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Alina FEDORCHUK¹, Artur GOŚ²

COMPARATIVE ANALYSIS OF RADAR SYSTEMS IN REGIONAL AVIATION: A CASE STUDY OF DEBLIN AIRFIELD

Summary. This article presents the results of an experimental study on the registration performance of two radar-based systems - GCA-2000 and AVIA-W - using flight operations between the regional airfields of Deblin and Radom as a case study. GPS satellite navigation data were employed as a reference source to enable both quantitative and spatiotemporal comparisons of radar registration characteristics. When the comparison was restricted to the common temporal window of each radar and the 1-s GPS reference series, GCA-2000 recorded 28.1% and 30.7% of the corresponding GPS epochs for flights 3117 and 3121, respectively, whereas AVIA-W recorded 11.9% and 12.3%. These values characterize the relative temporal sampling density of the radar records and not the overall spatial coverage or target-detection efficiency. A graphical analysis of the temporal characteristics showed that the average interval between successive GCA-2000 records was 3-4 seconds. This empirical interval characterizes the recorded COMBINED-mode display output and is not directly comparable with the 5-second refresh period of the ASR component alone, because GCA-2000 operated in COMBINED mode during the experiment. For AVIA-W, the mean registration

¹ Department of Geodesy and Astronomy, Institute of Geodesy, Lviv Polytechnic National University, Bandera 12 Street, 79013 Lviv, Ukraine. Email: alina.v.fedorchuk@lpnu.ua. ORCID: <https://orcid.org/0000-0003-0183-1132>

² Department of Navigation and Air Traffic Management, Institute of Navigation, Polish Air Force University, Dywizjonu 303 35 Street, 08-521 Deblin, Poland. Email: a.gos@law.mil.pl. ORCID: <https://orcid.org/0000-0002-4268-8830>

interval was approximately 8 seconds, which is longer than the nominal 6-second refresh period and therefore corresponds to a lower update frequency than the nominal value. The study also examined the spatial relationship between radar-registration gaps, terrain changes, and forested areas. Several gaps coincided spatially with these features; however, because only two flights were analyzed and no inferential statistical test was performed, these patterns are treated as descriptive spatial associations rather than statistically confirmed causal effects. These descriptive observations can support future studies of ground-based surveillance-system placement and integrated radar-satellite airspace monitoring.

Keywords: accuracy, flight monitoring systems, flight parameters, navigation, radar

1. INTRODUCTION

Before the implementation of modern flight monitoring systems such as GPS (Global Positioning System), flight management relied primarily on ground-based navigation aids and radar systems. Ground-based radio-navigation aids such as DME (Distance Measuring Equipment), VOR (VHF Omnidirectional Range), and NDB (Non-Directional Beacon) have historically supported aircraft navigation, with DME remaining an important stand-by positioning source in civil aviation (Pleter & Constantinescu, 2024; Ostroumov et al., 2021). Although these systems provided a basic level of safety, their accuracy and coverage were limited, particularly in remote or challenging environments such as mountainous or oceanic regions. Radar surveillance systems also played a significant role in real-time air traffic monitoring (Bloisi et al., 2012; Stahl et al., 2018). Nevertheless, these methods required substantial technical infrastructure and presented coverage limitations, which posed challenges to maintaining adequate positioning accuracy in specific areas (Stahl et al., 2018).

The introduction of GNSS (Global Navigation Satellite System) technologies, such as GPS, marked a new era in flight monitoring. GNSS enables high-precision real-time aircraft positioning, significantly improving flight safety and reducing the risk of mid-air collisions (Baburov et al., 2020). At the same time, GNSS performance can be degraded by antenna obscuration, ionospheric scintillation, multipath, and radio-frequency interference, which may cause tracking degradation or loss (Sabatini et al., 2017). To enhance reliability, monitoring systems are increasingly supported by modern radar-based solutions, including ADS-B (Automatic Dependent Surveillance-Broadcast), MLAT (Multilateration), and other technologies. ADS-B is a cooperative surveillance system that obtains aircraft position from onboard navigation systems and broadcasts position and other aircraft state information to ground stations and other equipped aircraft (Ali et al., 2015). In turn, MLAT determines aircraft position using triangulation based on signals from onboard transponders, making it especially effective in areas with limited GNSS coverage (Lo & Enge, 2012; Zekavat et al., 2021). Integrating GNSS with systems like ADS-B and MLAT minimizes the impact of external disturbances, enhancing the stability and accuracy of flight tracking even in challenging environments such as mountainous terrain or near large airfields (Inoue et al., 2022).

Different airfields utilize various flight monitoring systems depending on operational needs, geographic location, and financial capacity. Airfields with high traffic volumes are typically equipped with multifunctional radar platforms such as the GCA-2000 (Ground Controlled Approach 2000). In contrast, smaller regional airfields may rely on simpler systems based primarily on GNSS technologies. This approach allows the infrastructure to be tailored to each

airfield's specific characteristics while ensuring an adequate level of flight safety and operational efficiency. At the Deblin airfield, three main systems are used for navigation and flight monitoring, providing aircraft positioning capabilities. The first uses GPS position data recorded by the onboard S2-3a flight recording system; the GPS latitude and longitude channels are stored at 1-s intervals. However, GNSS-based positioning can be affected by signal obstruction, multipath, ionospheric effects, and radio-frequency interference (Sabatini et al., 2017). The second system is the GCA-2000 multifunctional radar platform, which operates in three modes: PAR (Precision Approach Radar), ASR (Airport Surveillance Radar), and COM (Communication). The PAR mode ensures accurate guidance during final approach, ASR monitors air traffic within the airfield zone, and COM integrates with air traffic management systems. Due to its multifunctional nature, GCA-2000 plays a critical role in ensuring flight safety (Farhadmanesh et al., 2024). The third system is the AVIA-W radar, which incorporates advanced technologies for monitoring flights under complex operational conditions. Its innovative features support comprehensive air traffic control with high accuracy and reliability.

Studies confirm that the GCA-2000 system complies with international accuracy standards established by the ICAO (International Civil Aviation Organization) for determining coordinates and azimuth angles (Ciećko et al., 2023). Additionally, analysis shows that the GCA-2000 radar performs its functions effectively even under conditions that may cause short-term target detection interruptions. The combined use of GPS, GCA-2000, and AVIA-W systems at the Deblin airfield ensures a high level of flight accuracy and safety, adapting each system to specific tasks and operational conditions. Nevertheless, each system requires ongoing testing and data analysis to ensure safe and efficient flight operations through regular quality assessments. The Deblin airfield serves as an important regional aviation hub, supporting both training and operational flights. Therefore, comprehensive analysis of flight monitoring system data remains a key task in maintaining the effectiveness and safety of aviation activities.

This study aims to conduct a detailed comparative analysis of the registration characteristics of the surveillance and navigation systems operating at the Deblin airfield. The systems under investigation include GPS position data recorded by the onboard S2-3a flight recording system, the GCA-2000 radar system operating in multiple modes (PAR/ASR/COM), and the AVIA-W radar. Special attention is given to comparing these systems in terms of their spatial and temporal registration characteristics.

2. METHODOLOGY AND EXPERIMENTAL DATA

To compare the registration characteristics of the GCA-2000 and AVIA-W radar systems using GPS data as the reference trajectory, a series of sequential testing and data-processing stages was conducted. Each stage was based on a comparative evaluation of the registration parameters of the GCA-2000 and AVIA-W radars against the synchronized GPS reference trajectory. Additionally, the analysis incorporated spatiotemporal characteristics of the flights, including registration timestamps, distances from the radar, and flight altitude. The study also accounted for the influence of topographic features, including both natural and artificial obstacles, which could affect the quality of data registration. All three datasets were transformed to UTC using the synchronization procedure described below. To avoid combining temporal sampling density with periods outside radar coverage, the radar-to-GPS ratio was calculated only within the common temporal window corresponding to each radar series. The absence of radar registrations outside this window was assessed separately in the spatial coverage analysis.

GPS latitude and longitude were obtained from the onboard S2-3a flight recording system at a sampling rate of 1 Hz (Józko, 2006). The specific installed GPS solution was not independently calibrated against an external geodetic reference during this experiment; therefore, the GPS series is treated as a reference trajectory rather than as error-free ground truth. For scale only, the published GPS Standard Positioning Service performance standard specifies global-average 95% position errors of ≤ 8 m horizontally and ≤ 13 m vertically, with worst-location values of ≤ 15 m horizontally and ≤ 33 m vertically (U.S. Department of Defense, 2020). These specification values are not used as an empirical uncertainty estimate for the particular S2-3a installation.

Temporal synchronization was established after the experiment by simultaneously comparing UTC displayed by a GPS receiver with the clocks shown on the GCA-2000 and AVIA-W radar displays. The GCA-2000 display clock was found to be 46 s ahead of UTC, whereas AVIA-W displayed Polish local summer time (UTC+2). The corrected radar times were therefore obtained as $t_{*GCA} = t_{GCA} - 00:00:46$ and $t_{*AVIA} = t_{AVIA} - 02:00:00$. After these corrections, the datasets were synchronized to UTC with an accuracy of 1 s, and each radar record was paired with the GPS position corresponding to the same UTC epoch. Accordingly, the 3-8 s values of Δt analyzed below are inter-record intervals within each radar sequence, not residual radar-to-GPS clock offsets.

At the first stage of the analysis, a relative temporal sampling ratio (n_{sys}) was determined for each radar-GPS pair. For each radar, the comparison window extended from its first to its last registered observation, and only GPS epochs falling within the same time interval were included in the denominator. The calculation was performed using the following formula:

$$n_{sys} = \frac{n_{rad}}{n_{GPS,win}} \times 100 \quad (1)$$

where: n_{sys} - relative temporal sampling ratio, %; n_{rad} - number of observations recorded by the radar within its registration window; $n_{GPS,win}$ - number of GPS observations recorded within the same temporal window (from the first to the last radar record, inclusive). Because GPS data were recorded at 1-s intervals, $n_{GPS,win}$ corresponds to the number of 1-s GPS epochs within the relevant radar window. This indicator characterizes relative temporal sampling density and does not quantify overall radar coverage or probability of target detection.

The second stage involved calculating the average data update interval for each surveillance system, as well as the average flight altitudes. For GCA-2000, the technical refresh characteristics are mode-dependent: the PAR component updates once per second, the ASR component has a maximum refresh interval of 5 seconds, and the SSR component updates every 4 seconds. During the experiment, GCA-2000 operated in COMBINED mode, integrating PAR and ASR information; therefore, the observed GCA-2000 record sequence cannot be evaluated against a single 5-second ASR interval. The GCA-2000 observations used in the analysis were extracted frame-by-frame from the recorded PPI display, with a timestamp assigned to each displayed change in aircraft position. For AVIA-W, the nominal refresh period is 6 seconds. Consequently, the empirical intervals derived from the recorded sequences were interpreted as intervals between successive displayed position updates rather than as direct estimates of the scan period of an individual GCA-2000 subsystem. For the temporal statistics reported in Table 3, radar records were ordered chronologically by UTC time and the inter-record interval was defined as $\Delta t_i = t_i - t_{i-1}$. The arithmetic mean and sample standard deviation were calculated from the complete sequence of successive intervals. Long intervals associated with

temporary registration gaps were retained because they form part of the empirical temporal behavior of the recorded sequence; therefore, the SD of Δt describes overall temporal variability rather than the nominal refresh period of an individual radar component.

At the third stage of the study, a detailed analysis of the topographic characteristics of the area between the Deblin and Radom airfields was carried out. The assessment included identifying elevation changes, natural and artificial obstructions, and examining their potential impact on the data accuracy of the GCA-2000, AVIA-W, and GPS systems. For this purpose, flight altitudes were converted into a relative height system using formula (2), with consideration of the geoid height based on the EGM2008 model:

$$\Delta H_{rel} = H_{norm/topo} - H_{norm/rad} \quad (2)$$

where: $H_{norm/topo}$ - is the orthometric height above sea level, calculated as the difference between the ellipsoidal height and the geoid height based on the EGM2008 model; $H_{norm/rad}$ - is the radar height above sea level. This approach is commonly used when analyzing the influence of elevation on the studied parameters, especially within local-scale investigations (Fedorchuk, 2022; Savchuk et al., 2024).

For each flight, map diagrams were generated to illustrate the relationship between flight altitude, topographic characteristics, and radar registration distance. Additionally, the flight trajectories were plotted on topographic maps of the study areas. The use of terrain maps allowed for a better understanding of the spatial patterns of radar registration and enabled the assessment of the relationship between terrain topography and radar data quality. The applied methodology ensures a comprehensive assessment of the performance of the GCA-2000 and AVIA-W surveillance systems under real-world operating conditions. The analysis considers the influence of natural obstacles, terrain topography, and flight trajectory complexity. This approach makes it possible to compare the observed registration characteristics with the available technical specifications and to identify potential factors affecting data registration. For the analysis of surveillance system parameters, flight data from two M28 «Bryza» aircraft (Fig. 1) were used. The experiment was conducted on 17 April 2023 using two M-28 «Bryza» turboprop aircraft operating from Warszawa-Radom and performing training approaches at Deblin. The aircraft were assigned individual transponder SQUAWK codes 3117 and 3121; these codes are used throughout the paper as the two flight identifiers. The source documentation also indicates that Mode 3/C altitude information was available on the radar displays. The radar reference coordinates used in the spatial calculations were GCA-2000: 51°33'00.39" N, 21°53'27.19" E and AVIA-W: 51°33'19.42" N, 21°54'09.00" E; these positions were obtained from MIL AIP Poland (MIL AIP Poland, 2023). For the spatial boundary analysis in Figs. 5-8, the distances corresponding to the first and last radar registration epochs were recalculated as WGS84 geodesic distances from the synchronized GPS position of the aircraft to the corresponding radar site. These values are reported to 0.1 km in Table 2 and represent observed boundary locations at registered epochs rather than distances estimated visually from the figures. To avoid ambiguity in the vertical quantities, Fig. 3 is interpreted as relative terrain elevation, whereas H in Figs. 9-11 denotes the QFE-referenced aircraft-altitude series ($QFE = 1008$ hPa).

A calibrated radar cross-section (RCS) for the particular M-28 aircraft and a systematic time series of instantaneous target aspect/elevation angles were not available in the experimental dataset. No separate time-varying transponder-mode log beyond the assigned SQUAWK identifiers and displayed Mode 3/C altitude information was retained for this analysis. These

variables are therefore treated as unobserved factors. In addition, because the study comprises only two flights and successive trajectory observations are serially dependent, no inferential significance test or confidence interval was used to establish terrain or forest effects. The spatial analysis is consequently descriptive and reports coincidence/association of registration gaps with mapped features rather than causal or statistically significant correlations.



Fig. 1. General view of the M28 “Bryza” aircraft

Both analyzed flights were conducted on 17 April 2023. The first flight, identified by SQUAWK 3117, began at 18:08:37 and ended at 20:32:10. GPS data were recorded throughout the entire flight, while the GCA-2000 system registered data from 18:19:57 to 20:22:29, and the AVIA-W system - from 18:18:02 to 20:23:03. The second flight, identified by SQUAWK 3121, started at 18:01:33 and ended at 20:24:43. GPS also provided continuous data, whereas GCA-2000 recorded information from 18:20:44 to 20:14:20, and AVIA-W - from 18:20:57 to 20:14:58. Selected technical and nominal update characteristics of the observation systems used for flight data analysis are presented in Table 1.

Tab. 1

Technical and Nominal Update Characteristics of the Surveillance Systems

Registration System	Maximum Registration Distance, R_{max} , km	Registration Period, T_{rad} , s	Theoretical number of registered data per hour, n , h^{-1}
GPS position data /S2-3a/	not applicable	~ 1 s	3600
Radar GCA-2000 (COMBINED during test)	ASR mode ~ 53 km	PAR: 1 s; ASR: max. 5 s; SSR: 4 s	mode-dependent; no single value for COMBINED
Radar AVIA-W	ASR mode ~ 100 km	~ 6 s	600

Sources for Table 1: S2-3a sampling characteristics - Jóźko (2006); GCA-2000 - POL-3 1P5-GCA-2000-2, Chapter 1, Technical Documentation; AVIA-W - AVIA-W Airfield Area Control Radar Station Technical Documentation (1988).

According to Table 1, the S2-3a flight recording system stores GPS position data at 1-s intervals, corresponding to up to 3,600 epochs per hour. This sampling rate provides a dense temporal reference series; a radar-style maximum registration distance is not applicable to GPS, and positional accuracy is considered separately. For GCA-2000, the refresh characteristics depend on the active radar component: PAR updates once per second, ASR has a minimum refresh interval of 5 seconds, and SSR updates every 4 seconds. During the test, GCA-2000

operated in COMBINED mode; therefore, the previously used value of 720 records per hour, derived from a 5-second ASR interval, does not represent the theoretical output of the analyzed COMBINED-mode sequence and is no longer used as a reference value. The ASR component has a maximum signal tracking distance of approximately 53 kilometers. The AVIA-W system features an extended maximum signal tracking range of about 100 kilometers. Its nominal data refresh interval is 6 seconds, corresponding to up to 600 updates per hour under uninterrupted operation. This larger nominal detection range provides a wider potential surveillance area than that specified for the GCA-2000 ASR component. To evaluate the performance of the tracking systems, actual flight data records were used, as presented in Table 2.

Tab. 2

Recorded (Actual) Flight Data and Registration-Boundary Distances

Registration System	Flight Number	Flight Duration /h:m:s/	Actual number of registered data /n/	Distance at first radar registration, km	Distance at last radar registration, km
GPS	3117	2:23:33	8614	-	-
	3121	2:23:10	8591	-	-
GCA-2000	3117	2:02:32	2066	23.6	43.7
	3121	1:53:36	2092	2.3	44.1
AVIA-W	3117	2:05:01	890	29.9	47.2
	3121	1:54:01	842	2.0	47.7

For flight 3117, GPS recorded 8,614 epochs over 2 h 23 min 33 s, GCA-2000 recorded 2,066 observations over 2 h 02 min 32 s, and AVIA-W recorded 890 observations over 2 h 05 min 01 s. For flight 3121, GPS recorded 8,591 epochs over 2 h 23 min 10 s, GCA-2000 recorded 2,092 observations over 1 h 53 min 36 s, and AVIA-W recorded 842 observations over 1 h 54 min 01 s. The experimental flights were conducted under comparable field conditions. The synchronized GPS position series from the S2-3a recorder was used as the reference trajectory for the spatial comparisons and was not treated as an error-free reference standard. The first and last registration distances in Table 2 were calculated from synchronized GPS positions at the corresponding radar epochs and were used in the spatial discussion instead of approximate distances read from the map figures.

3. RESULTS

The first analysis compared the number of radar observations with the number of 1-s GPS epochs within the same radar registration window. For flight 3117, the GCA-2000 window (18:19:57-20:22:29) contained 7,353 GPS epochs; 2,066 radar observations corresponded to a relative temporal sampling ratio of 28.1%. For AVIA-W, the window (18:18:02-20:23:03) contained 7,502 GPS epochs, and 890 radar observations corresponded to 11.9%. For flight 3121, the GCA-2000 window (18:20:44-20:14:20) contained 6,817 GPS epochs; 2,092 radar observations yielded 30.7%. The corresponding AVIA-W window (18:20:57-20:14:58) contained 6,842 GPS epochs, and 842 radar observations yielded 12.3%. GCA-2000 therefore showed a higher relative temporal sampling density than AVIA-W in both flights. The revised indicator excluded the GPS-only periods before the first and after the last radar registration;

those periods were considered separately in the spatial coverage analysis. The reported percentages characterized temporal sampling density within the radar registration interval and were not interpreted as overall registration or detection efficiency.

Successive inter-record intervals Δt were then analyzed for the GCA-2000 and AVIA-W radar sequences after UTC synchronization. The 1-s S2-3a GPS series provided the temporal reference cadence, whereas Δt was calculated between consecutive radar epochs and not as a radar-minus-GPS clock offset. For flights 3117 and 3121, Figure 2 illustrated the distribution of these inter-record intervals over the observation period.

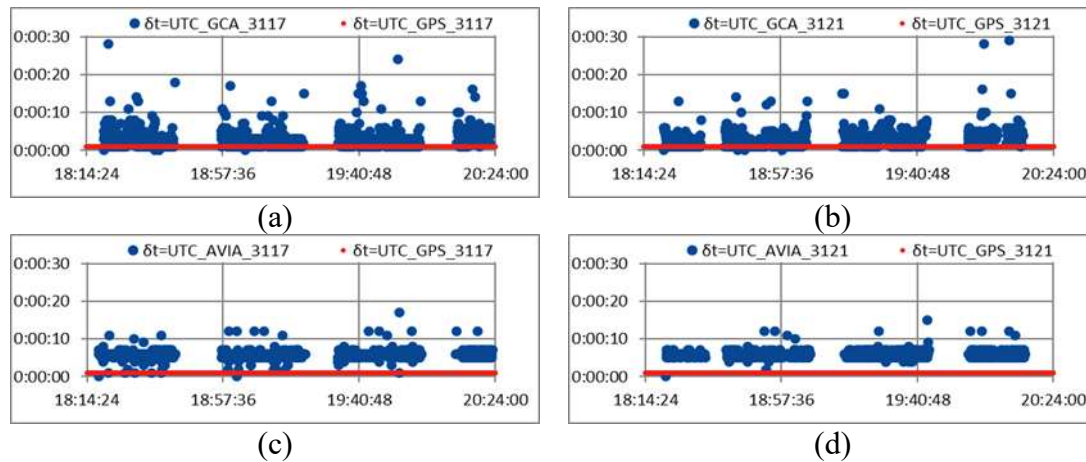


Fig. 2. Inter-record interval Δt as a function of observation time: (a) flight 3117, GCA-2000; (b) flight 3121, GCA-2000; (c) flight 3117, AVIA-W; (d) flight 3121, AVIA-W

Figures 2a-d showed that the intervals between successive radar registrations were non-uniform and included longer gaps in both flight records. Because fixed upper thresholds could not be established reliably by visual inspection, temporal variability was quantified in Table 3 using the mean and standard deviation of Δt . For GCA-2000, the empirical mean interval of 3-4 s characterized the COMBINED-mode display record and did not imply that the ASR component itself refreshed faster than its technical specification. The AVIA-W sequences also contained longer gaps, as reflected by the mean and SD values in Table 3. The plots were therefore used for qualitative visualization, whereas the numerical assessment was based on the tabulated statistics.

A topographic analysis was then conducted for the area between the Deblin and Radom airfields. Figure 3 presented the longitudinal terrain profile between the two airfields in the adopted relative height reference system.

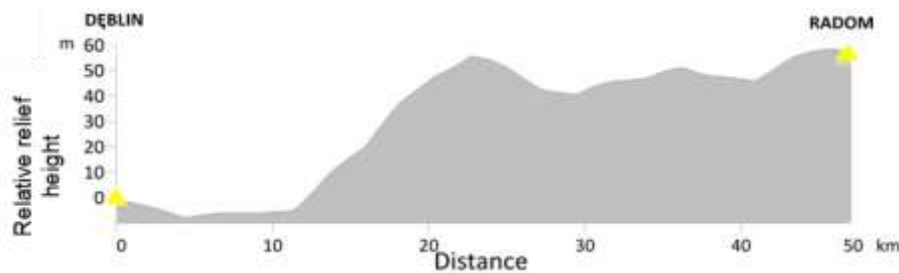


Fig. 3. Terrain profile between Deblin and Radom airfields in the relative height reference system

The relative terrain elevation along the route reached approximately +60 m in the adopted local reference system (Fig. 3). This value described the terrain profile only and was distinct from the aircraft-altitude parameter H used in Figures 9-11. The distance between the two airfields was approximately 50 km, within the nominal ASR coverage ranges reported for GCA-2000 (~53 km) and AVIA-W (~100 km). The terrain profile was retained as spatial context for interpreting registration gaps; no causal terrain effect was inferred from these two flights.

Figure 4 showed the relative elevation map and GPS trajectories of both flights. Flight 3121 followed a more complex route with sharper turns, multiple landing approaches, and additional maneuvers within the radar coverage area, reflecting the training exercises performed during the flight. Flight 3117 contained fewer maneuvers and a more structured landing pattern. This contrast supported a descriptive comparison of the two registration patterns, but with only two flights the study did not establish a general dependence or independence of radar performance on route complexity or flight duration.

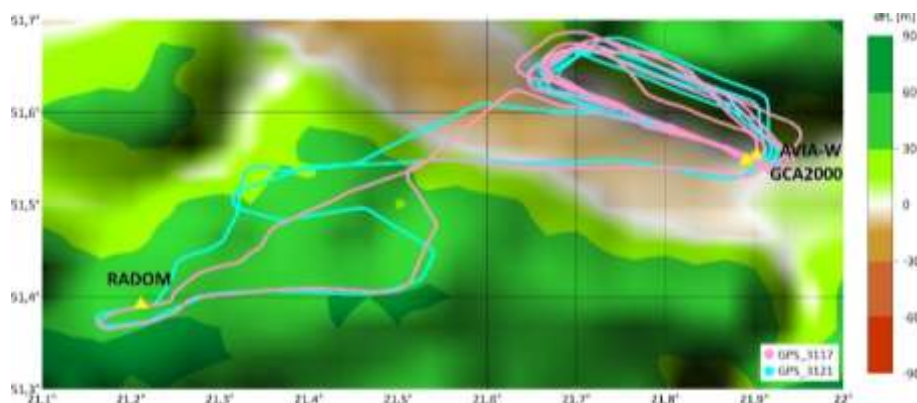


Fig. 4. Flight trajectories recorded by the GPS system

Figure 5 showed the GCA-2000 registration pattern for flight 3117 against the reference GPS trajectory and relative-elevation base layer. The corresponding first and last registration distances were summarized in Table 2.

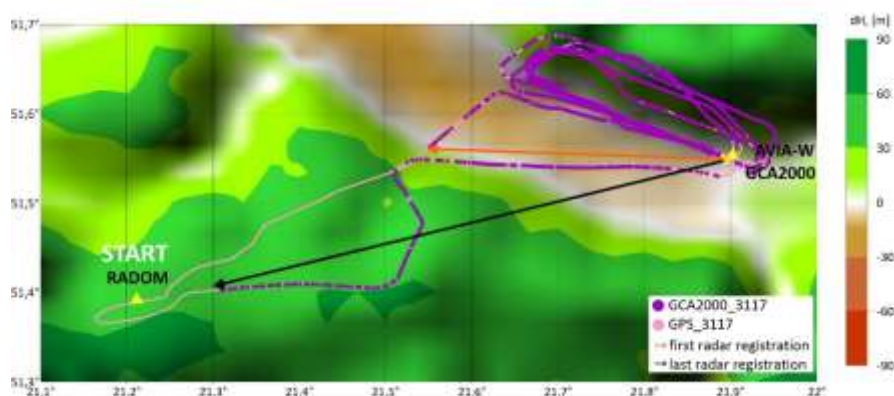


Fig. 5. Flight trajectory recorded by the GPS and GCA-2000 systems for the first flight (schematic distance annotations; quantitative registration-boundary distances are given in Table 2)

For flight 3117, GCA-2000 registration began at 23.6 km from the radar site and the last registered epoch occurred at 43.7 km (Table 2). The onset of the registered segment coincided spatially with a transition in relative terrain elevation, while the central part of the flight and the trajectory near Deblin contained the densest GCA-2000 registration.

Figure 6 showed the AVIA-W registration pattern for the same flight. AVIA-W registration began at 29.9 km from the radar site and the last registered epoch occurred at 47.2 km (Table 2). The onset again coincided spatially with a relative-elevation transition, and the last registered epoch occurred on the return leg toward Radom.

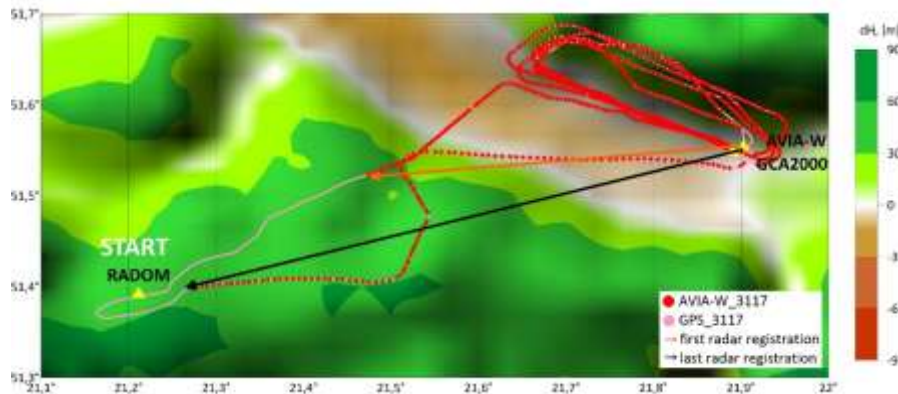


Fig. 6. Flight trajectory recorded by the GPS and AVIA-W systems for the first flight (schematic distance annotations; quantitative registration-boundary distances are given in Table 2)

Figure 7 showed the GCA-2000 registration pattern for flight 3121. Registration began at 2.3 km from the GCA-2000 site and the last registered epoch occurred at 44.1 km on the return leg (Table 2). Thus, a substantial initial part of the Radom-Deblin leg was not represented in the GCA-2000 record, and registration began only when the aircraft was already close to the radar site.

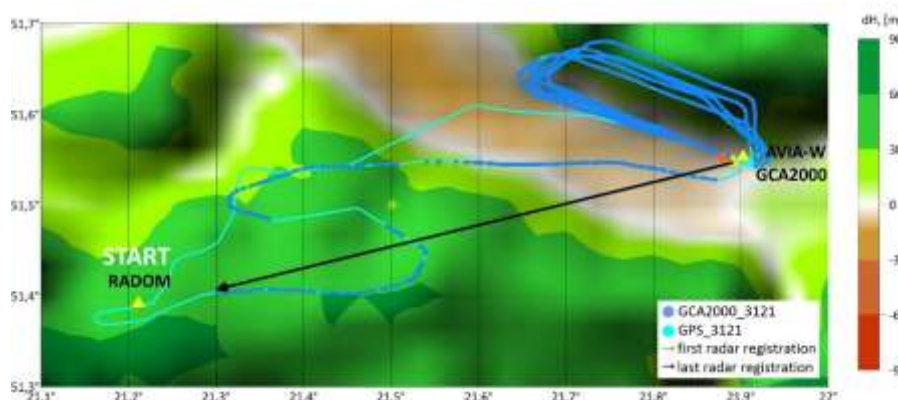


Fig. 7. Flight trajectory recorded by the GPS and GCA-2000 systems for the second flight (schematic distance annotations; quantitative registration-boundary distances are given in Table 2)

Figure 8 showed the AVIA-W registration pattern for flight 3121. Registration began at 2.0 km from the AVIA-W site and the last registered epoch occurred at 47.7 km on the return leg (Table 2). The pattern was similar to that of GCA-2000 for the same flight: radar registration began only after the aircraft approached the Deblin radar area and ended during the return toward Radom.

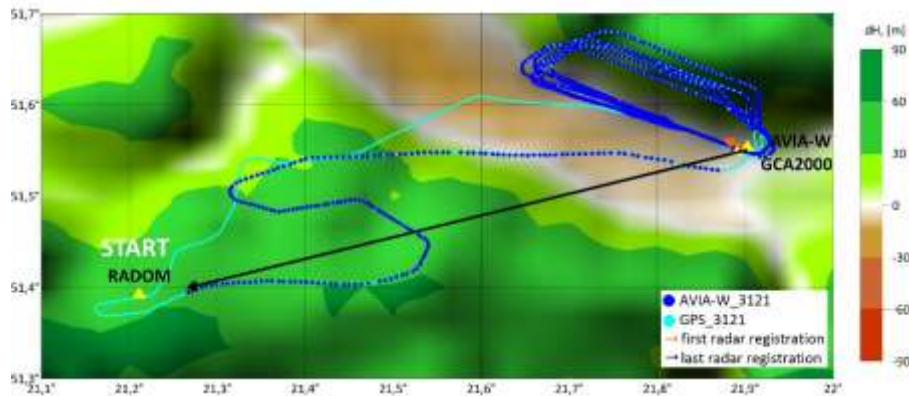


Fig. 8. Flight trajectory recorded by the GPS and AVIA-W radar systems for the second flight (schematic distance annotations; quantitative registration-boundary distances are given in Table 2)

Figure 9 showed the relationship between QFE-referenced aircraft altitude H ($QFE = 1008$ hPa) and relative terrain elevation for flights 3117 and 3121. The radar registration epochs were compared with the terrain profile. The two vertical quantities were distinct: H represented aircraft altitude, whereas relative terrain elevation characterized the ground surface.

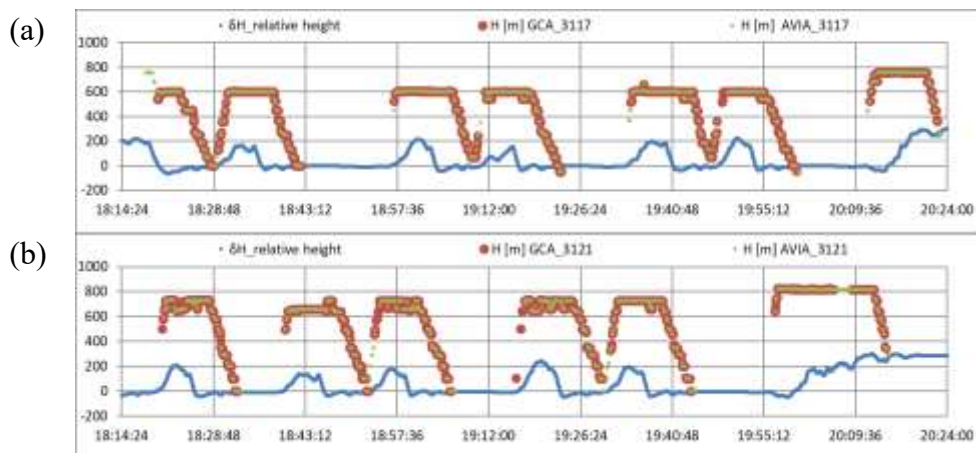
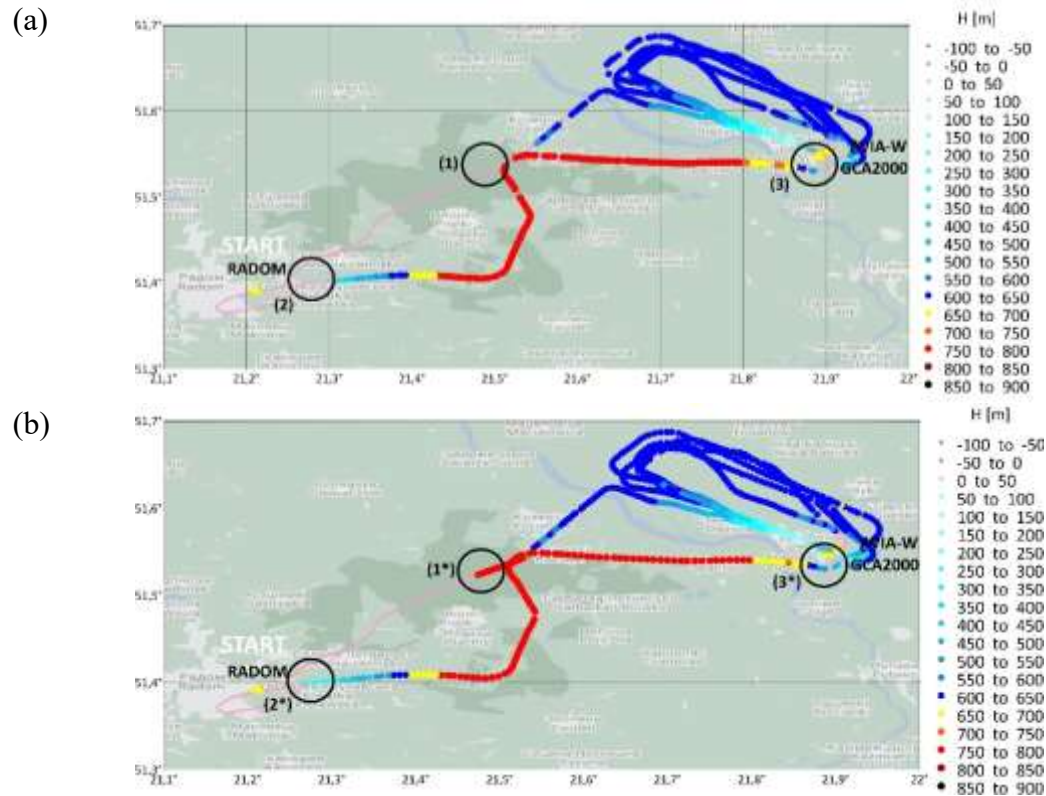


Fig. 9. Relationship between QFE-referenced aircraft altitude and relative terrain elevation: (a) flight 3117; (b) flight 3121

The altitude profiles in Figures 9a and 9b showed the takeoff, cruise, approach, and landing phases. Radar observations were comparatively dense during several approach and landing segments near the Deblin airfield. Lower observation density and gaps occurred mainly during the initial departure from Radom and in selected low-altitude or near-radar portions of

the trajectories. Consequently, missing observations were interpreted as segment-specific features of these flights rather than as a general characteristic of aircraft approaching the radars.

Figure 10 showed the spatial relationship between mapped natural and artificial features and radar registration during flight 3117. The radar-registration segments were color-coded by QFE-referenced aircraft altitude H (QFE = 1008 hPa), with values up to approximately 900 m. The color scale represented aircraft altitude rather than the relative terrain elevation shown in Figure 3 and used 50-m classes over the displayed range from -100 to 900 m.

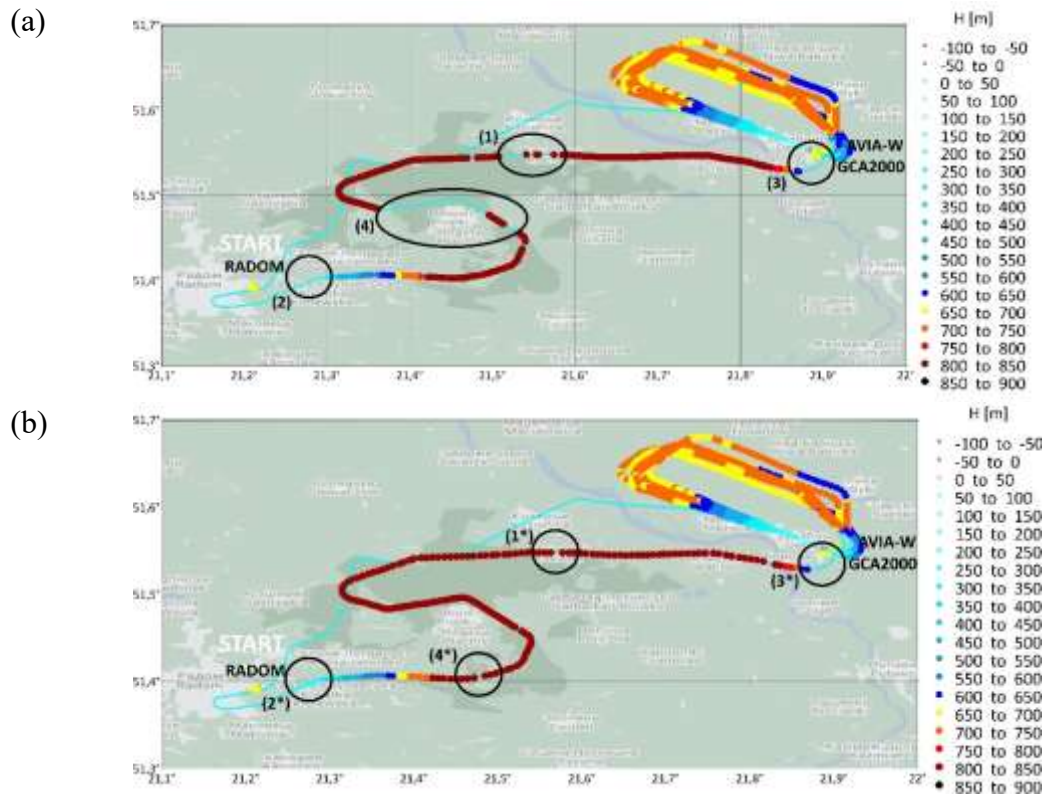


Zone legend: (1)-(3) - GCA-2000 registration-gap zones; (1*)-(3*) - corresponding AVIA-W registration-gap zones.

Fig. 10. Maps of natural and artificial objects relative to QFE-referenced aircraft altitude for flight 3117: (a) GCA-2000; (b) AVIA-W; color scale: H (m), QFE = 1008 hPa, 50-m classes

In Figure 10a, GCA-2000 did not register data in zone (1), located near the edge of a forested area. In Figure 10b, the first AVIA-W detection occurred in zone (1*) over the same forest segment. This spatial coincidence was not interpreted as an isolated forest effect because target aspect and RCS were not recorded. GCA-2000 data were also absent in zone (2), whereas AVIA-W continued to register the trajectory at point (2*). Registration interruptions occurred near both radar locations (zones 3 and 3*), with a larger gap for GCA-2000. These observations were treated as descriptive spatial associations; quantifying a forest effect would require additional flights with target-aspect and RCS information.

Figure 11 showed corresponding spatial registration patterns for flight 3121 for GCA-2000 (a) and AVIA-W (b). The mapped gaps and recoveries were compared descriptively with terrain and infrastructure features.



Zone legend: (1)-(4) - GCA-2000 registration-gap zones; (1*)-(4*) - corresponding AVIA-W registration-gap zones.

Fig. 11. Maps of natural and artificial objects relative to QFE-referenced aircraft altitude for flight 3121: (a) GCA-2000; (b) AVIA-W; color scale: H (m), QFE = 1008 hPa, 50-m classes

In Figure 11a, a sudden loss of GCA-2000 registration occurred in the central section of the flight, zone (1), at a QFE-referenced aircraft altitude H of approximately 800-850 m. These values described aircraft altitude and were distinct from the relative terrain elevation in Figure 3. AVIA-W showed more continuous registration in zone (1*), although a partial gap remained. Zones (2) and (2*) were similar to those observed during the first flight. In zones (3) and (3*), both radar systems showed larger registration gaps than in flight 3117. Additional interruptions appeared in zone (4) for GCA-2000 and zone (4*) for AVIA-W. The GCA-2000 interruption was more extensive, whereas AVIA-W retained observations along most of the corresponding trajectory segment. Because only two flights were available, these differences were reported descriptively and were not attributed causally to route complexity or flight duration.

Finally, the data collected during flights 3117 and 3121 were summarized statistically for GCA-2000 and AVIA-W (Table 3). The temporal statistics comprised the arithmetic mean and sample standard deviation (SD) of successive registration intervals Δt , while the altitude statistics comprised the corresponding mean and SD values of H . The SD of Δt quantified variability over the complete empirical registration sequence, including longer gaps between recorded observations.

Tab. 3

Statistical characteristics of the surveillance systems

Statistics	Δt (sec)				H (m)			
	3117		3121		3117		3121	
	GCA-2000	AVIA-W	GCA-2000	AVIA-W	GCA-2000	AVIA-W	GCA-2000	AVIA-W
avg	3.6	8.4	3.3	8.1	476	490	592	584
SD	28.6	41.9	24.2	36.3	209	216	201	239

For flight 3117, the mean interval between successive GCA-2000 records was 3.6 ± 28.6 s (mean $\pm$ SD), while AVIA-W yielded 8.4 ± 41.9 s. For flight 3121, the corresponding values were 3.3 ± 24.2 s for GCA-2000 and 8.1 ± 36.3 s for AVIA-W. The SD values substantially exceeded the means because the complete sequences included occasional long registration gaps; the mean interval alone therefore did not demonstrate a stable or uniform update cadence. For GCA-2000, the mean interval characterized the COMBINED-mode display record rather than the refresh period of the ASR component alone. Mean flight altitudes were 476 ± 209 m (GCA-2000) and 490 ± 216 m (AVIA-W) for flight 3117, and 592 ± 201 m (GCA-2000) and 584 ± 239 m (AVIA-W) for flight 3121.

The large SD values of Δt primarily reflected occasional long registration gaps included in the complete empirical sequences rather than variability in the nominal radar refresh periods. Therefore, the mean and SD values characterize the overall temporal structure of the recorded sequences, including both regular observations and longer interruptions, and should not be interpreted as direct measures of update-rate stability. For GCA-2000, the observed mean inter-record intervals characterize the COMBINED-mode display record and are not directly comparable with the 5-second refresh characteristic of the ASR component alone. Future analyses should distinguish inter-record intervals within continuous tracking segments from longer registration gaps to characterize nominal refresh behavior and interruption patterns separately.

4. CONCLUSIONS

This article presents an analysis of the temporal sampling characteristics of the GCA-2000 and AVIA-W radar systems in comparison with GPS, used as a reference system. The study is based on two flights conducted under lowland terrain conditions, with consideration of both natural and man-made obstacles. The focus is placed on evaluating the spatio-temporal characteristics of data registration of data registration, the temporal variability of the radar records, and the influence of external factors. The recalculated relative temporal sampling ratios, determined only within the corresponding radar-GPS common temporal windows, were 28.1% and 30.7% for GCA-2000 and 11.9% and 12.3% for AVIA-W for flights 3117 and 3121, respectively. These values describe temporal sampling density rather than total spatial coverage or detection efficiency. The mean $\pm$ SD of successive registration intervals were 3.6 ± 28.6 s and 3.3 ± 24.2 s for GCA-2000, and 8.4 ± 41.9 s and 8.1 ± 36.3 s for AVIA-W for flights 3117 and 3121, respectively. The large SD values reflect long registration gaps retained in the complete sequences and show that the mean intervals alone do not demonstrate uniform temporal stability. For GCA-2000, the 3-4 second mean value characterizes the empirical COMBINED-mode display record and is not directly comparable with the 5-second ASR

refresh period considered separately. Spatial analysis identified data-loss zones that spatially coincided with local terrain variations and forested areas. However, no statistically significant correlation or causal relationship was established within the present two-flight dataset. The altitude standard deviations were 209 and 216 m for GCA-2000 and AVIA-W, respectively, in flight 3117, and 201 and 239 m in flight 3121. Because only two flights were analyzed, the observed differences do not establish a general causal relationship between route complexity, flight duration, and radar registration performance. Within these two flights, GCA-2000 showed a higher temporal sampling density and shorter mean inter-record intervals than AVIA-W; these metrics describe only the analyzed temporal behavior and do not constitute an overall ranking of the systems. No independent quantitative acceptance criterion for regional monitoring was defined in this study; therefore, the results are not used to classify either radar as operationally “acceptable” or “suitable” for regional monitoring. AVIA-W showed a lower mean temporal sampling frequency, and the present Δt statistics do not support describing its temporal registration as uniformly more stable over the complete observation window. These conclusions may be useful for improving data fusion algorithms and optimizing coverage areas in radar-based airspace control systems. Future research should involve a larger dataset of flight records under varying terrain and weather conditions and should record target-aspect/RCS-related variables, so that the observed spatial associations can be tested quantitatively. The findings provide a basis for further adaptation of radar observation systems to challenging operational environments and for improvement of their processing algorithms. Such analyses can support identification of zones with potential signal-loss risk. They can also inform the design of hybrid radar-GNSS monitoring systems for tactical airspace surveillance and support flight-trajectory reconstruction under the variable topographic conditions typical of Central and Eastern Europe.

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