Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 127 **2025**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2025.127.3

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Cybulska-Gac, K., Krasuski, K., Ciećko, A. Accuracy analysis of Galileo code positioning for UAV. *Scientific Journal of Silesian University of Technology. Series Transport*. 2025, **127**, 39-55. ISSN: 0209-3324. DOI: https://doi.org/10.20858/sjsutst.2025.127.3

Klaudia CYBULSKA-GAC[1], Kamil KRASUSKI[2], Adam CIEĆKO[3]

ACCURACY ANALYSIS OF GALILEO CODE POSITIONING FOR UAV

Summary. Official ICAO certification for the Galileo satellite navigation system is currently being implemented for aeronautical applications. Hence, experimental studies are needed to verify the performance of Galileo for kinematic positioning of the user in aviation. The main objective of this work is to present an optimal computational strategy for determining the user's position and the accuracy parameter of Galileo positioning in civil aviation. The paper uses the least squares method and Kalman filtering to calculate the user position. The calculations were performed in two independent Galileo observation processing software, i.e., RTKLIB and Emlid Studio. Galileo navigation and observation data acquired from a DJI Matrice RTK300 unmanned platform was used in the calculations. The Galileo SPP code method algorithm was used to determine the UAV coordinates. The RTKLIB application uses a solution based on the least squares method model to determine user coordinates using the SPP method. The Emlid Studio application, respectively, is based on the Kalman filtering algorithm. On this basis, the UAV positions were determined for the two computational strategies, and the Galileo positioning accuracy was then determined in the form of position errors and RMS errors. The study shows that Emlid Studio software improves Galileo's kinematic

[1] Institute of Navigation, Polish Air Force University, Dywizjonu 303 nr 35 Street, 08-521 Dęblin, Poland. Email: k.cybulska-gac@law.mil.pl. ORCID: https://orcid.org/0000-0001-5060-5110
[2] Institute of Navigation, Polish Air Force University, Dywizjonu 303 nr 35 Street, 08-521 Dęblin, Poland. Email: k.krasuski@law.mil.pl. ORCID: https://orcid.org/0000-0001-9821-4450
[3] Faculty of Geoengineering, University of Warmia and Mazury, Oczapowskiego 2 Street, 10-720 Olsztyn, Poland. Email: adam.ciecko@uwm.edu.pl. ORCID: https://orcid.org/0000-0002-3984-0846

positioning accuracy by between 15 and 65% over the results obtained from the RTKLIB solution. The flight tests carried out, the software used, and the computational strategies can be utilized for other global GNSS systems.

Keywords: Galileo, SPP method, accuracy, position errors, UAV

1. INTRODUCTION

In air transport, Global Navigation Satellite Systems (GNSS) are mainly used to determine the position of an aircraft or unmanned aerial vehicle [1]. Therefore, the operation and performance of GNSS systems in aviation bring many benefits that have a significant impact on improving the user's positioning quality parameters [2]. In order to utilize the functionality of GNSS in aviation, they are subject to strict certification requirements, which are contained in Annex 10 of the Chicago Convention on International Civil Aviation – 'Aeronautical Telecommunications' [3]. Certified GNSS systems are intended to meet the criteria of accuracy, continuity, integrity, and availability [2]. However, at the moment, Annex 10 mainly describes certification for only two global systems, GPS (Global Positioning System) and GLONASS (Globalnaya Navigacionaya Sputnikovaya Sistema) [3]. Moreover, certification requirements for the European Navigation Satellite System (Galileo) are being implemented. The official certification of the Galileo system in aviation raises the question of the need to test positioning quality parameters and, in particular, the accuracy of Galileo's positioning for the use of its functionality in aviation applications. Galileo, unlike GPS and GLONASS, will only have civilian use, including in the area of air transport [4-6]. Furthermore, it is anticipated that there will be a surge of interest in the use of Galileo in aviation after 2020 [7].

2. RELATED WORKS

The literature review on the application of Galileo in air transport is quite diverse. Worth mentioning is the work on the integration of Galileo and EGNOS (European Geostationary Navigation Overlay Service) data for single- and dual-frequency GNSS positioning [8, 9] and including approach and landing procedures in research [10]. In terms of landing and approach procedures, research in the development of a GBAS (Ground-Based Augmentation System) based on the Galileo navigation system is worth highlighting. This area includes research into the use of Galileo in combination with both GBAS and SBAS (Satellite-Based Augmentation System) augmentation systems should be mentioned [11]. Furthermore, of interest in this field is the research shown in paper [12], where the results of the Galileo positioning quality within the SoL (Safety of Life) positioning service are demonstrated. Next, paper [13] presents the concept of operation of a Ground-Based Regional Augmentation System (GRAS) using the Galileo navigation system. On the other hand, [14] describes the results of a study on the determination of HPL (Horizontal Protection Level)/VPL (Vertical Protection Level) protection levels for a GBAS augmentation system with Galileo and GPS solutions. Another subject area is the kinematic positioning of Galileo during flight test. Thus, a paper [15] describes the first flight test, during which the position of an aircraft was determined from the Galileo solution within the OS (Open Service) positioning service. Another paper [16] shows a simulation study of the determination of ionospheric scintillations occurring along an aircraft flight path. GPS, GLONASS, Galileo and BeiDou (BeiDou Navigation Satellite System) observations were used in the study, and the calculation additionally determined GNSS satellite positioning quality parameters according to ICAO (International Civil Aviation Organization) requirements. The next paper [17] presents the possibility of using Galileo, GPS, GLONASS and BeiDou data to monitor navigation parameters and aircraft trajectories. Publication [18] presents the results of Galileo kinematic positioning during a mobile flight test. In particular, the parameters shown are: signal-to-noise ratio SNR (Signal Noise to Ratio), geometric coefficients DOP (Dilution of Precision), number of Galileo satellites tracked, standard deviations and position errors. Publication [19] is an extension of the work [18] and additionally contains the results of aircraft position determination based on a multi-frequency Galileo solution. Furthermore, paper [20] compares the results of Galileo and GPS kinematic positioning accuracy during a flight test. The achieved GPS positioning accuracy was higher than the Galileo positioning accuracy. A very interesting study was shown in paper [21], which used an Orolia GNSS simulator to determine the position of an aircraft. The study simulated the effect of jamming on multisystem GPS+Galileo+GLONASS positioning and determined the accuracy parameters. In the studies of Galileo positioning in aviation, it is also important to develop RAIM (Receiver Autonomous Integrity Monitoring) algorithms for the control of navigation calculations and the elimination of coarse errors. Thus, in the studies [22-26], research was carried out on determination of availability within the RAIM module for the LPV-200 procedure using a multisystem GPS+GLONASS+Galileo solution, application of RAIM simulation algorithms within the CAT-III approach procedure using GNSS/Galileo navigation systems, application of ARAIM (Advances RAIM) algorithms for the determination of the predicted position of an aircraft using GPS/GLONASS/Galileo constellations, development of coarse error detection algorithms based on statistical tests and taking into account GPS/GLONASS/Galileo/BeiDou observations, application of RAIM algorithms for GPS+Galileo positioning in the GNSS Non-Precision Approach (NPA) procedure. The use of Galileo in aviation is also the subject of implementation and validation of GNSS receivers. Thus, in this case, it is worth mentioning research on: E1 Galileo signal strength for OS/SoL positioning services [27], validation of ICAO certification requirements for single- and dual-frequency GPS and Galileo receivers [28], development of a dual-frequency Galileo receiver architecture for aeronautical applications [29], development of algorithms for integrating GPS and Galileo signals into a GNSS receiver [30, 31]. For Galileo satellite receivers used in aviation, it is also worth noting the possibility of using the E5 frequency. For example, paper [32] shows the architecture of a Galileo receiver with the possibility of receiving the E5 signal for aviation purposes. On the other hand, papers [33-35] describe the interoperability and compatibility of E5 (Galileo) and L5 (GPS) signals in civil aviation. In the area of air transport, Galileo can be used for air traffic control and management, as shown in [36]. In addition, Galileo has a SAR (Search and Rescue) service, which is of considerable importance for improving the safety of flight operations [37-38]. Galileo will not only have its uses for aircraft, but also for UAV (Unmanned Aerial Vehicle) technology. It is possible to talk about the use of Galileo for UAVs in the areas of photogrammetric and geoinformation studies [39], the development of RNP (Required Navigation Performance) specifications for UAVs [40], the use of UAVs in the operation of the Galileo OS positioning service [41], the use of UAVs equipped with a Galileo receiver to measure and test mobile networks [42], the use of UAVs equipped with a Galileo receiver to collect data on electricity distribution networks [43].

On the basis of the literature reviewed, and the state-of-the-art analysis carried out; it can be concluded that:

- the problem of determining the accuracy parameter is important for Galileo to meet ICAO certification requirements,

- the accuracy of Galileo kinematic positioning was mainly determined using code observations on E1 or E5 frequencies,
- the number of flight tests and flight trials performed was not very extensive from the point of view of Galileo kinematic positioning,
- Galileo will be used in aviation to improve the quality of GNSS positioning and the implementation of approach and landing procedures,
- an important element of research is the interoperability and compatibility of Galileo with other global GNSS systems,
- in-flight research using Galileo should be developed for both aircraft and UAVs.

3. RESEARCH PROBLEM

As the state-of-the-art analysis has shown, more ongoing research is needed on the application and implementation of the Galileo navigation system in precision GNSS positioning for aeronautical applications. This concerns both the kinematic positioning aspect of Galileo for aircraft and unmanned aircraft. Hence, it is necessary to first carry out experimental flight tests using the Galileo solution, then use appropriate software to develop Galileo kinematic observations, then select a suitable computational strategy, and finally determine the user position. The user position coordinates obtained will further allow the determination of the Galileo kinematic positioning accuracy, which is crucial from the point of view of the certification of the Galileo system according to ICAO standards. Without further flight tests, it will be difficult to estimate the acceptable tolerance level of accuracy according to ICAO requirements.

Thus, this paper proposes the implementation and validation of two computational strategies for determining the accuracy of Galileo's kinematic positioning. Namely, on the one hand, a least-squares method algorithm was used and, on the other hand, Kalman filtering was used to determine user coordinates using SPP (Single Point Positioning) [44]. Coordinate calculations were carried out in RTKLIB and Emlid Studio software. The determined coordinates were compared with the reference trajectory of the flight calculated using the PPK (Post Processing Kinematic) method, which allowed an accuracy analysis to be carried out. At this stage, position errors and mean squared errors were calculated as accuracy measures. Accuracy measures were determined for the calculated coordinates from the two calculation strategies. This will make it possible to determine which computational strategy is better for Galileo kinematic positioning in aeronautical applications.

The article is structured into 6 main sections (1. Introduction, 2. Related works, 3. Research problem, 4. Research method and materials, 5. Research results and discussion, 6. Conclusions), and a literature list is added at the end.

4. RESEARCH METHOD AND MATERIALS

The research methodology was divided into several main stages, i.e.:

- Stage I concerns the execution of the test flight, recording Galileo navigation and observation data with a given time interval,
- Stage II concerns the processing of Galileo kinematic observations in a given software using a given computational strategy,

- Stage III concerns the determination of the accuracy parameter in the form of position errors and mean squared errors.

Figure 1 shows a block diagram for the presented test methodology.

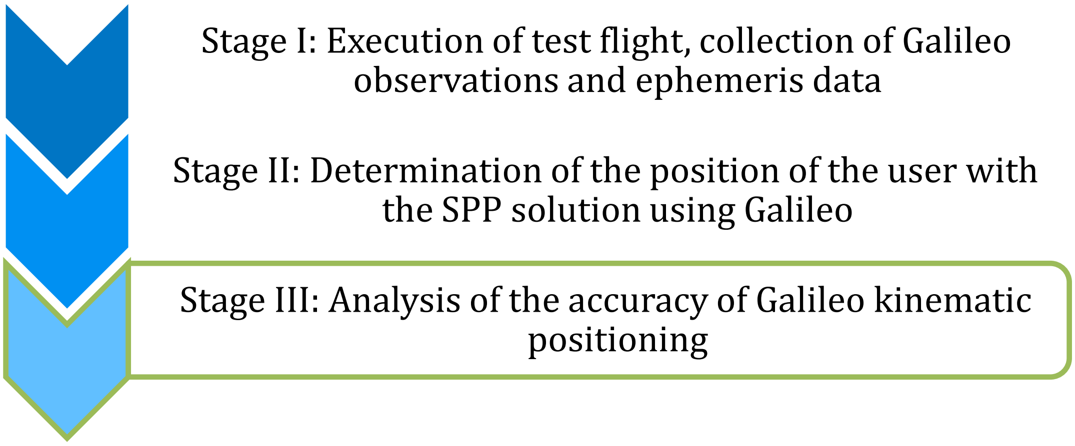

Fig. 1. The flowchart of research method

In Stage I of the research methodology, the most important element was the execution of the aerial experiment. For this purpose, the DJI Matrice RTK300 unmanned platform [45] was used, which has a built-in GNSS receiver with the option to track and record Galileo observations and ephemeris data. As part of the experimental study, 2 test flights were carried out in Olsztyn in October 2021 and March 2022, respectively. The first flight lasted more than 20 minutes, while the second flight lasted about 15 minutes, respectively. Figures 2 and 3 show the horizontal and vertical trajectory of the UAV flight during experiment 1. During the flight performed, the B-coordinate of the UAV varied from 53.7465150° to 53.7532620°, while the L-coordinate varied from 20.4530280° to 20.4622110°. The ellipsoidal altitude of the UAV flight ranged from 138,275 m to 277,166 m. In addition, Figure 4 shows the number of Galileo satellites tracked during the flight. The number of satellites ranged from 6 to 8 during flight 1. In turn, Figures 5 and 6 show the horizontal and vertical trajectory of the UAV flight during experiment 2. During this flight, the B coordinate of the UAV ranged from 53.7498530° to 53.7516180°. The L coordinate reached values from 20.4502370° to 20.4623430°. The ellipsoidal altitude of the UAV flight ranged from 246.155 m to 288.416 m. Additionally, Figure 7 shows the number of Galileo satellites tracked during this flight. The number of satellites ranged from 5 to 6 during flight 2. It can be deduced that during flight 1, the GNSS receiver on the unmanned platform tracked more Galileo satellites than during flight 2.

In Stage II of the research methodology, the recorded observations and Galileo ephemeris data were processed in RTKLIB v.2.4.3 [46] and Emlid Studio v.1.7 [47] software. For this purpose, the SPP code method algorithm was used to determine the UAV coordinates. In RTKLIB, a computational strategy based on the least squares method algorithm [48] is used to determine the coordinates, while in Emlid Studio, respectively, we have a Kalman filter implemented [49]. In both programs, the resulting coordinates of the user's position are stored using BLh ellipsoidal coordinates. The scheme of the applied computational strategies in both programs is shown in Table 1.

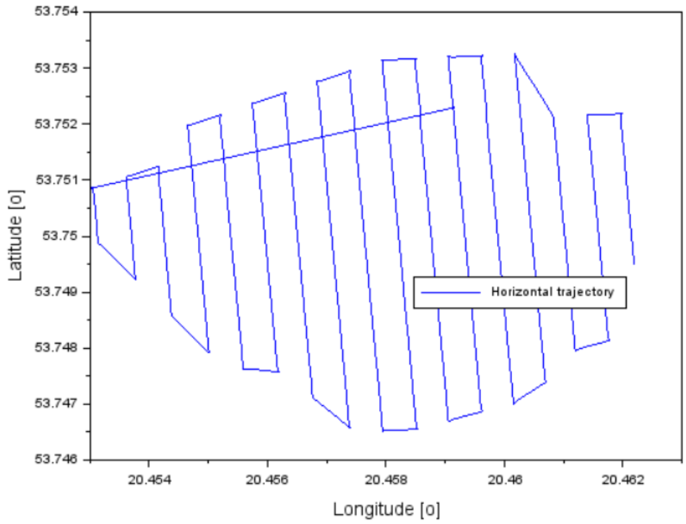

Fig. 2. The horizontal trajectory during flight test 1

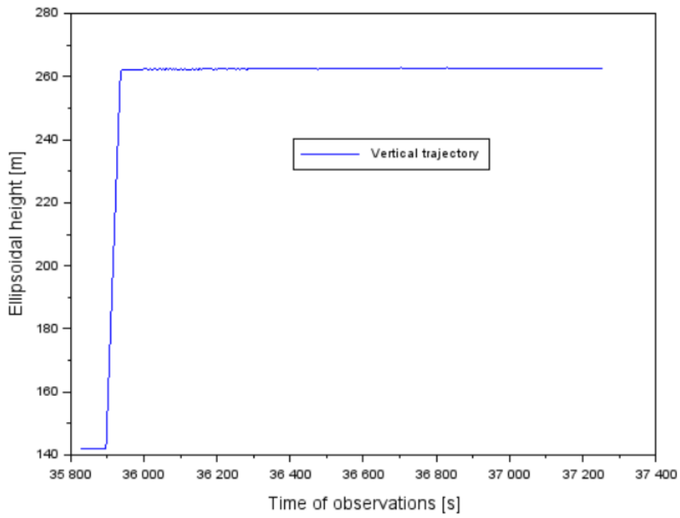

Fig. 3. The vertical trajectory during flight test 1

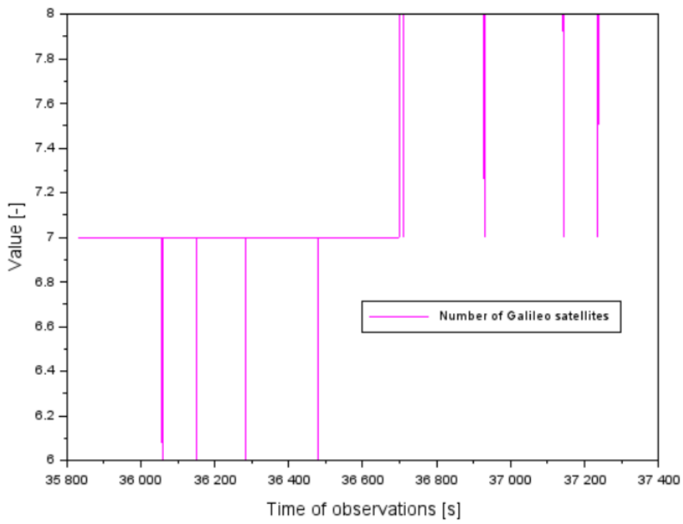

Fig. 4. Number of Galileo satellites during flight test 1

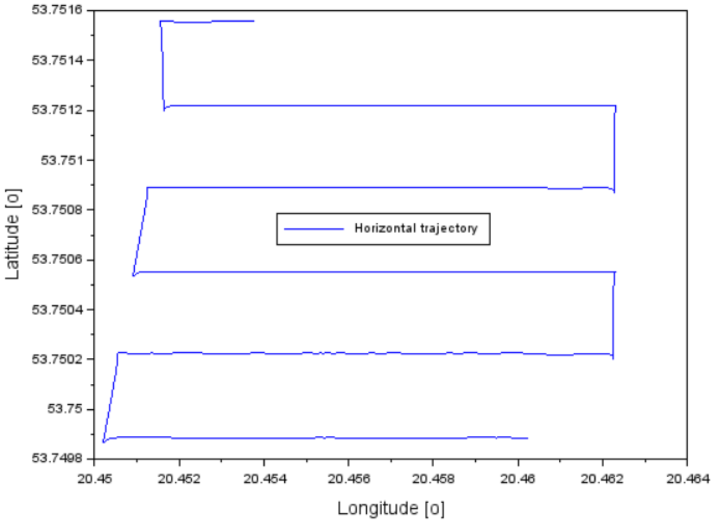

Fig. 5. The horizontal trajectory during flight test 2

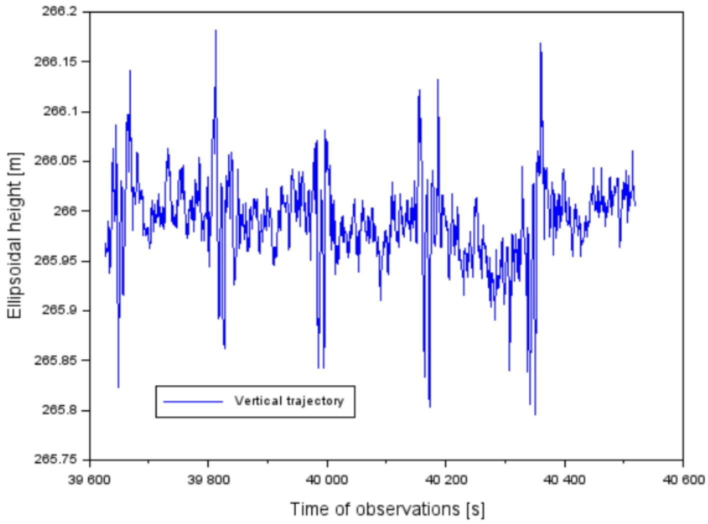

Fig. 6. The vertical trajectory during flight test 2

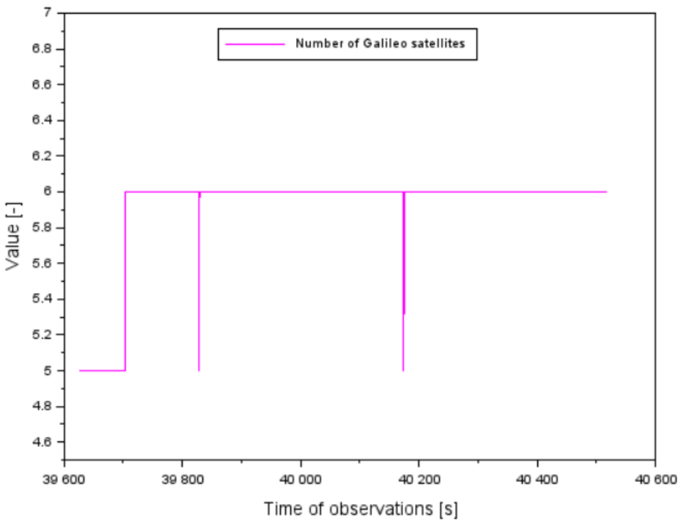

Fig. 7. Number of Galileo satellites during flight test 2

Tab. 1
The comparison of computing strategies in RTKLIB and Emlid Studio software

Parameter	RTKLIB software	Emlid Studio software
Positioning mode	SPP method	SPP method
Source of broadcast data	Galileo navigation message	Galileo navigation message
Source of observation data	Galileo code observations on E1 frequency	Galileo code observations on E1 frequency
Cut-off elevation	5^0	5^0
Model of orbit	Based on Galileo navigation message	Based on Galileo navigation message
Model of satellite bias correction	Based on Galileo navigation message	Based on Galileo navigation message
Model of ionosphere correction	Based on Galileo navigation message	Based on Galileo navigation message
Model of troposphere correction	Saastamoinen model	Saastamoinen model
Interval of computation	1 s	1 s
Computing strategy	Least Square estimation	Kalman filter
Output coordinates	Ellipsoidal coordinates BLh (B-Latitude, L- Longitude, h-ellipsoidal height)	Ellipsoidal coordinates BLh (B-Latitude, L- Longitude, h-ellipsoidal height)
GNSS system	Galileo	Galileo

Stage III of the research methodology involved an analysis of the accuracy of the computed UAV coordinates. For this purpose, position errors were first calculated for BLh ellipsoidal coordinates as [50]:

$$\begin{bmatrix} dB \\ dL \\ dh \end{bmatrix} = \begin{bmatrix} B - B_{ref} \\ L - L_{ref} \\ h - h_{ref} \end{bmatrix} \quad (1)$$

where:
(dB, dL, dh) – position errors,
(B, L, h) – UAV coordinates determined from the Galileo SPP solution in the RTKLIB and Emlid Studio applications,
$(B_{ref}, L_{ref}, h_{ref})$ – flight reference position calculated in Topcon MAGNET Tools v.6.1.2.0 software [51].

Root mean square (RMS) errors were then calculated as [52]:

$$\begin{cases} RMS_{dB} = \sqrt{\frac{[dB^2]}{N}} \\ RMS_{dL} = \sqrt{\frac{[dL^2]}{N}} \\ RMS_{dh} = \sqrt{\frac{[dh^2]}{N}} \end{cases} \tag{2}$$

where:
RMS_{dB}– RMS error to determine the accuracy of the determination of the B coordinate,
RMS_{dL}– RMS error to determine the accuracy of the determination of the L coordinate,
RMS_{dh}– RMS error to determine the accuracy of the determination of the h coordinate,
N – number of measurement epochs.

Stage III is carried out in the Scilab v.6.1.1 environment [53], in which a numerical script with computational commands was developed and written to carry out the accuracy analysis. In addition, graphical function commands were developed and written in the script to create Figures 2-13.

5. RESEARCH RESULTS AND DISCUSSION

Section 5 presents an analysis of the Galileo kinematic positioning accuracy for the UAV platform and a discussion on the results. Figures 8 and 9 show the position errors for the B-coordinate during flight 1 and flight 2. In flight 1, the position errors from the RTKLIB solution ranged from -5.7 m to 10.8 m, while those from Emlid Studio ranged from 0.4 m to 1.9 m, respectively. In flight 2, position errors from the RTKLIB solution ranged from -8.4 m to 9.2 m, while in Emlid Studio they ranged from -1.4 m to 4.7 m, respectively. From the RTKLIB solution, frequent spikes in position error values can be seen due to the changing number of Galileo satellites being tracked. The results from Emlid Studio, on the other hand, are smoothed by applying Kalman filtering. In addition, the Klaman filtering suppressed the random errors present in the RTKLIB solution quite significantly.

Figures 10 and 11 show the results of the position errors for the L coordinate for both flights. In flight 1, the position errors from the RTKLIB solution ranged from -2.3 m to 5.1 m, while in Emlid Studio they ranged from 0.7 m to 1.5 m, respectively. In flight 2, position errors from the RTKLIB solution ranged from -0.6 m to 3.2 m, while in Emlid Studio they ranged from -4.9 m to 2.6 m, respectively. It is worth noting on the example of flight 2 and the Emlid Studio solution that the low number of Galileo satellites results in a deterioration of kinematic positioning accuracy. In addition, sudden changes in the number of Galileo satellites tracked can also result in degradation of kinematic positioning accuracy (see measurement epochs: 40164 s to 40166 s).

Figures 12 and 13 visualize the position errors obtained for the h coordinate during flights 1 and 2. In flight 1, the position errors from the RTKLIB solution ranged from -12.8 m to 14.8 m, while in Emlid Studio they ranged from -4.1 m to -0.4 m, respectively. In flight 2, position errors from the RTKLIB solution ranged from -19.8 m to 22.4 m, while in Emlid Studio they ranged from -9.3 m to 7.3 m, respectively. Out of all coordinates, the worst positioning accuracy occurred for the ellipsoidal height h. As with the horizontal B and L coordinates, the accuracy of the vertical component h is affected by the number of Galileo satellites being tracked. It is worth noting that the particularly low accuracy of the determination of the vertical coordinate h is evident from the RTKLIB solution, which is based on the use of the least squares method algorithm in the stochastic process of processing Galileo observations. To summarize the position error results obtained, the adoption of an appropriate computational strategy quite significantly affects the accuracy of Galileo kinematic positioning for the UAV platform. In addition, the changing number of Galileo satellites being tracked also affects the estimation of the accuracy parameter.

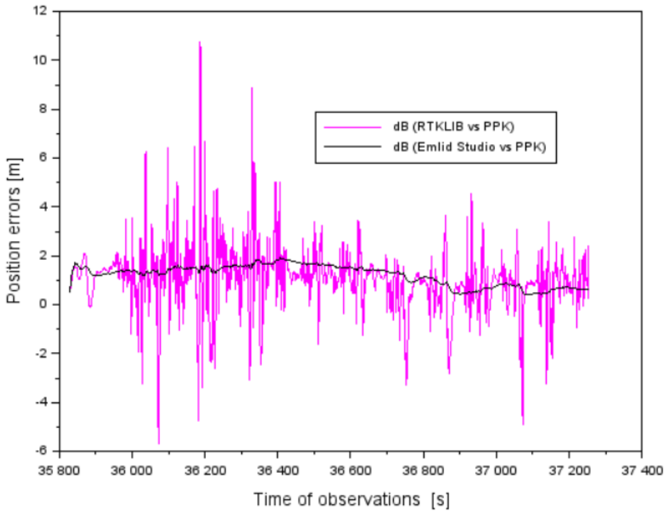

Fig. 8. Position errors of B coordinate during flight test 1

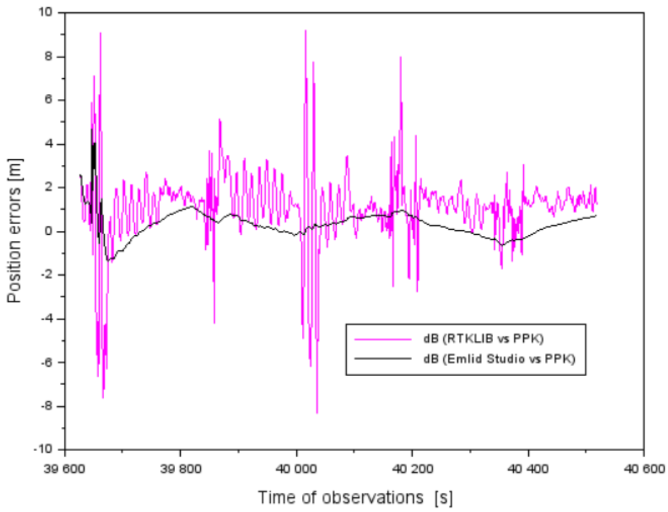

Fig. 9. Position errors of B coordinate during flight test 2

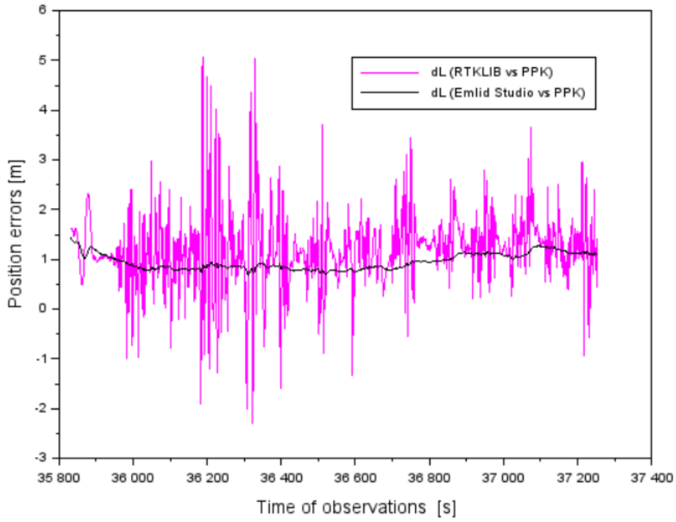

Fig. 10. Position errors of L coordinate during flight test 1

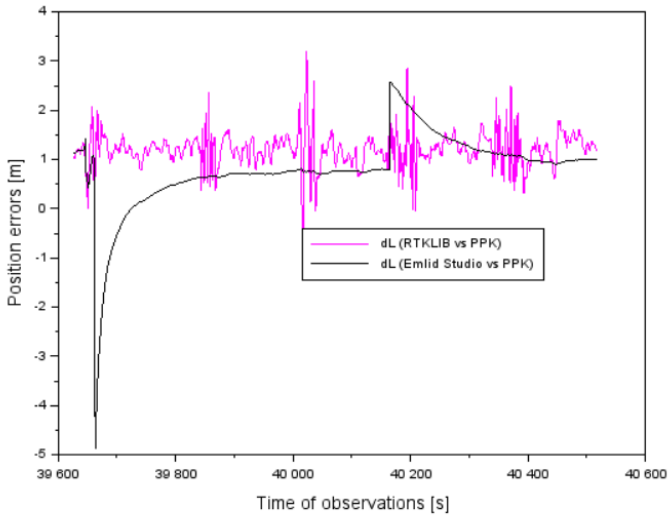

Fig. 11. Position errors of L coordinate during flight test 2

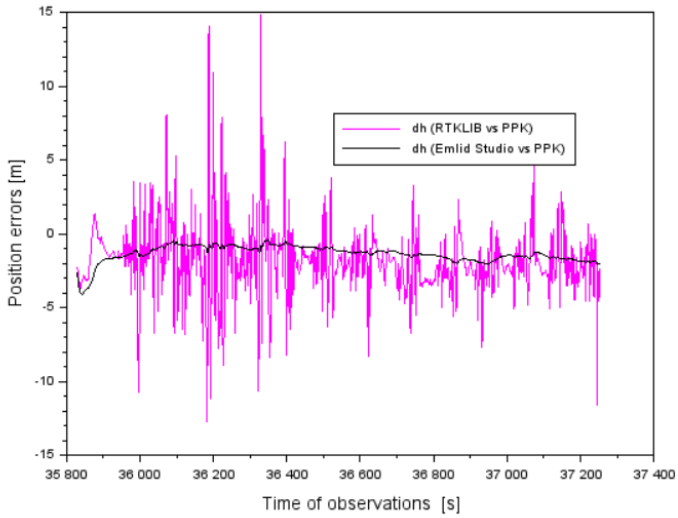

Fig. 12. Position errors of h coordinate during flight test 1

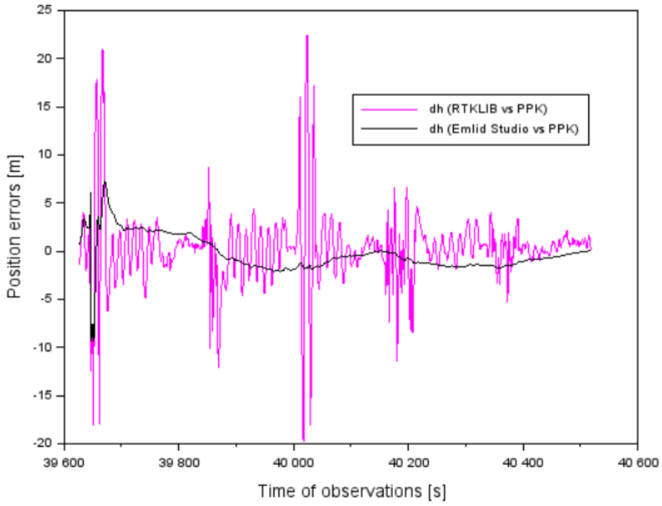

Fig. 13. Position errors of h coordinate during flight test 2

The second part of the discussion of the test results obtained concerns the comparison of the RMS errors. Table 2 summaries the calculated RMS errors for all BLh coordinates for both tests. Thus, the RMS errors from the RTKLIB solution ranged from 1.3 m to 4.1 m for all BLh components for both tests. Correspondingly, from the Emlid Studio solution, they ranged from 0.7 m to 1.8 m. Successively for the individual BLh coordinates, higher Galileo positioning accuracy was obtained from the Emlid Studio solution compared to RTKLIB by respectively:

- 28% to 65% for the B coordinate,
- 15% to 29% for the L coordinate,
- 50% to 56% for the h coordinate.

Thus, the effectiveness of the Emlid Studio solution was confirmed for Galileo kinematic positioning.

Tab. 2

The comparison of obtained RMS errors

RMS Parameter	Flight no. 1	Flight no. 2
RMS_{dB}	1.8 m for RTKLIB solution, 1.3 m for Emlid Studio solution	2.0 m for RTKLIB solution, 0.7 m for Emlid Studio solution
RMS_{dL}	1.4 m for RTKLIB solution, 1.0 m for Emlid Studio solution	1.3 m for RTKLIB solution, 1.1 m for Emlid Studio solution
RMS_{dh}	3.0 m for RTKLIB solution, 1.5 m for Emlid Studio solution	4.1 m for RTKLIB solution, 1.8 m for Emlid Studio solution

The final research topic of section 5 concerns the comparison of the obtained research results in relation to the analysis of the state of the art and the published scientific literature. Comparing the results of Galileo kinematic positioning accuracy with the literature on the subject, it can be said that:

- the study used Galileo code observations at E1 frequency similarly to the articles [18-21, 27-28],

- the research used a UAV platform similarly to the articles [39-43],
- higher or similar positioning accuracy was obtained in the calculations as in papers [16, 18-21],
- the study demonstrated and applied the SPP code positioning algorithm similarly to the papers [18-21].

6. CONCLUSIONS

This paper shows the results of a study on determining the accuracy of Galileo kinematic positioning. Accuracy as one of the four quality parameters of GNSS satellite positioning is crucial for horizontal and vertical navigation. Hence, flight tests as well as the study and analysis of this parameter according to ICAO requirements for the Galileo navigation system are necessary. This paper presents two main computational strategies for determining accuracy. Namely, the first used RTKLIB and the least squares method to determine position coordinates. The second, on the other hand, used Klaman filtering in Emlid Studio. Galileo navigation and code observation data acquired from a DJI Matrice RTK300 unmanned platform were used in the calculations. The resulting coordinates from both solutions were compared with the reference trajectory of the flight so that the Galileo positioning accuracy could be determined. In the accuracy analysis, the position errors and RMS errors were determined. The RMS errors of the RTKLIB solution ranged from 1.3 m to 4.1 m, while those of the Emlid Studio solution ranged from 0.7 m to 1.8 m. In addition, the study shows that Emlid Studio improves Galileo's kinematic positioning accuracy by 15 to 65% over the results obtained with the RTKLIB solution. Further flight tests are planned in the near future, in which the accuracy parameter for the Galileo navigation system will be further investigated.

References

1. Grzegorzewski M., W. Jaruszewski, A. Fellner, S. Oszczak, A. Wasilewski, Z. Rzepecka, J. Kapcia, T. Popławski. 1999. “Preliminary results of DGPS/DGLONASS aircraft positioning in flight approaches and landings”. *Annual of Navigation* 1: 41-53.
2. Mrozik M. 2023. „Application of the SBAS positioning method in the aircraft approach procedure”. *PhD thesis.* Silesian University of Technology, Gliwice.
3. International Civil Aviation Organization. 2006. ICAO Standards and Recommended Practices (SARPS), Annex 10, Volume I (Radio Navigation Aids). Available at: http://www.ulc.gov.pl/pl/prawo/prawomi%C4%99dzynarodowe/206-konwencje.
4. GPS Official Website. “GALILEO System Update”. Available at: https://www.gps.gov/cgsic/international/2002/brussels/berkes.pdf.
5. van Dam R.D. 1999. “Legal Panel GNSS and Aviation”. *Proceedings of the 12th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 1999)*. Nashville, TN, September 1999. P. 975-982.
6. Vejrazka F. 2007. “Galileo and the Other Satellite Navigation Systems”. *Proceedings of the 2007 17th International Conference Radioelektronika*, Brno, Czech Republic, 2007. P. 1-4. DOI: 10.1109/RADIOELEK.2007.371446.
7. ESA Website. “Galileo to augment systems guiding aircraft in 2020”. Available at: https://www.esa.int/Applications/Navigation/Galileo_to_augment_systems_guiding_aircraft_in_2020.

8. EGNOS User Support Website. "New achievement for Galileo and civil aviation". Available at: https://egnos-user-support.essp-sas.eu/news-events/news/new-achievement-galileo-and-civil-aviation.
9. Collins Aerospace Website. "Multi-Mode Global Positioning System and Galileo (MUGG) Project". Available at: https://www.collinsaerospace.com/what-we-do/industries/commercial-aviation/flight-deck/navigation-and-guidance/gps-devices/glu-2100/multi-mode-global-positioning-system-and-galileo-mugg-project.
10. Murcia J., L. Chocano, P. Haro, R. Farnworth, H. de With. 2010. "Operational Implementation of EGNOS and LPV Approaches in Aviation in Europe". *Proceedings of the 23rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2010).* Portland, OR, September 2010. P. 1440-1448.
11. Bitter M., T. Feuerle, B. von Wulfen, M. Steen, P. Hecker. 2010. "Testbed for dual-constellation GBAS concepts". *Proceedings of the IEEE/ION Position, Location and Navigation Symposium.* Indian Wells, CA, USA, 2010. P. 680-687. DOI: 10.1109/PLANS.2010.5507220.
12. Di Girolamo S., F. Luongo, M. Marinelli, A. Zin, L. Scaciga, L. Rocco, L. Campa, L. Marradi. 2008. "Galileo Test User Segment design and performances related to aeronautical safety of life applications". *Proceedings of the 2008 Tyrrhenian International Workshop on Digital Communications - Enhanced Surveillance of Aircraft and Vehicles.* Capri, 2008. P. 1-6. DOI: 10.1109/TIWDC.2008.4649024.
13. Frisk G. 2000. "A ground based augmentation service for gate-to-gate operations". *Proceedings of the IEEE 2000. Position Location and Navigation Symposium (Cat. No.00CH37062).* San Diego, CA, USA, 2000. P. 527-534. DOI: 10.1109/PLANS.2000.838349.
14. Song J., C. Milner. 2023. "Assessment of Number of Critical Satellites for Ground-Based Augmentation System Continuity Allocation to Support Category II/III Precision Approaches". *Sensors* 23: 8273. DOI: 10.3390/s23198273.
15. NLR Webiste. "Worlds first: Galileo's first aerial fix of aircraft during flight". Available at: https://www.nlr.org/news/worlds-first-galileos-first-aerial-fix-of-aircraft-during-flight/.
16. Hu T., G. Zhang, L. Zhong. 2023. "Software Design for Airborne GNSS Air Service Performance Evaluation under Ionospheric Scintillation". *Electronics* 12: 3713. DOI: 10.3390/electronics12173713.
17. Ilyin V., I. Kopylov, E. Kharin, V. Kopelovich, A. Yakushev, P. Zhabin. 2022. "Flight Tests of Onboard SNS Equipment Characteristics During Operation with Different Global Navigation Satellite Systems". *Proceedings of the 2022 29th Saint Petersburg International Conference on Integrated Navigation Systems (ICINS).* Saint Petersburg, Russian Federation, 2022. P. 1-5. DOI: 10.23919/ICINS51784.2022.9815371.
18. Magalhãe A., J. A. Gonçalves, L. Bastos. 2021. "Assessing Galileo Positioning Using a Smartphone in an Airborne Platform". *WiP Proceedings of the International Conference on Localization and GNSS (ICL-GNSS 2021).* Tampere, Finland, June 1-3, 2021. P. 1-10.
19. Gonçalves J. A., A. Magalhãe, L. Bastos. 2021. "Galileo Performance Assessment for Aerial Navigation". *WiP Proceedings of the International Conference on Localization and GNSS (ICL-GNSS 2021)*. Tampere, Finland, June 1-3, 2021. P. 1-9.
20. Bastos L., P. Buist, R. Cefalo, J. A. Goncalves, A. Ivan, A. Magalhaes, A. Pandele, M. Porretta, A. Radutu, T. Sluga, P. Snider. 2022. "Kinematic Galileo and GPS Performances in Aerial, Terrestrial, and Maritime Environments". *Remote Sensing* 14: 3414. DOI: 10.3390/rs14143414.

21. Elmezayen A., M. Karaim, H. Elghamrawy, A. Noureldin. 2023. "Enhanced GNSS Reliability on High-Dynamic Platforms: A Comparative Study of Multi-Frequency, Multi-Constellation Signals in Jamming Environments". *Sensors* 23: 9552. DOI: 10.3390/s23239552.
22. Muhammad B., E. Cianca, A. M. Salonico. 2014. "Multi GNSS Advanced RAIM: An availability analysis". *Proceedings of the 2014 IEEE Metrology for Aerospace (MetroAeroSpace).* Benevento, Italy, 2014. P. 28-33. DOI: 10.1109/MetroAeroSpace.2014.6865889.
23. Oehler V., G.W. Hein, B. Eissfeller, B. Ott. 2000. "GNSS-2/Galileo End-to-End Simulations for Aviation, Urban and Maritime Applications". *Proceedings of the IAIN World Congress and the 56th Annual Meeting of The Institute of Navigation (2000).* San Diego, CA, June 2000. P. 461-468.
24. Paternostro S., T. Moore, C. Hill, J. Atkin, H.P. Morvan. 2016. "Evaluation of Advanced Receiver Autonomous Integrity Monitoring Performance on Predicted Aircraft Trajectories". *Proceedings of the IEEE/ION PLANS 2016.* Savannah, GA, April 2016. P. 842-856.
25. Joerger M., B. Pervan. 2014. "Solution separation and Chi-Squared ARAIM for fault detection and exclusion". *Proceedings of the 2014 IEEE/ION Position, Location and Navigation Symposium - PLANS 2014.* Monterey, CA, USA, 2014. P. 294-307. DOI: 10.1109/PLANS.2014.6851388.
26. Ober P.B., D. Harriman. 2006. "On the use of Multiconstellation-RAIM for Aircraft Approaches". *Proceedings of the 19th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2006)*. Fort Worth, TX, September 2006. P. 2587-2596.
27. Julien O., Jean-Luc I., Lionel R. 2011. "Investigation of Galileo E1 OS/SoL Acquisition, Tracking and Data Demodulation Thresholds for Civil Aviation". *Proceedings of the 24th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2011).* Portland, OR, September 2011. P. 1264-1276.
28. Novella G., Garcia-Pena A. J., C. Macabiau, A. Martineau, P. Ladoux, P. Estival, O. Troubet-Lacoste. 2022. "GNSS Acquisition Thresholds for Civil Aviation GNSS Receivers". *Proceedings of the 35th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2022)*. Denver, Colorado, September 2022. P. 166-191. DOI: 10.33012/2022.18357.
29. Blais A. 2014. „Feasibility of a Direct Sampling Dual-Frequency SDR Galileo Receiver for Civil Aviation|". *PhD thesis*. INP Touluse.
30. Garcia-Pena A., O. Julien. 2016. "Data Integrity for GPS and Galileo Signals used by Civil Aviation". *Proceedings of the 29th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2016)*. Portland, Oregon, September 2016. P. 2826-2838. DOI: 10.33012/2016.14572.
31. Fyfe P., K. Davis, I. Jeng, C. Kelley, C. Mosley. 2002. "GPS and Galileo - Interoperability for Civil Aviation Applications". *Proceedings of the 15th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 2002)*. Portland, OR, September 2002. P. 289-302.
32. Bastide F., B. Roturier, O. Julien, C. Macabiau, E. Rebeyrol, M. Raimondi, C. Ouzeau, D. Kubrak. 2006. "Civil Aviation GALILEO E5 receivers architecture". *Proceedings of the 1st Workshop on GALILEO Signals and Signal Processing*. October 2006, Toulouse, France. P. 1-11.

33. Schuster A.B., R. Jeans, E. Chatre, G. Alcouffe. 2003. "Aviation Applications for Galileo". *Proceedings of the 16th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS/GNSS 2003).* Portland, OR, September 2003. P. 849-856.
34. Bastide F. 2004. "Galileo E5a/E5b and GPS L5 Acquisition Time Statistical Characterization and Application to Civil Aviation". *Proceedings of the 17th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2004).* Long Beach, CA, September 2004. P. 2623-2635.
35. Garcia-Pena A., C. Macabiau, O. Julien, M. Mabilleau, P. 2020. "IGNSS Computation Models and Values for GPS and GALILEO L5/E5a Civil Aviation Receivers". *Proceedings of the 33rd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2020).* September 2020. P. 206-218. DOI: 10.33012/2020.17571.
36. De Angelis M., R. Fantacci, S. Menci, C. Rinaldi. 2005. "Analysis of air traffic control systems interference impact on Galileo aeronautics receivers". *Proceedings of the IEEE International Radar Conference, 2005.* Arlington, VA, USA, 2005. P. 585-595. DOI: 10.1109/RADAR.2005.1435897.
37. Cinar T., F. Ince. 2005. "Contribution of GALILEO to search and rescue". *Proceedings of 2nd International Conference on Recent Advances in Space Technologies, 2005. RAST 2005*, Istanbul, Turkey, 2005. P. 254-259. DOI: 10.1109/RAST.2005.1512572.
38. Alegre-Godoy R., I. Stojkovic. 2014. "Improving the availability of the SAR/Galileo return link service via network coding". *Proceedings of the 2014 7th ESA Workshop on Satellite Navigation Technologies and European Workshop on GNSS Signals and Signal Processing (NAVITEC).* Noordwijk, Netherlands, 2014. P. 1-6. DOI: 10.1109/NAVITEC.2014.7045149.
39. Causa F., M. Asciolla, R. Opromolla, P. Molina, A. Mennella, M. Nisi, G. Fasano. 2022. "UAV-based LiDAR Mapping with Galileo-GPS PPP Processing and Cooperative Navigation". *Proceedings of the 2022 International Conference on Unmanned Aircraft Systems (ICUAS)*. Dubrovnik, Croatia, 2022. P. 938-947. DOI: 10.1109/ICUAS54217.2022.9836183.
40. Haro P., C. Aguilera, G. Lucchi. 2023. "Required Navigation Performances for Drone Flight Operations". *Engineering Proceedings* 54: 51. DOI: 10.3390/ENC2023-15459.
41. Damy S., L. Cucchi, A. Mennella, G. Luisi, M. Paonni, I. Fernandez-Hernandez. 2023. "Increasing the Robustness of Drone Operations with Galileo Open Service Navigation Message Authentication (OSNMA)". *Proceedings of the 2023 International Conference on Localization and GNSS (ICL-GNSS).* Castellón, Spain, 2023. P. 1-6. DOI: 10.1109/ICL-GNSS57829.2023.10148917.
42. Buggiani V., J.C.Ú. Ortega, G. Silva, J. Rodríguez-Molina, D. Vilca. 2023. "An Inexpensive Unmanned Aerial Vehicle-Based Tool for Mobile Network Output Analysis and Visualization". *Sensors* 23: 1285. DOI: 10.3390/s23031285.
43. Fasano G., F. Causa, R. Opromolla, M. Asciolla, M. Nisi, L. Pozzoli, M. Lisi, A. Mennella, G. Gagliarde, G. Luisi, P. Molina, M. Blazquez, I. Colomina, P. Cabrera, G. Rodriguez, R. Poggi, L. Lisi, G. Fagioli, R. Muscinelli. "AMPERE: exploiting Galileo for electrical asset mapping in emerging countries". *Proceedings of the 2021 IEEE 8th International Workshop on Metrology for AeroSpace (MetroAeroSpace).* Naples, Italy, 2021. P. 709-714. DOI: 10.1109/MetroAeroSpace51421.2021.9511736.

44. Robustelli U., G. Pugliano. 2019. "Galileo Single Point Positioning Assessment Including FOC Satellites in Eccentric Orbits". *Remote Sensing* 11: 1555. DOI: 10.3390/rs11131555.
45. DJI Enterprise Webiste. "Matrice 300 RTK". Available at: https://enterprise.dji.com/matrice-300.
46. RTKLIB website. Available at: https://www.rtklib.com/.
47. Emlid Website. Available at: https://emlid.com/emlid-studio/.
48. Takasu T., "RTKLIB ver. 2.4.2 Manual, RTKLIB: An Open Source Program. Package for GNSS Positioning". Available online: http://www.rtklib.com/prog/manual_2.4.2.pdf.
49. Kaniewski P., R. Gil, S. Konatowski. 2016. "Algorithms of position and velocity estimation in GPS receivers". *Annual of Navigation* 23: 53-68. DOI: 10.1515/aon-2016-0004.
50. Grzegorzewski M. 2005. "Navigating an aircraft by means of a position potential in three dimensional space". *Annual of Navigation* 9: 1-111.
51. Topcon Website. Available at: https://mytopcon.topconpositioning.com/support/products/magnet-tools.
52. Specht C., J. Pawelski, L. Smolarek, M. Specht, P. Dabrowski. 2019. "Assessment of the Positioning Accuracy of DGPS and EGNOS Systems in the Bay of Gdansk using Maritime Dynamic Measurements". *Journal of Navigation* 72(3): 575-587. DOI: 10.1017/S0373463318000838.
53. Scilab Website. Available at: https://www.scilab.org.

Received 08.01.2025; accepted in revised form 30.03.2025