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RESEARCH AND COMPARATIVE ANALYSIS OF THE ACCURACY IN DETERMINING THE PARAMETERS OF THE POSITION OF AIRCRAFT BY AIR TRAFFIC CONTROL RADARS AVIA-W AND GCA-2000

Badanie i analiza porównawcza dokładności określania parametrów położenia statku powietrznego przez radary kontroli ruchu lotniczego Avia-W oraz GCA-2000

Abstract: *The aim of the article "Research and comparative analysis of the accuracy in determining the parameters of the position of aircraft by air traffic control radars Avia-W and GCA-2000" is to test the difference in determining the parameters of the position of aircraft objects by radars used at Dęblin airfield. In particular, the paper presents the results of positioning accuracy, azimuth and distance accuracy for two radars: GCA-2000 and Avia-W.*
Keywords: *radars, GCA-2000, Avia-W, position determination, azimuth accuracy, range accuracy*

Streszczenie *Celem pracy „Badanie i analiza porównawcza dokładności określania parametrów położenia statku powietrznego przez radary kontroli ruchu lotniczego Avia-W oraz GCA-2000" jest zbadanie różnicy określania parametrów położenia obiektów powietrznych przez radary używane na lotnisku w Dęblinie. W szczególności w pracy pokazano wyniki dokładności wyznaczenia pozycji, dokładności pomiaru azymutu i odległości dla dwóch radarów GCA-2000 i Avia-W.*
Słowa kluczowe: radary, GCA-2000, Avia-W, wyznaczenie pozycji, dokładność azymutu, dokładność odległości

1. Introduction

The functioning of radars is part of a radio engineering, referred to as radiolocation. Air traffic control radars use active radiolocation with a passive response as well as active radiolocation with an active response in order to determine aircraft position and flight characteristics [4].

A radar using active radar with an active response is called a Primary Surveillance Radar (PSR). It is made up of a transmitter and a receiver. In its operation, it uses a transmitting and receiving antenna to radiate pulse energy in the form of a focused beam of electromagnetic waves. The radiated pulse energy encounters an object capable of reflecting electromagnetic waves and then bounces it off. Part of the reflected energy returns to the radar receiver in the form of a radar echo and part of the energy is scattered in all directions.

Radar that uses active response radar is called secondary SSR (*Secondary Surveillance Radar)* surveillance radar. During the SSR radar operation, the detected object exerts a significant role as it takes an active part in the process of data generation. A secondary radar uses the aircraft transponder to gather radiolocation data. A transponder is an on-board device which consists of a receiver, an encoder for the transmitted information and a transmitter. Owing to this device, the pilot is capable of assigning an individual aircraft code (squawk) that enables identification and allows radar air traffic control. In order to acquire radar information from the transponder, the radar uses a ground-based device called an interrogator. The interrogator consists of a transmitter, a receiver, a transmit-receive antenna switch and an antenna. The transponder receives interrogation signals sent by the ground device at a frequency of 1030 MHz and then transmits the response signals at a frequency of 1090 MHz. The received response signal is decoded and the information contained appears on the radar display [5, 6, 9].

2. Scientific knowledge analysis

Determining the position of an aircraft is one of the most important tasks of a radar device. The radar's knowledge of an aircraft's position can be expressed in both polar and Cartesian coordinates. It can therefore be concluded that when positioning an aircraft using radar data, the aircraft coordinates may refer to a 2D plane or a 3D space. In the case of a 2D plane, the radar allows the distance and azimuth to the aircraft to be determined. In turn, in 3D space, the radar additionally determines the height of the aircraft [7].

So far, research experiments with the use of radar data in aircraft positioning have been carried out in Poland. In the work [8], the accuracy of the radar station was tested during the "BRDA" aviation experiment. In the research, the horizontal and vertical position of the aircraft was determined, and the accuracy of the aircraft position was determined using the distance error, azimuth error and altitude error. The article [1] presents the basic properties of the RST-12M long-range radar and the results of research on the accuracy of estimating the coordinates of detected airborne objects using aircraft flights with a GPS receiver and position recorder installed on board. The article [2] presents the assumptions of the method of testing the discrimination of air objects by radar devices with the use of aircraft flights, the three-dimensional position of which is determined with an accuracy of about 1 m with a time interval of 1 s using differential GPS positioning techniques. The second part of the article presents the results of the tests carried out according to the proposed method, performed as part of the NUR-22N-(3D) radar type tests. The publication [3] presents selected issues in the field of research on modern radar devices manufactured by Polish industrial plants with the use of military flights of various types of aircraft. In particular, the positioning accuracy of the PZL-130 Orlik aircraft during a test flight around the airport in Radom was determined. In the research, the aircraft coordinate readings in the horizontal and vertical planes were compared between the radar data and the data from the on-board GPS receiver.

The main goal of the article is to perform experimental research aimed at determining the position of an aircraft with the use of radar data. According to the analysis of the state of knowledge [1, 2, 3, 7, 8], so far, during test flights, one radar was used to determine the position of the aircraft. However, in the presented work, the position of the aircraft was determined with the use of two independently operating radars, i.e. Avia-W and GCA-2000, located at the EPDE military airport in Dęblin. The article proposes a research methodology for the analysis of the accuracy of determining the distance and azimuth to the aircraft. The study relies on the findings obtained in a research experiment, which consisted in determining the position parameters recorded during a flight of an M-346 Master aircraft. The GCA-2000 and Avia-W radars simultaneously recorded the aircraft attitude parameters. Next the parameters were compared.

The presented research method is universal and can be used in other aviation tests. The developed research methodology can be adapted to various types of navigation radars used in aviation. Such an approach is extremely interesting because different types of radars can be used in aviation experiments, which translates into different accuracy in measuring the distance and azimuth to the aircraft. The control of aircraft coordinate results obtained with the use of radar data can improve the precise positioning of the aircraft and improve flight safety.

3. Methodology for the measurement of position parameters

The measurement of aircraft position parameters by the Avia-W radar was taken by means of the TU-20L airfield terminal. For the sake of the measurements, the terminal was switched into reading the polar coordinates - oblique distance and azimuth angle. A record of the image was downloaded as files. The aircraft position data were recorded for further analysis. The position points recorded by the Avia-W radar altered with constant frequency, exactly every 6 seconds. The Avia-W radar is a military version of the radar based on the Avia-C radar type. It has a primary radar and is additionally fitted with a secondary radar. The Avia is designed to control and manage air traffic in an airfield area. Primary radar imaging provides information on the oblique distance and azimuth of the detected targets. It was developed in the early 1980s. Initially, an aerial situation was displayed on an analogue indicator. Technological advances have resulted in the retrofitting of the radar with a TU-20L surveillance data processing device. The radar antenna is mounted on top of an approximately 20-meter high tower together with a sub-antenna cabin. The 13 x 9 m span parabolic radar reflector is powered by two tubes, which translates into a beamwidth of 1÷ 2° in azimuth. The minimum speed of the antenna is 10 rpm, thus the data are updated at a rate of every 6 s. In order to achieve the required reliability and ensure long-term operation, the radar uses two transmit/receive channels. Each of them is capable of acting as a working and standby channel. In order to optimise performance, the Avia has got fixed echo suppression systems with frequency conversion processing. The polarisation of the radiated electromagnetic wave is adjustable, which ensures the possibility of obtaining good suppression of meteorological interference. The radar transmitter is equipped with magnetron power generators that are tuned in to the frequencies of high-stability quartz heterodynes. The eight-fold conversion of the repetition period, used in the receiver, increases the station's resistance to non-synchronous pulse interference and improves the characteristics of the fixed echo suppression filter [6, 10].

The ASR operation type on the Plan Position Indicator (PPI) was used to measure the aircraft position parameters by the GCA-2000 radar. In this mode of operation, the parameters of the detected object are visualised in the polar coordinates. The ASR mode indicator designed for radar maintenance was used during the experiment. The image recording is carried out on a continuous basis. On completion of the experiment, the video file was downloaded onto a separate medium that was later used to record the flight parameters. Unlike the Avia-W radar, the GCA-2000 radar features a variable pulse period. As a result of the experiment, the GCA-2000 radar recorded more position points than the Avia-W radar. The ratio of the amount of data collected by the GCA-2000 radar to data gathered by the Avia-W airfield radar equals 1.48. The GCA-2000 (Ground Control Approach) radar is an airfield tactical control and precision approach system, fully compliant with the ICAO requirements. A radar is used to observe the airspace in the vicinity of an airfield and to bring aircraft in for landing in all meteorological conditions. A radar system consists of three main subsystems such as an antenna subsystem, a radar equipment subsystem and an operational subsystem. Using the same set of antennas, it acts as a precision approach radar (PAR) and an approach control radar (ASR). The GCA-2000 is equipped with a primary radar and a secondary radar. The information obtained from the primary radar is distance and an azimuth angle. The secondary radar additionally enables identification of the aircraft and gathering information about altitude and airspeed. Precision approach is ensured by an additional elevation antenna, which is used to measure the flight altitude of the object, and the azimuth antenna of the primary radar [11].

The synchronisation of the measurement timings was to take into account two factors affecting the time differences. The first one is a problem related to a variable pulse period of the GCA-2000 radar, and the second one is lack of synchronisation of the two radars in relation to each other.

Both radars are equipped with clocks, indicating the local time. Coordinated Universal Time (UTC) was used to synchronise their timings. The times indicated by both radars were coordinated with the UTC time which, for the Avia-W radar, showed a time difference indicating 22 seconds more than for the GCA-2000 radar. The Avia-W radar clock was ahead in relation to the time indicated by the GCA-2000 radar clock. The synchronised time was specified by t, calculated by the following formula:

$$t = t_{GCA} = t_{AVIA} - 22\,s \tag{1}$$

where:

t – reference time,

t_{GCA} – GCA-2000 radar clock,

t_{AVIA} – Avia-W radar clock.

The larger amount of positional data recorded by the GCA-2000 radar had to be reduced to the amount of data collected by the Avia-W radar in order to analyse the difference in their indications. The calculated ratio of position points showed that for some of the position points recorded with the Avia-W radar, there was more than one point recorded by means of the GCA-2000 radar. In the data analysis section, the position points were adjusted against each other so that their ratio was 1:1, which occurred after converting the polar coordinates to the Cartesian coordinate system. In the case where two position points were recorded by the GCA radar for one point, determined by the Avia-W radar, the point whose position was most similar to the one recorded by the Avia-W radar was selected, after a previous analysis of the coordinated time.

4. Methodology for the comparative analysis of the accuracy of positioning parameters

The aircraft position data recorded by both radars are expressed by two polar coordinates projected on a horizontal plane [7]. The origin of the GCA-2000 radar coordinate system is the position of its antenna. By analogy, the Avia-W radar antenna is the origin of the coordinate system for the points recorded by the Avia radar. The oblique distance, which is the first coordinate of the position, is specified in kilometres and denoted by the letter R. The second coordinate is the azimuth angle, specified in degrees and denoted by the letter B. In order to make a comparative analysis of the position parameters of objects, it is necessary to determine one common Cartesian coordinate system (rectangular) in which each position point has its own coordinates (X,Y). The polar coordinates R_{GCA}, R_{AVIA}, B_{GCA}, B_{AVIA} were first transformed into rectangular coordinates X_{GCA}, X_{AVIA}, Y_{GCA}, Y_{AVIA} using Microsoft Excel by means of formulas 2, 3, 4, 5, 6. The azimuth angle value of the detected objects, recorded by Avia-W radar, is decreased or increased by 180°. This is due to the fact that the polar axis of the Avia-W radar coordinate system is oriented to the south, thus a value of 180° had to be added to any azimuth angle value, originally recorded by the radar. The azimuth angle is a value between 0° and 360°, so the formula number 5 was extended with additional information - if the initial azimuth angle B has a value greater than 180° then 360° must be subtracted from the summed azimuth angle value. The equations (2-6) are presented as below:

$$\mathrm{B_{AVIA}} = \mathrm{B} + 180°\ ;\ \text{if B} > 180° => \ \mathrm{B_{AVIA}} = (\mathrm{B} + 180°) - 360° \quad (2)$$

$$X_{AVIA} = R_{AVIA} \cdot \ cos(B_{AVIA}) \quad (3)$$

$$Y_{AVIA} = R_{AVIA} \ \cdot \ sin(B_{AVIA}) \quad (4)$$

$$X_{GCA} \ = \ R_{GCA} \cdot \ cos(B_{GCA}) \quad (5)$$

$$Y_{GCA} \ = R_{GCA} \ \cdot \ sin(B_{GCA}) \quad (6)$$

where:

$\mathrm{B_{AVIA}}$ – azimuth from Avia-W radar,
B – initial value of azimuth,
$\mathrm{B_{GCA}}$ – azimuth from GCA-2000 radar,
(X_{AVIA}, Y_{AVIA}) – Cartesian coordinates from Avia-W radar,
(X_{GCA}, Y_{GCA}) – Cartesian coordinates from GCA-2000 radar,
R_{AVIA} – range from Avia-W radar,
R_{GCA} – range from GCA-2000 radar.

The above - mentioned comparative analysis of the position parameters of the detected objects denotes that two separate Cartesian coordinate systems must be defined as one, common to both radars. For this purpose, the QGIS program [12] was used, defining all position points (X,Y), as recorded by the Avia-W radar in the GCA-2000 radar rectangular coordinate system (see fig. 1). The origin of the new common coordinate system is the GCA-2000 radar antenna.

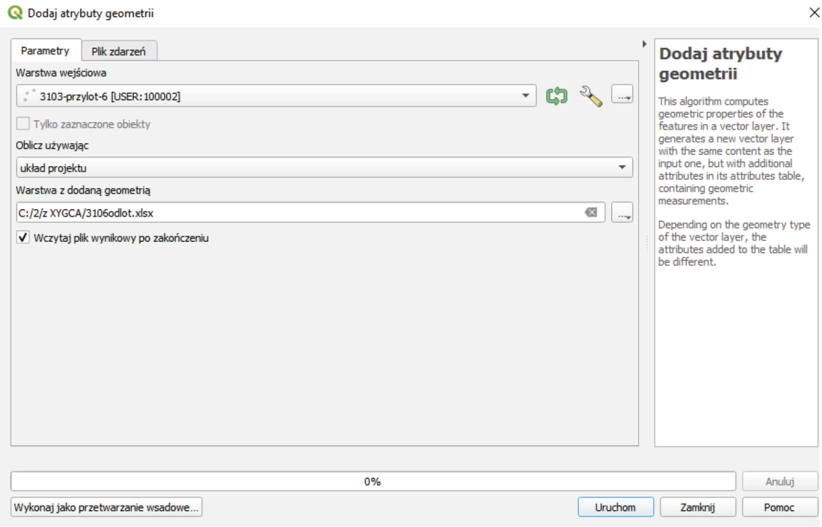

Fig. 1. A screen shot of GQIS is used to determine the common coordinate system

Next, formulas 7, 8, 9 were used to determine the difference in position of aircraft $\Delta(X,Y)$, the difference in measuring the azimuth angle ΔB and the difference in determining the range ΔR for each pair of measurement points, as below:

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

$$\Delta B = B_{GCA} - B_{AVIA} \tag{8}$$

$$\Delta R = RS_{GCA} - R_{AVIA} \tag{9}$$

where:
$\Delta(X,Y)$ - difference in position of aircraft,
ΔB- difference in measuring the azimuth angle,
ΔR- difference in determining the range.

The obtained results for presented algorithms (7-9) are showed in Chapter 6.

5. Comparative analysis of the accuracy of position parameter determination

The first position parameter subjected to a comparative analysis is the position determination difference $\Delta(X, Y)$. Figure 2 presents differences in position determination as a function of distance from the radar antenna. Pairs of points that had previously been matched and synchronised in relation to the recorded time were placed on a single graph. The points corresponding to the calculated values of the distance from the radar antenna, determined by the GCA-2000 radar, are marked red, while the points for which the distance was determined by the Avia-W radar are marked yellow. The values of the positioning difference, together with the recorded distance, determined by both radars, are presented in tab. 1.

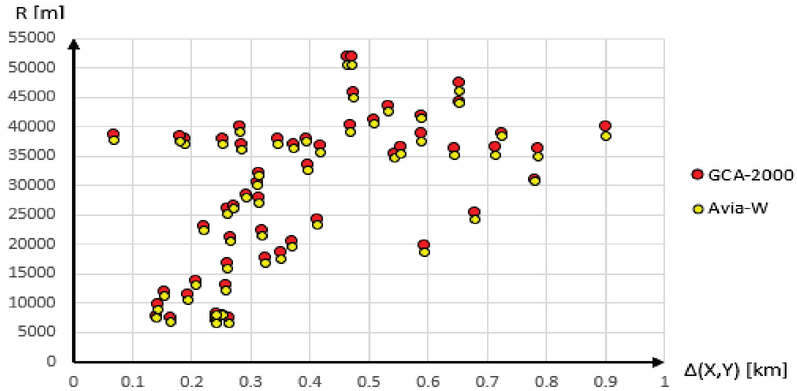

Fig. 2. Difference in position determination as a function of distance from the radar antenna.

Table 1

Difference values for the determination of position as a function of distance

Number of measurement	RGCA [m]	RAVIA [km]	Δ(X,Y) [km]	Mean value Δ(X,Y)[km]
1	6.917	7.000	0.243	0.286
2	9.795	8.900	0.142	
3	24.195	23.200	0.412	
4	38.026	36.900	0.347	

Table 1 presented the difference values for the determination of position as a function of distance. Based on the collected data, the trend of the change in the difference of the determined position cannot be clearly determined, as the values Δ(X,Y) do not change significantly depending on the indicated distance by both radars. The mean value of the position determination difference is 0.447 km. It was calculated for 73 pairs of measurement points.

The graph in fig. 3 shows the differences in the indicated position as a function of the azimuth angle value. Similarly to the case of the difference in position as a function of distance from the radar antenna, the data recorded by the GCA-2000 radar were marked red, and the data collected by the Avia-W radar were marked yellow.

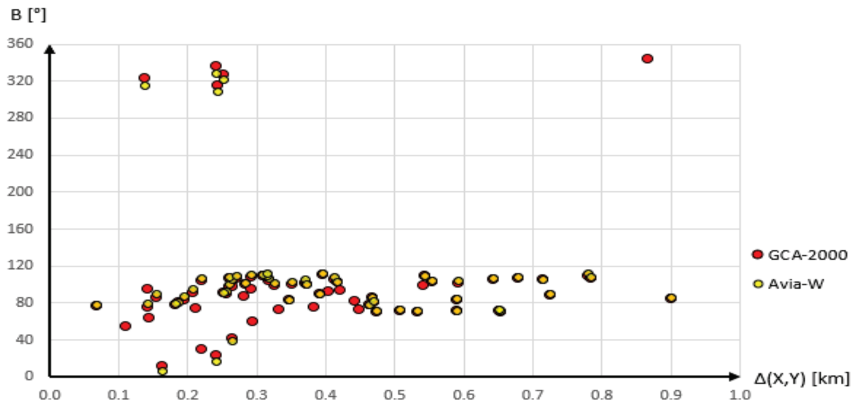

Fig. 3. Difference of position determination as a function of azimuth angle value

On the basis of the collected data shown in the graph above, it is noticeable that the azimuth angle does not affect the value of the position difference, either. This difference takes on different values for the same azimuth angle, at which the object is located. The range of values for the determined azimuth angle during aircraft departure was between 360° and 120°. In order to make a more accurate comparative analysis of the difference in position as a function of azimuth angle, it is necessary to study the flight of an aircraft that would perform operations over a full range of positions in relation to the radar antenna, from 0° to 360°.

The position parameters that are to be later investigated are the differences in azimuth angle determination and the range determination, as illustrated in the graph into fig. 4.

The presented data and the azimuth angle difference values indicate that the value of ΔB decreases with an increasing range of the aircraft from the radar antenna. The smallest difference in azimuth angle was 0.5° at a distance of 40268 m - determined by the GCA-2000 radar - and at a range of 39000 m - determined by the Avia-W radar. The biggest difference in ΔB was 7.9° at a range of 7660 m by the GCA and at a range of 7600 m by the Avia-W. Taking into account the fact that the TU-20L device of the Avia-W radar records the oblique distance with an accuracy of hundreds of meters, the computed range can be regarded as similar to the one determined by the GCA-2000 radar. This relationship is shown on the graph as a trend line, which takes the form of a logarithmic function.

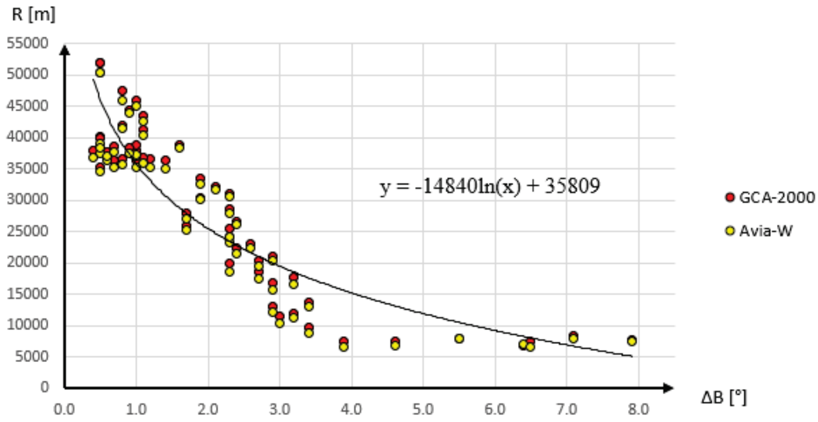

Fig. 4. Difference in distance determination as a function of distance from the radar antenna

Figure 5 presents difference in range measurement as a function of range determined by both radars. In the range measured by both radars, the difference in range measurement of the aircraft takes on different values. The range measurement difference values do not depend on the range of the detected object in relation to the radar antenna. The smallest value of the difference in the indicated range equals 78 m, whereas the highest value of the difference is 1468 m.

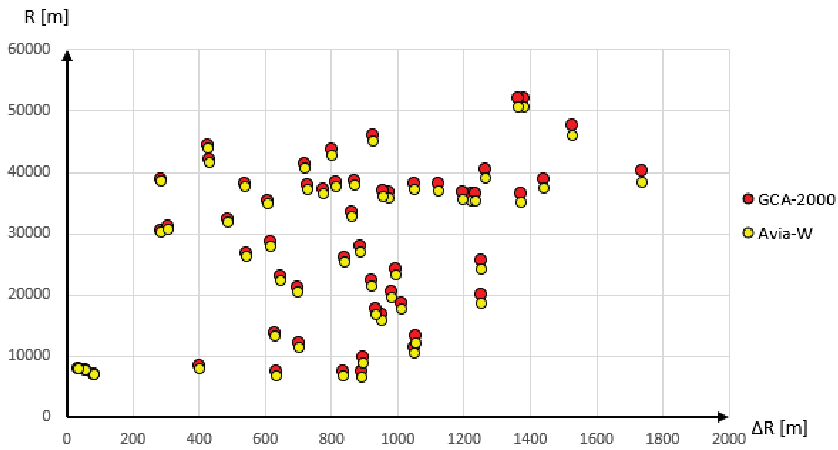

Fig. 5. Difference in range measurement as a function of range determined by both radars

6. Conclusion

The value of the position measurement difference in the investigated range of distances from the radar antenna is variable, which makes it impossible to determine the dependence on the investigated parameters - oblique range and azimuth angle. The conducted comparative analysis showed no dependence of the determined position difference in relation to the described position parameters.

However, the conducted analysis of the difference in determining the azimuth angle showed a relationship between the range of the detected object and the azimuth angle. The value of the determined difference decreased with the range from the radars. The values of the aircraft azimuth angle, recorded by both radars, were close to each other, the further was the object away from point (0.0) of the common rectangular coordinate system. The smallest recorded difference ΔB was 0.5° at a range of 40000 m. In contrast, the greatest difference in azimuth angle measurements was determined at a range of 8000 m, equalling 7.9°. The tendency of the change in the difference of the determined azimuth angle is shown as a logarithmic function.

The determined difference in range measurement is shown in the graph as a function of the range recorded by both airfield radars. The comparative analysis showed no relationship between the range of the aircraft and the difference in radar readings. The smallest value of the difference in the indicated range equals 78 m and the average value of the difference is 852 m.

The conducted comparative analysis of determining the differences in the position of airborne objects by the GCA-2000 and Avia-W radars can be repeated and additionally extended by data obtained from the GPS receiver mounted on board a detected aircraft. A GPS receiver would allow comparison of the accuracy of positioning parameters, as it would act as reference for the collected data. Therefore, it would also be possible to study the effect of flight altitude on the accuracy of the determined differences in attitude determination.

The proposed research method allows to determine the position of the aircraft for various types of navigation radars. Therefore, the applied calculation algorithm can be used to verify the position of the aircraft on the basis of various radar data.

7. References

1. Brzozowski M., Myszka M., Lewandowski Z., Modrzewski A.: Wykorzystanie metod precyzyjnego wyznaczania pozycji obiektów powietrznych za pomocą GPS do badań radaru dalekiego zasięgu RST-12M. Problemy Techniki Uzbrojenia, r. 36, z. 101, 2007.

2. Brzozowski M., Lewandowski Z., Metoda określania rozróżnialności obiektów powietrznych przez urządzenia radiolokacyjne z wykorzystaniem lotów samolotów z zamontowanymi na pokładzie odbiornikami i rejestratorami pozycji (Method of definition aircrafts distinction by radiolocation devices, using flights of aircrafts witch GPS receivers and position recorders installed on board). Problemy Techniki Uzbrojenia, r. 38, z. 112, 2009.
3. Brzozowski M., Pakowski M., Myszka M., Michalczewski M., Winiarska U.: The research of modern radar equipment conducted in the Air Force Institute of Technology by the application of military air-crafts. Aviation Advances & Maintenance, No. 1(40) 2017.
4. Czekała Z.: Parada radarów. Wydawnictwo Bellona, Warszawa 2014.
5. Doc 8071, Manual on Testing of Radio Navigation Aids - Volume III - Testing of Surveillance Radar Systems, International Civil Aviation Organization, 1998.
6. Goś A.: Charakterystyka porównawcza radarów AVIA i GCA2000, w: Współczesna Nawigacja, tom I, Redakcja naukowa: J. Ćwiklak, Dęblin 2019.
7. Goś A., Krasuski K.: Model matematyczny wyznaczenia pozycji statku powietrznego na podstawie danych radarowych. [w:] Współczesna Nawigacja, tom III, red. M. Grzegorzewski, Dęblin 2021.
8. Grzegorzewski M.: Navigating an aircraft by means of a position potential in three dimensional space. Annual of Navigation, 2005, nr 9, s. 1–111.
9. Polak Z., Rypulak A.: Awionika, przyrządy i systemy pokładowe. Wyższa Szkoła Oficerska Sił Powietrznych, Dęblin 2002.
10. http://www.radary.az.pl/arsr.php, current on 2022.
11. http://www.radary.az.pl/gca-2000.php, current on 2022.
12. https://www.qgis.org/pl/site/, current on 2022.