2001)", Albuquerque, NM, June 2001, p. 280–290.

24 R. Gazit, *Aircraft Tracking Using GPS Position and Velocity Reports*, "Proceedings of the 8th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 1995)", Palm Springs, CA, September 1995, p. 281–290.

25 S. Bachmann, V. Debrunner, D. Zrnic, *Detection of Small Aircraft with Doppler Weather Radar*, "Proceedings of the 2007 IEEE/SP 14th Workshop on Statistical Signal Processing", DOI: 10.1109/SSP.2007.4301297, p. 443–447.

26 B. Lilly, D. Cetinkaya, U. Durak, *Tracking Light Aircraft with Smartphones at Low Altitudes*, "Information" 2021, vol. 12, DOI: 10.3390/info12030105, p. 105.

27 J.W. Rogers, C.J. Tidwell, A.D. Little, *Terminal area surveillance system*, "Proceedings of the International Radar Conference 1995", DOI: 10.1109/RADAR.1995.522598, p. 501–504.

28 M.S. Raboaca, C. Dumitrescu, I. Manta, *Aircraft Trajectory Tracking Using Radar Equipment with Fuzzy Logic Algorithm*, "Mathematics" 2020, vol. 8, DOI: 10.3390/math802020, p. 207.

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– tracking of aircraft position by a high frequency radar[29].

Based on the available data it appears that:

– the use of radar is essential to determine the precise position of an aircraft during a flight;
– the navigational parameters of an aircraft flight collected by the radar were compared with the performance of GPS satellite technology;
– the surveys mainly used dual-coordinate radars to determine azimuth and range to the aircraft;
– the use of a radar is essential to maintain management and air traffic control in a given area;
– the range of research carried out in scientific publications was quite extensive for radar technology, which indicates its enormous application in air navigation.

As the analysis of the current state of knowledge shows, determining the position of an aircraft is the main task posed to radar equipment. The position of the aircraft can be defined in both polar and Cartesian systems. Furthermore, it can be said that range (R) and azimuth (β) in the polar system or a pair of numbers (X, Y) in the Cartesian system can be used to determine the coordinates of the aircraft. When presenting the results in this way, it is also necessary to analyse the accuracy of the calculated navigational parameters of the aircraft position. Hence, the main objective of this paper is to present an analysis of the accuracy of aircraft positioning using radar data for the AVIA-W radar installed at the EPDE military airfield in Dęblin. The paper aims to demonstrate a methodology for determining the accuracy of aircraft position for both polar and Cartesian coordinates. The study will use actual measurement data recorded by the AVIA-W radar and, in addition, on-board data from a GPS satellite receiver mounted on an aircraft.

In conclusion, the authors' main contribution to the work is as follows:

– the development of a methodology for determining the position of the aircraft for both polar coordinates;
– development of a methodology for determining aircraft position both for Cartesian coordinates;
– establishing position error, azimuth error and range error for determining aircraft location;
– determination of the characteristics of the changes of the determined errors in the form of a linear trend.

The whole work has been divided into 6 chapters, i.e.: Chapter One. Introduction, Chapter Two. Analysis of the available expertise, Chapter Three. Research Method, Chapter Four Research test, 5. Research findings and discussion, Chapter Six. Conclusions. The article is complete with a concise list of the available scientific literature.

[29] R.H. Khan, D. Power, *Aircraft detection and tracking with high frequency radar*, "Proceedings of the International Radar Conference 1995", DOI: 10.1109/RADAR.1995.522517, p. 44–48.

3. RESEARCH METHOD

Chapter Three describes the mathematical model for determining the position of the aircraft using radar data. Moreover, it presents the accuracy analysis algorithm for the obtained results.

The position of an object (point) defined by AVIA-W radar is expressed by two polar planar coordinates projected on a horizontal plane. The origin of a system with such coordinates is the position of the radar antenna. The first coordinate is the oblique distance between the origin of the system and the detected object (point). The oblique distance is specified in kilometres and denoted by the symbol *R*. The second coordinate is the azimuth angle, which, in the case of the radar, is measured between the south direction and the direct line connecting the origin of the system with the target. This angle takes on the value from 0° to 360° and is measured clockwise. The azimuth is indicated by the symbol *B*.

In order to transform the polar coordinates R_{AVIA} and B_{AVIA} of the points defined by the radar into the rectangular plane coordinates X_{AVIA} and Y_{AVIA}, the following mathematical formulas described by equations (1–3) were used:

$$\alpha_{AVIA} = 270° - B_{AVIA} \tag{1}$$

$$X_{AVIA} = R_{AVIA} \cdot cos(\alpha_{AVIA}) \tag{2}$$

$$Y_{AVIA} = R_{AVIA} \cdot sin(\alpha_{AVIA}) \tag{3}$$

where:

(X_{AVIA}, Y_{AVIA}) – plane rectangular coordinates of the aircraft based on radar data;

α_{AVIA} – azimuth in a plane rectangular system based on radar data;

B_{AVIA} – azimuth to the polar position of an object based on radar data.

As the B_{AVIA} azimuth angle is measured to the right of the south direction. An additional angle was determined for the purpose of the calculations, which is denoted by the symbol α_{AVIA}. In the Cartesian system, the angles are measured to the left of the positive part of the axis of abscissas. The South direction in the Cartesian system corresponds to the negative part of the axis of ordinates. The angle between the positive part of the abscissa axis and the negative part of the ordinate axis is equal to 270°. Determining the angle α involves changing the reference axis of the B_{AVIA} azimuth angle from the negative part of the axis of ordinates to the positive part of the axis of abscissa. This proves essential because of the use of trigonometric functions to determine the X_{AVIA} and Y_{AVIA} coordinates.

Comparison of positions determined by a radar and a GPS receiver is possible when the points determined by both devices are in the same coordinate system. For this purpose, all the points were placed in a new common rectangular planar (Cartesian) coordinate system XAVIA and YAVIA related to the position of the radar antenna. The Cartesian system consists of two perpendicular number axes – the abscissa axis denoted by *x* and the ordinate axis denoted by *y*. The axes intersect at the origin of the coordinate system. Each point in the system can be uniquely assigned coordinates

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(X, Y) by creating a rectangular projection of the point on the abscissa and ordinate axes. The radar antenna, which is the origin of the system, lies at a point with coordinates (0,0). Both axes of the system are scaled in kilometres. The knowledge of the plane rectangular coordinates of two points makes it possible to calculate the distance between them.

A GPS satellite receiver determines the position of a point on the Earth's surface (on the WGS-84 representation of the Earth's ellipsoid) using angular quantities called geodetic coordinates. The geodetic coordinates are latitude and longitude and are measured in degrees, minutes and angular seconds[30].

The distribution of points recorded by a GPS satellite receiver in the X_{GPS} and Y_{GPS} plane polar coordinate system makes it possible to be transformed into the plane polar coordinate system, whose origin is the antenna of the AVIA-W radar in Dęblin. This enables to express the position of points determined by a GPS receiver by means of the same positioning parameters, used by radar. It needs to be observed, however, that in this case the distance of the point from the origin of the system is not actually the oblique distance of the object from the antenna, but the horizontal distance of the object from the antenna. The transformation of the rectangular coordinates of the flat points determined by the GPS receiver into the same coordinates, used by the radar, does not take into account the effect of a flight altitude, since it is not relevant for the determination of the GPS position. In order to transform the X_{GPS} and YGPS planar rectangular coordinates into R_{GPS} and B_{GPS} planar polar coordinates, algorithms (4–6) were applied as follows:

$$R_{GPS} = \sqrt{X_{GPS}^2 + Y_{GPS}^2} \tag{4}$$

$$\alpha_{GPS} = arctg(\frac{Y_{GPS}}{X_{GPS}}) \tag{5}$$

$$B_{GPS} = 270° - \alpha_{GPS} \tag{6}$$

where:

(X_{GPS}, Y_{GPS}) – plane rectangular coordinates of the aircraft based on GPS satellite data;

α_{GPS} – azimuth in a plane rectangular system based on radar data;

B_{AVIA} – azimuth of the polar position of an object based on radar data.

In order to investigate the accuracy of the determination of position parameters by the radar, the absolute error of measurement was determined. An absolute error is a measure of accuracy that determines how far a measurement result deviates from the real value of the measured value. For the purpose of this analysis, it was assumed that the coordinates of the points determined by the GPS satellite receiver correspond to the real position of the aircraft at a certain time during the experiment. By placing all the measurement points in the Cartesian coordinate system, it is possible to calculate the difference in distance between them. The difference in distance between a point determined by a radar and the actual position of the aircraft, i.e. the point determined by a GPS receiver at a given time, is the absolute error

30 E. Osada, *Geodezja*, Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2001, p. 230–250.

of the position determination. The absolute error of the position determination by the radar is denoted by $\Delta(X, Y)$ and calculated for each pair of points with the same synchronized measurement time in accordance with the following formula:

$$\Delta(X,Y) = \sqrt{(X_{GPS} - X_{AVIA})^2 + (Y_{GPS} - Y_{AVIA})^2} \tag{7}$$

An absolute position error arises from an inaccurate determination of object position parameters by a radar. Expressing a position of points determined by a GPS receiver by means of identical positioning parameters that are exploited by the radar, makes it possible to compare them directly. The difference between the distance from the origin of the coordinate system of the point specified by the radar and the distance from the origin of the coordinates of the point defined by the GPS receiver at a given time is the absolute error of distance measurement. The absolute error of measuring the distance from the antenna is denoted by ΔR and calculated for each pair of points with the same synchronized measurement time in accordance with formula 8. The difference between the azimuth angle of a point determined by the radar and the azimuth angle of a point determined by a GPS receiver at a given time is the absolute error of azimuth angle measurement. The absolute measurement error of the azimuth angle at which the object is located was denoted by the symbol ΔB and was calculated for each pair of points with the same synchronized measurement time in accordance with formula 9. The mathematical formulas for determining the parameters (ΔB, ΔR) have been described below:

$$\Delta R = R_{AVIA} - R_{GPS} \tag{8}$$

$$\Delta B = B_{AVIA} - B_{GPS} \tag{9}$$

Finally, the mathematical algorithms (1–9) were implemented in navigation calculations with the results shown in Chapter Five.

4. RESEARCH TEST

In order to explore the subject of the article, an experiment was carried out on 27 October 2020 at Dęblin airfield using a Nautiz X8 GPS receiver, which was mounted on board a Diamond DA40 NG aircraft. The aircraft used in the experiment is shown in Fig. 1[31]. The aircraft belongs to the Academic Aviation Training Centre of the Polish Air Force University. The Diamond DA40 NG is a small four-seater aircraft powered by a single 168-horsepower piston engine. It reaches a maximum speed of 285 km/h[32].

[31] https://www.wojsko-polskie.pl/law/akademickie-centrum-szkolenia-lotniczego/#gallery-4/ [access: 17.05.2023].

[32] https://www.diamondaircraft.com/en/private-pilots/aircraft/da40/overview/ [access: 17.05.2023].

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Figure 1. Example photo of Diamond DA40 NG aircraft
Source: https://www.wojsko-polskie.pl/law/akademickie-centrum-szkolenia-lotniczego/#gallery-4/ [access: 17.05.2023].

The start of the experiment was assumed as 10:13:28 local time. This is the moment of the first detection of the operated aircraft by the AVIA-W radar at Dęblin, which occurred during the execution of the take-off operation. During the experiment, the object performed a curved line flight over a varied terrain within and outside the radar range. The experiment ended at 15:26:35, local time, during landing, when the radar visualized the aircraft position on the indicator for the last time. Since between the takeoff and landing operations, the aircraft flew out of the range of the radar, for the sake of the analysis, the authors distinguished the departure and arrival phases. The beginning of the departure phase is the start of the experiment, whereas its completion is the last determination of the object's position parameters by the radar eastwards, at 10:42:03 local time. The arrival phase lasts until the end of the experiment from the moment of the first imagery of the aircraft position westwards, at 15:05:47 local time. Apart from the takeoff and landing operations, the aircraft maintained an absolute altitude (above sea level) of approximately 1,500 feet (457.2 metres) for most of the flight.

In order to measure the position parameters of the aircraft operated in the experiment determined by the AVIA-W radar in Dęblin, the airport terminal TU-20L[33] was used. The TU-20L is operated from the control tower at Dęblin airfield. For measurement purposes, prior to the onset of the experiment, the device was configured to display, on its screen, next to the detected object, the parameters of its position that had been determined by the primary binary radar - oblique distance and azimuth angle (see Fig. 2). The image displayed by the TU-20L airfield terminal is recorded in case it is necessary to determine the course of an abnormal situation that may occur in the area of Dęblin airfield. The video recording is done continuously using AVI format video files that are created in 30-minute intervals. After the experiment had been completed, the video files were used to transcribe the on-screen position

33 A. Goś, *Charakterystyka porównawcza radarów*…, op. cit., p. 161–174.

parameters of the aircraft used in the experiment during the flight. When analysing the image frame by frame, the recorded parameters were assigned a local time, which was displayed on the device screen each time new radar information appeared. The oblique distance and azimuth angle values were recorded by the device every 6 seconds on average. The experiment resulted in 477 measurement points. Fig. 2 shows the measurement of one of the points.

Figure 2. Example of TU-20L device screen

Source: own study.

Since the TU-20L airfield terminal displays radiolocation information within the boundaries of a circuit whose centre is the radar antenna and whose radius depends on the selected operation mode, at the initial stage of the experiment the device was set in such a way that the reading of position parameters of the aircraft could be made within the full range of object detection capabilities of the AVIA-W radar in Dęblin – up to the distance of 100 km away from the antenna. Due to increased air traffic in the area of Dęblin airfield, in the final stage of the experiment this range was reduced to 50 km in order to visualize the air situation in a more accurate manner, taking into account the need to ensure safe traffic flow through the Approach Control Surveillance rating.

On board the Diamond DA40 NG aircraft, a Nautiz X8 GPS receiver[34] was fixed in a pocket located by the right seat in the pilot cockpit. The instrument measurement began prior to takeoff and was completed soon after landing. During the experiment, the receiver recorded its exact route, determining its points at each second. Each point has got a specific geodetic latitude, geodetic longitude, altitude above sea level and GPS date and time of measurement. The route and its points are stored in the device memory as a GPX file. Files in this format are used to exchange GPS data between receivers and desktop computers. Using the device's USB port, the file was

[34] https://www.handheldgroup.com/globalassets/downloads/product-information/data-sheets/low-res-website/en/nautiz-x8-data-sheet-en.pdf [access: 17.05.2023].

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copied onto a portable memory disc and then onto a desktop computer memory disc. Using a GPX file, the QGIS program[35] converted the geodetic coordinates of the route points into plane rectangular coordinates, taking into account the curvature of the Earth. This was done by defining its own coordinate system in the QGIS programme settings. Defining a own coordinate system in QGIS requires the user to have adequate knowledge of the PROJ4 mapping library in the C++ programming language. The origin of the new plane rectangular coordinate system was determined by entering the exact geographical coordinates of the position of the AVIA-W radar antenna in Dęblin, into the program, read out from MIL AIP Poland[36]. The rectangular plane coordinates of the points defined by the GPS receiver, transformed in QGIS, were exported to a Microsoft Excel file[37]. Using Microsoft Excel functions, the graphs were created to simultaneously depict two routes of the aircraft flights, used in the experiment (one based on the points determined by the radar and the other in accordance with the points determined by the GPS receiver) in the Cartesian coordinate system. Additionally, the origin of the coordinate system (position of the radar antenna) was marked on the diagrams and the position of the runway at Dęblin airfield was marked by reading out the coordinates of its origin and ending in the QGIS programme. The runway width on the charts is not shown in scale due to insufficient clarity. In addition, the points determined by the radar were imported into QGIS in order to graphically illustrate the measurement results in the flat polar coordinate system and as maps. A precision analysis was also performed in Microsoft Excel for the test results obtained.

It should be mentioned that the time synchronization of the measurements was done after the experiment in post-processing mode. In order to determine the exact difference between the GPS tGPS time and the local time displayed on the screen of the TU-20L tAVIA airport terminal, the Nautiz X8 GPS receiver was mounted in an open area and started in the GPST (GPS Time) display mode. As the TU-20L's control panel is located in an enclosed room that prevents the reception of GPS signals, the current time indicated by the GPS receiver was set on a Timex Expedition T49852 digital watch. This was followed by a comparison between the GPS time set on the digital watch and the time displayed on the screen of the TU-20L. The time shown on the screen was found to be 1 hour 0 minutes and 0 seconds behind the time set on the digital watch. The synchronized time of all measurements is denoted by t and calculated for each point according to the following formula. The time determined by the Nautiz X8 tGPS receiver is equal to the synchronized measurement time t, as shown below:

$$t = t_{GPS} = t_{AVIA} - 1\ hour\ 0\ min.\ 0\ sec \tag{10}$$

[35] https://gis-support.pl/co-to-jest-qgis/ [access: 17.05.2023].
[36] https://www.ais.pansa.pl/publikacje/aip-mil/ [access: 17.05.2023].
[37] https://www.microsoft.com/pl-pl/microsoft-365/excel [access: 17.05.2023].

where:
t_{GPS} – time indicated by the GPS system;
t_{AVIA} – time indicated by AVIA-W radar.

5. RESULTS AND DISCUSSION

Chapter Five shows the findings of the calculations along with the presented research methodology. Fig. 3 shows two flight paths of the aircraft used in the experiment in the planar polar coordinate system. The origin of this system is the antenna of the AVIA-W radar in Dęblin, marked by the point in red. The diagram shows points corresponding to the location of larger towns in the area and an arrow indicating the North direction, labelled as N. The circles with the centre at the origin of the coordinate system and radii increasing every 5 km make it possible to read out the distance from the point to the antenna. Fig. 3 is visually similar to the scheme in which the air situation is depicted on the screen of the TU-20L airfield terminal. However, the graph does not show the successively detected points, and the route was created by connecting them.

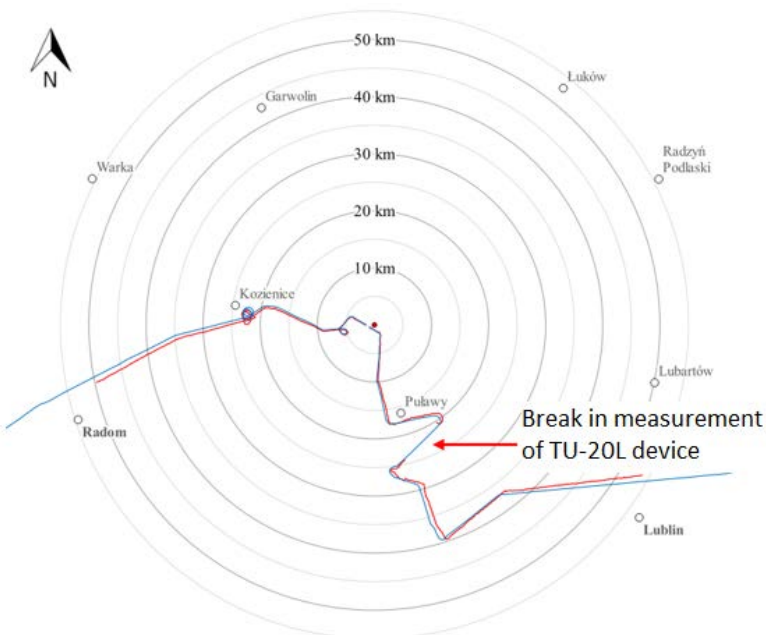

Figure 3. The flight route according to the GPS receiver and AVIA-W radar
Source: own study.

The two flight paths of the aircraft used in the experiment (based on the points determined by the AVIA-W radar in Dęblin and based on the points determined by the Nautiz X8 GPS receiver) presented in Fig. 3 do not coincide. It can be noted that the

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greater the distance of the object from the radar antenna, the more the route specified by the points which had been determined by the radar deviates from the route specified by the points given by the GPS receiver. During the departure at a distance of approximately 20–24 km from the antenna, the radar did not determine the parameters of the object's position – the measurement was interrupted. The start of the measurement interval is 9:23:13. The object was invisible on the screen of the TU-20L for 2 minutes and 39 seconds. The radar determined the position parameters of the aircraft used in the experiment again at 9:25:52. During the measurement interval made by the TU-20L, the GPS receiver was continuously recording its positions. During the departure phase, the measurement of the position parameters of the aircraft was taken within the full range of radar object detection capabilities – up to a distance of 100 km away from the antenna. The last point in this phase was determined by the radar at 9:42:03. It lies at a distance of approximately 54 km from the antenna. The distance of the designated point from the antenna is the limit of the actual radar range at the corresponding azimuth for the Diamond DA40 NG aircraft, which is at an absolute altitude of approximately 1,500 feet (457.2 m).

During the arrival phase, the attitude parameters of the aircraft were measured up to a distance of 50 km away from the radar antenna. It is, therefore, impossible to determine the actual range of the radar on arrival, as the first point measured with the TU-20L lies approximately 50 km away from the antenna. In fact, the radar could determine the position parameters of an object at a distance of more than 50 km from the antenna. Since the maximum actual radar range does not significantly depend on the direction of the emitted pulses, it can be expected that on arrival the distance of the aircraft from the antenna at which it was detected by the radar was similar – approximately 54 km.

During the experiment, the aircraft performed a flight with turns. Making turns by the object results in a change in the azimuth angle at which it is located. On arrival, at a distance of approximately 22 km from the aerial, the aircraft made two sharp left turns of approximately 360°. Again the aircraft made one sharp right turn of approximately 230° at a distance of approximately 6 km from the antenna. During the course of the above-mentioned turns and the remaining turns, the radar determined the parameters of the object's position in a way that slightly deviated from the rest of the route. This means that rapid changes in an object's azimuth angle can affect the accuracy of the radar's position determination.

Fig. 4 shows an absolute error of position determination by radar $\Delta(X, Y)$ as a function of the distance from the radar antenna to the point determined by the GPS receiver (R_{GPS} coordinate) The points corresponding to the calculated error values at a given distance are marked blue for the departure phase and yellow for the arrival phase. The graph shows the trend line determined by the least squares method from 472 observations at departure and arrival. The standard deviation of all observations from the trend line and its formula can be found in Table 1. The trend line formula can be written as: $y = 0.0235\mathrm{x} + 0.0332$. The standard deviation of the absolute position error is 0.117 km.

Table 1. Trend line pattern and standard deviation of absolute position error *Δ*(*X, Y*)

Parameter	Value
Function of trend line $y = bx + a$	y = 0.0235x + 0.0332
Standard deviation	0.117 km

Source: own study.

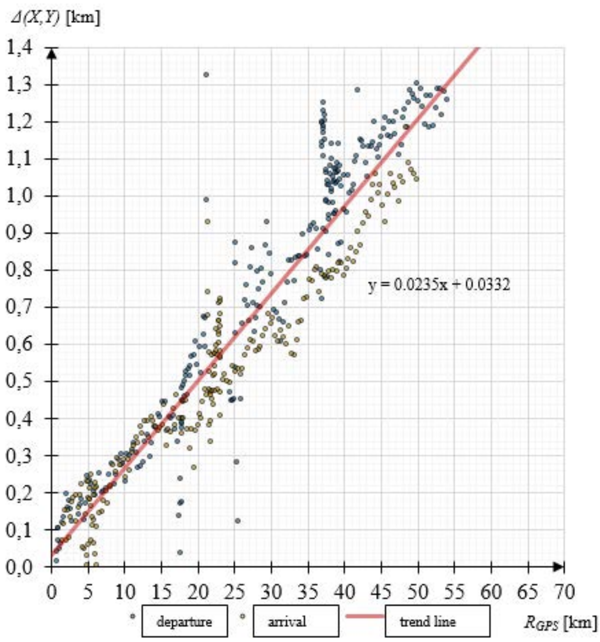

Figure 4. The values of absolute position error as function of distance from radar
Source: own study.

Fig. 5 shows the absolute error of position determination by radar $\Delta(X, Y)$ as a function of the azimuth angle at which the point determined by the GPS receiver is located (B_{GPS} coordinate). The points corresponding to the calculated error values, at a given azimuth have been marked blue on the chart for the departure phase and yellow for the arrival phase. The absolute error of position determination by the radar increases as the distance of the aircraft from the radar antenna increases in a linear manner. This means that the further away the object is from the radar, the greater is the difference in distance between the position determined by the radar and its actual position.

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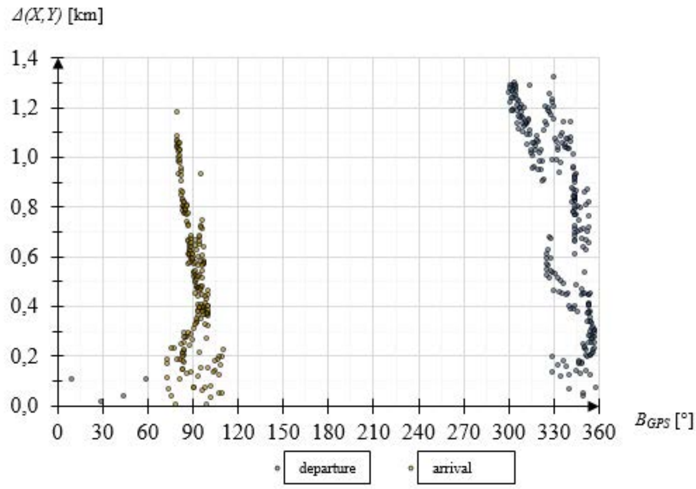

Figure 5. Values of absolute position error as a function of azimuth from the radar
Source: own study.

The four extremes of error deviating from the trend line are due to the turns and local conditions present at a given measurement site. The extremely low error values, which deviate significantly from the trend line, are consequently a result of the intersection of two routes created by combining points determined by the radar and the GPS receiver during a turn. The magnitude of the absolute error in the determination of the radar position is not constant for a given value of the azimuth angle at which the object is located. The error takes on different values for the same azimuth angle. This is due to the nature of the flight path of the aircraft used in the experiment - the aircraft was forced to perform a flight with a small range of changes in the azimuth angle at which it was located. The absolute error of the radar position determination reached its maximum value just before the interruption of the measurement with the TU-20L device at 9:23:13. The minimum difference in distance between the point determined by the radar and the approximate actual position of the aircraft is at 9:34:56. The minimum and maximum values of the absolute error in the determination of position by the radar are shown in Table 2.

Table 2. Minimum and maximum value of absolute position error *Δ*(*X*, *Y*)

Type of value	Value $\Delta(X, Y)$	Time	Point coordinates determined by AVIA-W radar in Dęblin		Point coordinates determined by Nautiz X8 GPS receiver	
$\Delta(X, Y)$	[km]	t	*R* [km]	*B* [°]	*R* [km]	*B* [°]
Maximum	1.3250	9:23:13	20.3	327.5	21.2	330.3
Minimum	0.0042	9:34:56	37.0	323.5	37.0	323.3

Source: own study.

Fig. 6 shows the absolute error of the position determination by radar $\Delta(X, Y)$ as a function of the distance from the object calculated along the route based on the points determined by the GPS receiver during the departure phase of $S_{DEPARTURE}$. The dashed lines visible on the graph mark the moment when the interruption in the measurement of the object's position parameters by the radar occurred. Fig. 7 shows the absolute error of position determination by radar $\Delta(X, Y)$ as a function of the distance from the object calculated along the route based on the points determined by the GPS receiver during the $S_{ARRIVAL}$ arrival phase. The values of absolute errors of position determination by the radar on both diagrams are connected by a continuous line. In both diagrams there is also a continuous green line, which corresponds to the absolute altitude of the terrain along the route, based on the points determined by the GPS receiver. It is expressed in metres and referred to the right vertical axis. The absolute error in determining the position by the radar increases with a growing distance from the object calculated along the route based on the points determined by the GPS receiver. This is due to the fact that the conducted experiment an increase in the distance from the object along the route, in the vast majority of cases, also results in an increase in the object's distance from the radar antenna. This rule does not apply to certain turns. In Fig. 6, the distance ranges of approximately 17–21 km, 27–30 km and 39–43 km show rapid fluctuations in the absolute error of the radar determination of position. Similar fluctuations in error values can be seen in Fig. 7 for distances of approximately 6–9 km and 26–39 km. These are ranges of distances along the route in which the aircraft used in the experiment made turns.

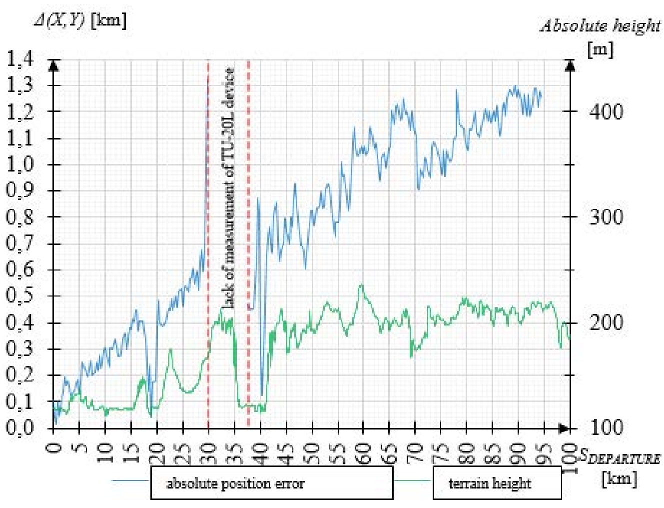

Figure 6. Values of absolute position error during the departure phase
Source: own study.

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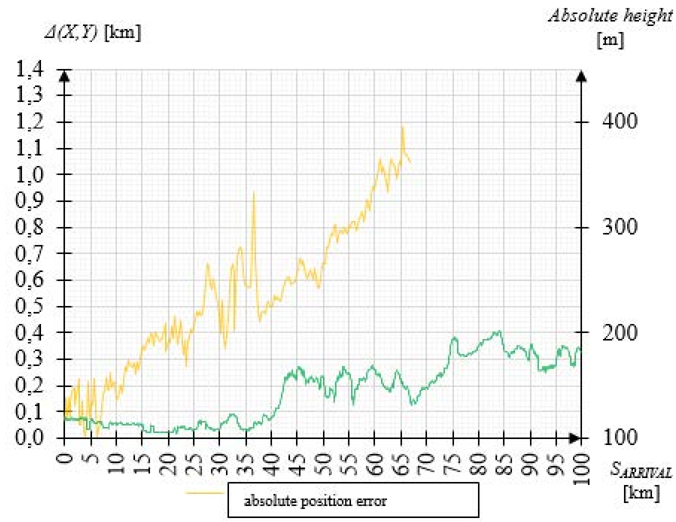

Figure 7. Values of absolute position error during the arrival phase
Source: own study.

In Fig. 6 and 7, a relationship is observed between the shape of the line that connects the absolute error values of the position determination by the radar and the terrain along a given route section. The shape of the line connecting the values of the absolute errors of the position determination by the radar in places nears the shape of the line corresponding to the absolute height of the terrain. In Fig. 6, the terrain is highly varied and it coincides with the interruption in the measurement of the object's position parameters by the radar. Just before the measurement interruption occurred, the absolute error of the radar position determination reached its maximum.

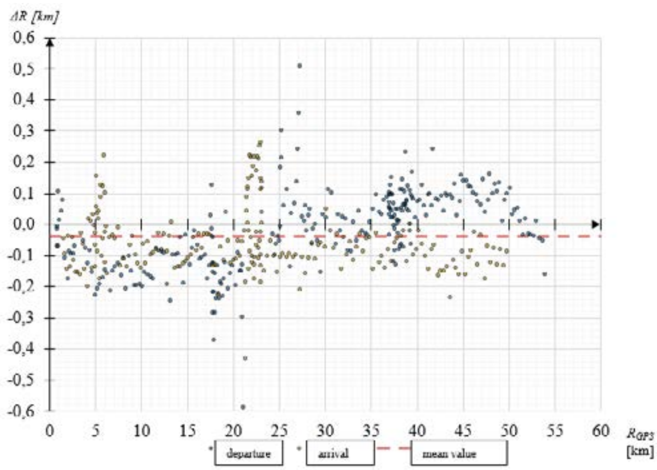

Figure 8. Values of the range error as a function of distance from the radar
Source: own study.

The absolute position error is caused by the radar incorrectly determining the distance of the object from the antenna and the azimuth angle at which it is located. Fig. 8 shows the absolute error in the measurement of the distance of the object from the antenna ΔR as a function of the distance from the antenna of the point defined by the GPS receiver (R_{GPS} coordinate). The points corresponding to the calculated error values, at a given azimuth, the authors marked blue on the chart for the departure phase and yellow for the arrival phase. The red dashed line marks the arithmetic mean value of 472 observations at departure and arrival. The value of the standard deviation of all observations from their arithmetic mean value can be found in Table 3.

Table 3. Statistical parameters of range error

Parameter	Value
Mean value	–0.0373 km
Standard deviation	0.0153 km

Source: own study.

Fig. 9 shows the absolute error of distance determination from $\Delta(X, Y)$ antenna as a function of the azimuth angle, at which the point determined by the GPS receiver is located (B_{GPS} coordinate). The points corresponding to the calculated error values, at a given azimuth, have been marked blue on the chart for the departure phase and yellow for the arrival phase, by the authors.

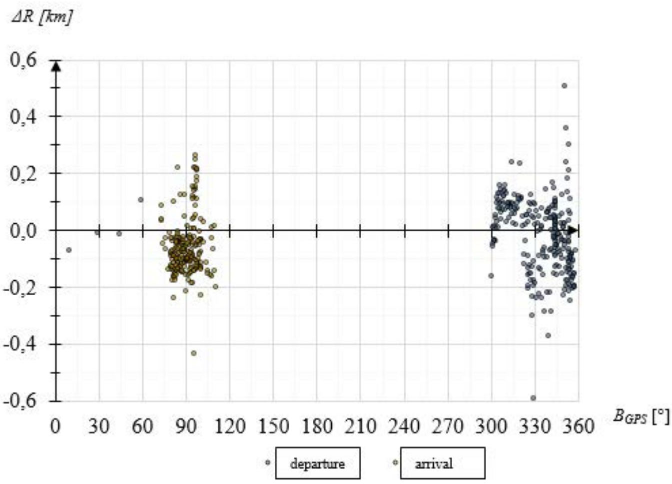

Figure 9. Values of range error as function of azimuth from the radar

Source: own study.

 DOI: 10.55676/asi.v3i1.35

The absolute measurement error of the object's distance from the antenna over the measured distance range takes on different values. The values of individual errors over the entire distance range deviate significantly from the line determining the arithmetic mean value of all errors. This means that the size of the absolute error of distance measurement in the examined distance range results mainly from the local conditions occurring at a given measurement location, such as state of the medium of propagation of an electromagnetic wave and terrain. The influence of local conditions in this case makes it impossible to make a clear statement how moving the object away from the antenna affects the distance value determined by the radar, since the scatter of points on the graph is too large. The absolute error in measuring the distance of an object from an antenna by a radar takes on different values for the same azimuth angle. The apparent accumulation of points with similar values at the same place on the graph is due to the nature of the flight path of the aircraft used in the experiment. The absolute error of the radar position determination reached its highest deviation from zero just before the interruption of the measurement made by the TU-20L device at 9:23:13. This is the point at which the difference in distance between the point determined by the radar and the approximate actual position of the aircraft, i.e. the point determined by the GPS receiver, was the largest. The value of the absolute error of the distance measurement of the object from the antenna was closest to zero. It approximately equalled zero at 9:34:56. However, the difference in distance between the point determined by the radar and the point determined by the GPS receiver is not the smallest at this time because the radar incorrectly determined the azimuth angle at which the object was located. The error in measuring the azimuth angle at which the object is located causes the radar position determination error to increase as the object's distance from the antenna increases. The values of the smallest and the largest deviation of the absolute error of the measurement of the object's distance from the antenna can be found in Table 4. The point corresponding to the largest deviation of the absolute error of the measurement of the object's distance from the antenna, from zero, in Fig. 8 and 9 is outside the range of the vertical axis, since its value significantly deviates from the values of the other points.

Table 4. Minimum and maximum value of range error

Deviation ΔR from value zero	Value ΔR [km]	Time t	Point coordinates determined by AVIA-W radar in Dęblin		Point coordinates determined by Nautiz X8 GPS receiver	
			R [km]	B [°]	R [km]	B [°]
Maximum	–0.8715	9:23:13	20.3	327.5	21.2	330.3
Minimum	0.0003	9:33:35	37.8	332.4	37.8	333.8

Source: own study.

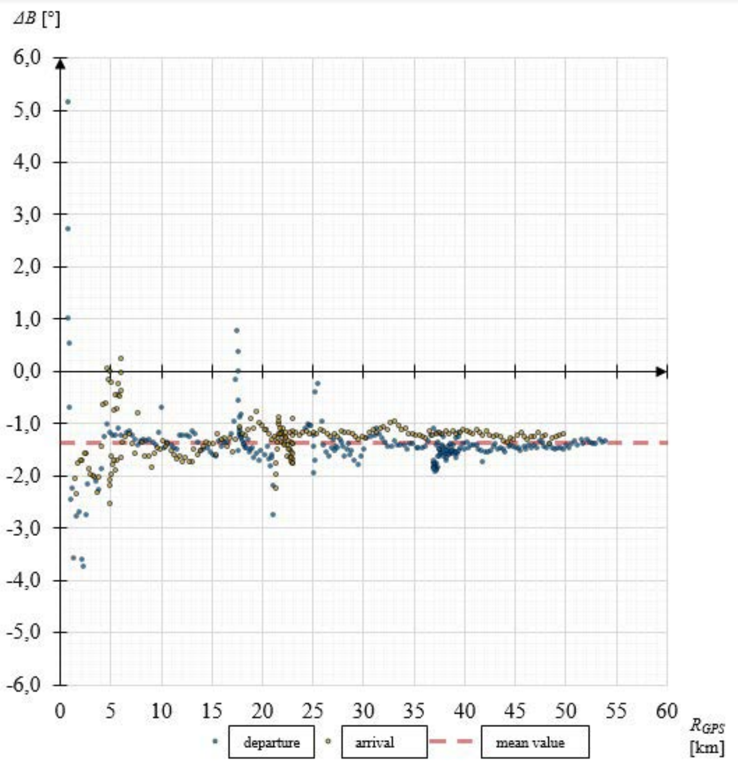

Figure 10. The values of azimuth error as a function of distance from the radar
Source: own study.

Fig. 10 shows the absolute error in the measurement of the azimuth angle at which the object is located ΔB as a function of the distance from the antenna of the point defined by the GPS receiver (R_{GPS} coordinate). The points corresponding to the calculated error values, at a given azimuth, have been marked blue on the chart for the departure phase and yellow for the arrival phase, by the authors. The red dashed line marks the arithmetic mean value of 472 observations at departure and arrival. The value of the standard deviation of all observations from their arithmetic mean value can be found in Table 5.

Table 5. Statistical parameters of azimuth error

Parameter	Value
Mean value	–1.3549°
Standard deviation	0.3291°

Source: own study.

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Figure 11 shows the absolute error of the measurement of the azimuth angle at which the object is located ΔB as a function of the azimuth angle at which the point determined by the GPS receiver (B_{GPS} coordinate) is located. The points correspon-ding to the calculated error values, at a given azimuth, have been marked blue on the chart for the departure phase and yellow for the arrival phase by the authors.

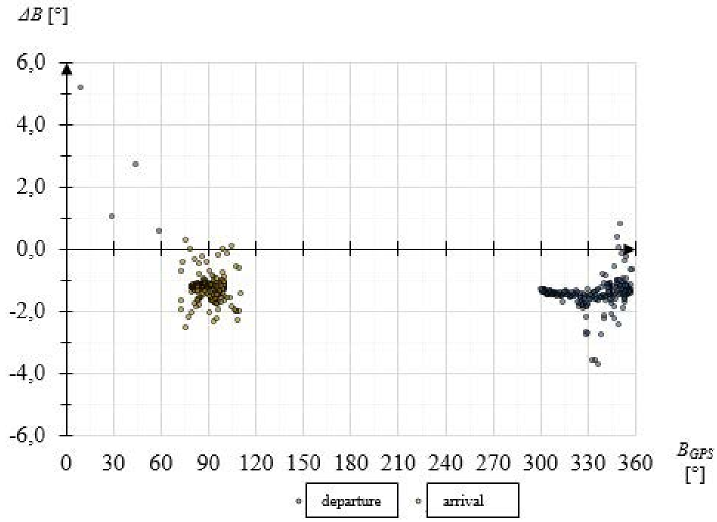

Figure 11. Values of azimuth error as a function of azimuth from the radar
Source: own study.

In Fig. 11, at close proximity of the object to the radar antenna during departure, significant deviations of the absolute error value of the azimuth angle measurement from the arithmetic mean value of all observations are visible. These are due to the high angular velocity relative to the radar antenna at which the aircraft used in the experiment was moving when the takeoff operation was performed. The bigger is the change in the azimuth angle of an object in the same unit of time, the higher is the value of the object's angular velocity in relation to the radar antenna. The angu-lar velocity of an aircraft that maintains a constant course and speed relative to the ground will be greater, the closer it is to the radar, provided it is not flying exactly from or towards the antenna. This means that during one antenna rotation, which took an average of 6 seconds in the experiment, the actual change in the azimuth angle at which the aircraft is located is greater, the closer the aircraft is to the radar, assuming it maintains a constant course and speed relative to the ground and does not fly exactly from or towards the antenna. Large changes in the azimuth angle at which an object is located over a short period of time are subject to an increased absolute error in its measurement. For this reason, deviations of the absolute error value of the azimuth angle measurement from the arithmetic mean value of all ob-servations at a further distance from the antenna are also visible. These are due to the rapid change in the azimuth angle at which the object is located during one antenna rotation, owing to the turns made by the aircraft in the experiment. The most likely cause of the ambiguous azimuth angle readings determined by the radar in the cases described is too many data changing in quick succession.

Apart from the cases described above, the absolute error in measuring the azimuth angle at which an object is located takes on similar values over the measured distance range. The points representing the value of the majority of errors over the entire distance range are in close proximity to the line representing the arithmetic mean value of all errors. At a distance of approximately 26 km from the antenna and beyond, it can be seen that the azimuth angle measurement error takes on values below the average during departure and above the average during arrival. The small scatter of points around the line marking the arithmetic mean value of all errors suggests that most of the azimuth angles determined by the radar, at which the object was located, are subject to an error whose value is approximately constant at approximately –1.4°. The constant error value is probably due to an incorrect orientation of the radar with respect to the geographical direction of the south, which is the reference axis for the measured azimuth angles. The reason for this may be an incorrect (outdated) magnetic declination value that is entered into the radar system.

Due to the large difference between the arithmetic mean value of the absolute error in the measurement of the azimuth angle at which the object is located and the zero value, the largest and smallest deviation of the individual error values were related to the arithmetic mean value. The absolute error of the measurement of the azimuth angle at which the object is located reached the largest deviation from the arithmetic mean value of all observations at 9:13:46. This is the moment when the aircraft used in the experiment was in close proximity to the radar and performed the take-off operation. The value of the absolute error of the measurement of the azimuth angle at which the object is located was closest to the average at 9:19:28. The difference in distance between a point determined by the radar and a point determined by the GPS receiver is small at this time, but it is not the smallest. The values of the smallest and the largest deviation of the absolute error of the measurement of the object's distance from the antenna can be found in Table 6.

Table 6. Minimum and maximum value of azimuth error

Deviation ΔB from value zero	Value ΔB [°]	Time t	Point coordinates determined by AVIA-W radar in Dęblin		Point coordinates determined by Nautiz X8 GPS receiver	
			R [km]	B [°]	R [km]	B [°]
Maximum	6.5138	9:13:46	0.8	14.7	0.9	9.5
Minimum	0.0001	9:19:28	16.2	351.8	16.3	353.2

Source: own study.

DOI: 10.55676/asi.v3i1.35

6. CONCLUSIONS

The conducted experiment makes it impossible to clearly state how moving the object away from the radar affects the accuracy of determining the distance of the object from the antenna. The value of the absolute error in measuring the distance of an object from an antenna by the radar in the examined range is variable and results from local conditions occurring in a given place of measurement such as, among others, the state of the propagation medium of electromagnetic waves and terrain. The arithmetic mean and the standard deviation of the absolute error of measurement of the distance of an object from an antenna, rounded to the nearest tenth of a kilometre, are equal to zero.

Large changes in the azimuth angle at which an object is located over a short period of time (at short distances from the antenna and when making turns) are loaded with reduced accuracy. Most of the azimuth angles determined by the radar at which the object was located are subject to an error whose value is approximately constant and corresponds to the arithmetic mean value of all the errors. The arithmetic mean of the absolute error of measurement of the azimuth at which the object is located, rounded to the nearest tenth, equals –1.4°. The standard deviation of the absolute error of measurement of the azimuth angle at which an object is located, rounded to the nearest tenth, is equal to 0.3°. The constant error value of measuring the azimuth angle is likely to derive from an incorrect orientation of the radar with respect to the geographical direction of the south, which is the reference axis for the measured angles. This results in an increase in the absolute error of the radar determination of position as the distance of the object from the radar antenna increases in a linear manner.

During the experiment there was an interruption in the measurement of the object's position parameters by the radar. At the site of the interruption, the terrain is largely varied, also with a river meander. The interruption in the measurement presumably derives from a small effective reflecting surface of the Diamond DA40 aircraft and the interference phenomenon, which causes the signal reflected from the object to overlap with the signals reflected from the hills in the area of the flight path.

The research methods in this work can be used to validate the performance of other radars. The study of accuracy of determination of parameters of the position of airborne objects by the AVIA-W radar may be repeated in the future and additionally extended by the GCA-2000 radar, which is also mounted at Dęblin military airfield. Extending the scope of the research by an additional radar will enable a direct comparison of two radars mounted at Dęblin airfield as well as deciding which of them has greater accuracy in determining parameters of object positioning. Future research could use an aircraft that is equipped with an on-board GPS receiver which has a centrally located external satellite antenna.

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