

Navigating the Skies of Tomorrow: Integrating Advanced Technologies for a Safer, Efficient, and Sustainable Air Traffic System

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The air navigation environment is undergoing a profound transformation driven by technological advances and increasing demands for safety, efficiency, and environmental sustainability. As the aviation industry prepares to handle unprecedented growth in air traffic, innovative solutions are being developed to break current limitations and shape the future of air navigation.

A fundamental shift in communication protocols is one of the primary pointers to change. The transition from traditional voice communications to digital modes, such as Controller-Pilot Data Link Communications (CPDLC) and more efficient use of the well-known Aircraft Communications Addressing and Reporting System (ACARS), is improving communication clarity and operational efficiency. Text-based messages reduce misunderstandings, enhance crew situational awareness, and speed up communication with air traffic control (ATC), thus improving overall flight safety.

The second major breakthrough is the increasing reliance on satellite-based navigation systems like the Global Navigation Satellite System (GNSS) (Oliveira *et al.* 2023; Rodrigues *et al.* 2022). The synergy between inertial and satellite-based positioning – with more and more emphasis on satellite-derived information – results in better accuracy and reliability in aircraft location information. The estimation of conservative errors based on satellite geometry and the quality and precision of signal measurements ensures that navigation performance meets the required specifications for optimal airspace utilization, while providing flight crews with timely alerts in case of deviations.

The response to automatic dependent surveillance – contract (ADS-C) adds further to situational awareness through the automatic reception of position reports by ATC based on pre-contracted agreements (Lüscher *et al.* 2024). This enables proactive surveillance of lateral deviation and maximizes the utilization of airspace, particularly over oceanic and sparsely covered areas where radar is limited.

Artificial intelligence (AI) is also playing a revolutionary role in air navigation development (Abdillah *et al.* 2024; Sadou and Njoya 2023). By analyzing vast amounts of flight data, AI systems can deliver significant benefits across various phases of flight operation. In real-time contexts, AI-driven algorithms can predict and prevent potential conflicts, reducing the workload of pilots

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and controllers, and support decision-making during flight-critical phases. In post-operational analysis, AI assists in identifying patterns and cause-effect relationships, which contributes to more effective airspace design, better anticipation of events, and more efficient implementation and doctrine of air traffic flow management (ATFM) measures (Degas *et al.* 2022; Taylor *et al.* 2024).

One of the most promising developments in navigation resilience is the advancement of Ground-Based Augmentation Systems (GBAS) with multi-constellation capability (Marini-Pereira *et al.* 2021). The use of constellations such as Galileo and others from the GNSS family, in addition to the traditional GPS, enables the conservative identification and rejection – or mitigation – of signals potentially affected by ionospheric anomalies. Also, the simultaneous two-frequency implementation of GBAS, using GPS L5 and Galileo E5 with GPS L1 and Galileo E1, allows ionosphere-free observables to be derived, which, in general, may improve the accuracy as well as the reliability/integrity of positioning. These advantages in GBAS contribute to better performance and safety in navigation, particularly for precision approaches and maneuvering in adverse propagation environments (Sousasantos *et al.* 2021).

Significant advancements in satellite-based air navigation have also been driven by strategic research initiatives in Brazil, such as the National Institute of Science and Technology for GNSS Air Navigation Support (INCT NavAer), established in 2017. With a specific focus on the challenges imposed by the ionosphere in low-latitude regions, the program has supported the development of scientific knowledge and technical capabilities to ensure safer satellite-based air navigation over Brazilian airspace (Monico *et al.* 2022). Over nearly a decade of collaborative efforts, led by major Brazilian research and academic institutions specializing in geodesy, space weather, aeronautics, and aerospace engineering, the initiative expanded ionospheric monitoring networks, promoted statistical characterization of scintillation, and advanced research in GNSS-based navigation techniques.

Despite these achievements, many open issues remain – particularly regarding the modeling of ionospheric threats to augmentation systems, which still demand refinement to effectively support safety-critical applications. At the same time, the growing reliance of aviation on GNSS has introduced additional vulnerabilities, notably spoofing attacks – intentional broadcasts of fake satellite signals – and operation in GNSS-denied environments, where satellite signals are degraded or unavailable. These threats are growing in relevance due to the aviation sector's increasing dependence on satellite positioning and the broader availability of spoofing devices. The consequences are significant, compromising position integrity and flight safety during critical operations, and disrupting broader airline safety systems (Kauranen 2024; Khalil 2024). The aviation industry's growing reliance on GNSS has heightened concerns over vulnerabilities such as spoofing and GNSS-denied environments. Recent incidents underscore the prevalence of these threats. In Eastern Finland, airports have reinstated radio navigation systems to counteract suspected Russian GPS interference, which has led to flight diversions and operational challenges (Kauranen 2024). Similarly, pilots operating in the Middle East and Eastern Europe have reported navigation anomalies attributed to spoofing, raising concerns about flight safety (Khalil 2024).

To mitigate these challenges, research and innovation are focusing on enhancing the resilience of navigation systems. Promising strategies include the integration of inertial sensors, which provide continuity during GNSS outages (Inside GNSS 2024), GNSS signal authentication mechanisms, such as Galileo's Open Service Navigation Message Authentication (OSNMA) (Anderson *et al.* 2024; Galan *et al.* 2024), and AI algorithms capable of detecting anomalous signal patterns in real time (AlAbidy *et al.* 2024). Additionally, cooperative navigation architectures, which leverage data sharing between multiple platforms, are emerging as a novel strategy to enhance navigation robustness and security. These combined efforts aim to ensure the reliability and safety of air navigation in increasingly contested and complex electromagnetic environments.

Building upon this concept, cooperative navigation systems, although still experimental and awaiting further validation and regulatory approval, have the potential to address both current and emerging navigational challenges. Future advancement in navigation reliability could be realized through the Cooperative-Based Augmentation System using Bayesian Filtering, which improves positioning accuracy via cooperative processes among multiple aircraft (Silva *et al.* 2024a; b). Distributed estimation algorithms enable information sharing, enhancing navigation reliability during GPS loss or signal attenuation. Bayesian filtering techniques update position estimates using prior information and new measurements, improving accuracy in challenging environments. The development of such cooperative frameworks represents a promising vision for future navigation strategies, particularly in complex and dynamic airspaces. The use of these marks a significant leap in providing robust navigation capabilities in dense airspaces and adverse weather conditions, strengthening safety, operational efficiency, and enhancing next-generation air mobility solutions and unmanned aerial vehicles (UAVs) by mitigating GPS vulnerabilities.

Finally, sustainability is today a key element in modern air navigation (Pinheiro Melo *et al.* 2020). To achieve this, the aviation industry focuses on several strategies, beginning with the utilization of alternative fuels (sustainable aviation fuels [SAFs]). These fuels offer a promising avenue for reducing environmental impact, as SAFs provide a direct drop-in replacement for traditional kerosene, requiring minimal changes to existing infrastructure and delivering similar performance in terms of energy content and combustion characteristics. In addition to fuels, innovations in materials science have led to the development of composites such as carbon fiber-reinforced polymers, which offer superior strength-to-weight ratios compared to traditional materials like aluminum and steel. As a result, the use of advanced lightweight materials enhances not only fuel efficiency, but also performance and safety (Ranasinghe *et al.* 2019). Moreover, the exploration of electric propulsion technology still faces challenges related to energy density and storage (Tariq *et al.* 2017). Despite these issues, electric propulsion technology stands at the forefront of this sustainability revolution, promising a dramatic reduction in emissions, particularly in domestic and regional flights where most pollution occurs during takeoff and landing phases. Collectively, these innovations are aligned with global initiatives to reduce carbon emissions and with the industry's own vision for cleaner operations.

The future of air navigation lies in the seamless integration of these emerging technologies. As electronic communication, space-based navigation, AI solutions, and cooperative frameworks evolve, they will collectively shape a safer, more efficient and sustainable aviation future. Collective action by industry, government agencies, and academia remains essential to this vision and to ensure safe and efficient aviation globally.

CHALLENGES FOR THE FUTURE

There are several challenges to the future of air navigation, impacting both traditional air traffic management (ATM) and the integration of new technologies like UAVs. These challenges span technological, regulatory, and operational domains, as follows.

Modernization and adaptation

The growing complexity of airspace, driven by the expansion in business aviation and the introduction of next-generation air mobility vehicles such as electric planes and unmanned aircraft systems (UAS) (drones), requires adaptive rulemaking, update infrastructure, and restructuring of air navigation service providers (ANSPs). Additionally, it is imperative to transform ATM systems to facilitate air traffic growth, as testified by initiatives like NextGen in the United States, Single European Sky Air Traffic Management Research (SESAR) in Europe, Collaborative Actions for Renovation of Air Traffic Systems (CARATS) in Japan, and the SIRIUS program in Brazil, which all emphasize performance-based navigation. Furthermore, the integration of AI into navigation systems and ANSP operations is another cornerstone, with applications in route optimization, predictive maintenance, anomaly detection, and unmanned traffic management.

Safety and security

Growing reliance on digital technologies introduces new cyber risks, which must be addressed through effective protection strategies. Integrating UAS into the airspace makes it even more challenging, with new processes and technologies required to enable safe sharing with manned aircraft. Ensuring security in the context of evolving threat scenarios continues to be a top activity for aviation stakeholders.

Signal resilience and innovation

With the prevalence of spoofing attacks and GNSS-denied zones on the increase, and their sophistication as well, developing next-generation signal processing technologies is of foremost importance. This is based on employing cooperative frameworks and AI-driven solutions to strengthen and improve navigation systems. Rao-Blackwellized particle filters (RBPF) (Silva *et al.* 2025) and sensor fusion are among the methods of foremost importance in improving navigation accuracy and the continuity of navigation within hostile or degraded operating environments. Promoting innovation in this field motivates the scientific community to develop strong solutions that can guarantee the future of air navigation.



Financial and operational factors

The aviation industry is faced with the problem of financing, which compromises the ability to invest in modernization programs. Reduced traffic can create resource gaps needed for system upgrades and upkeep. Investments in infrastructure are required for new equipment (capital expenditure [CAPEX]) and skilled personnel (operating expenditure [OPEX]). Furthermore, variations in international policies require greater coordination between countries to harmonize directives and enhance global safety.

Environmental impact

The push for decarbonization is accelerating, with the aviation sector aiming at a significant reduction in carbon emissions by 2050. This necessitates the application of alternative fuels, lightweight materials, and improved routing methods to optimize fuel consumption and minimize environmental effects (Griffiths *et al.* 2024; Timmons and Terwel 2022). These initiatives are in line with the United Nations' Sustainable Development Goals (SDGs) vision, particularly SDG 7 (affordable and clean Energy), SDG 9 (industry, innovation, and infrastructure), and SDG 13 (climate action), in highlighting the industry's role towards a sustainable future. The future of air navigation lies in the harmonious unification of these new technologies and overcoming the challenges that lie in between. As digital communication, satellite navigation, AI-based applications, and cooperative frameworks continue to advance, collectively they will shape a more secure, efficient, and sustainable aviation system. Industry, regulatory, and academic collaborative efforts continue to be fundamental in making this vision a reality and ensuring safe and efficient aircraft movement worldwide.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Moraes AO; **Methodology:** Silva PRP and Monico JFG; **Formal analysis:** Moraes AO and Monico JFG; **Investigation:** Marini-Pereira L, Silva PRP and Moraes AO; **Data Curation:** Marini-Pereira L and Silva PRP; **Writing - Original Draft:** Marini-Pereira L, Silva PRP and Moraes AO; **Supervision:** Moraes AO and Monico JFG; **Project administration:** Moraes AO and Monico JFG; **Final approval:** Marini-Pereira L.

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REFERENCES

- Abdillah RE, Moenaf H, Rasyid LF, Achmad S, Sutoyo R (2024) Implementation of artificial intelligence on air traffic control-a systematic literature review. Paper presented 2024 18th International Conference on Ubiquitous Information Management and Communication IEEE; Kuala Lumpur, Malaysia. <https://doi.org/10.1109/IMCOM60618.2024.10418350>
- AlAbidy A, Zaben A, Abu-Sharkh OM, Noman HA (2024) A survey on AI-based detection methods of GPS spoofing attacks on UAVs. Paper presented 2024 12th International Conference on Intelligent Systems. IEEE; Varna, Bulgaria. <https://doi.org/10.1109/IS61756.2024.10705273>
- Anderson J, Lo S, Walter T (2024). Authentication security of combinatorial watermarking for GNSS signal authentication. *J Navig* 71(3). <https://doi.org/10.33012/navi.655>
- Degas A, Islam MR, Hurter C, Barua S, Rahman H, Poudel M, Ruscio D, Ahmes MU, Begum S, Rahman A, et al. (2022) A survey on artificial intelligence (ai) and explainable ai in air traffic management: current trends and development with future research trajectory. *Appl Sci* 12(3):1295. <https://doi.org/10.3390/app12031295>
- Galan A, Iñiguez C, Fernandez-Hernandez I, Pollin S, Seco-Granados G (2024) OSNMAlib improvements and real-time monitoring of Galileo OSNMA. Paper presented 2024 International Conference on Localization and GNSS. IEEE; Antwerp, Belgium. <https://doi.org/10.1109/ICL-GNSS60721.2024.10578487>
- Griffiths S, Uratani JM, Ríos-Galván A, Andresen JM, Maroto-Valer MM (2024). Green flight paths: a catalyst for net-zero aviation by 2050. *Energy Environ Sci* 17(24):9425-9434. <https://doi.org/10.1039/D4EE02472A>
- Inside GNSS (2024) Hanwha selects advanced navigation in \$6 million deal for GNSS-denied navigation. Inside GNSS. [accessed Apr 11 2025]. <https://insidegnss.com/hanwha-selects-advanced-navigation-in-6-million-deal-for-gnss-denied-navigation/>
- Kauranen A (2024) Three finish airports mitigate Russian GPS interference with radio navigation. Reuters. [accessed Apr 11 2025]. <https://www.reuters.com/business/aerospace-defense/three-finnish-airports-mitigate-russian-gps-interference-with-radio-navigation-2024-11-07/>
- Khalil J (2024) GNSS spoofing threatens airline safety, alarming pilots and aviation officials. GPS World. [accessed Apr 11 2025]. <https://www.gpsworld.com/gnss-spoofing-threatens-airline-safety-alarming-pilots-and-aviation-officials/>
- Lüscher T, Strohmeier M, Lenders V (2024) On the security of satellite-based air traffic control (ADS-C). Paper presented 2024 Workshop on Security of Space and Satellite Systems. Network and Distributed System Security Symposium; San Diego, USA.
- Marini-Pereira L, Pullen S, Moraes ADO, Sousasantos J (2021) Ground-Based Augmentation Systems operation in low latitudes-part 1: challenges, mitigations, and future prospects. *J Aerosp Technol Manag* 13:e4621. <https://doi.org/10.1590/jatm.v13.1236>
- Monico JFG, Paula ERD, Moraes ADO, Costa E, Shimabukuro MH, Alves DBM, Souza JR, Camargo PO, Prol FS, Vani BC, et al. (2022) The GNSS NavAer INCT project overview and main results. *J Aerosp Technol Manag* 14:e0722. <https://doi.org/10.1590/jatm.v14.1249>
- Oliveira D, Moraes A, Junior MC, Marini-Pereira L (2023) Safety analysis of RNP approach procedure using fusion of FRAM model and Bayesian belief network. *J Navig* 76(2-3):286-315. <https://doi.org/10.1017/S0373463323000152>
- Pinheiro Melo S, Barke A, Cerdas F, Thies C, Mennenga M, Spengler TS, Herrmann C (2020) Sustainability assessment and engineering of emerging aircraft technologies – Challenges, methods and tools. *Sustainability* 12(14):5663. <https://doi.org/10.3390/su12145663>



- Ranasinghe K, Guan K, Gardi A, Sabatini RK, Guan K, Gardi A, Sabatini R (2019). Review of advanced low-emission technologies for sustainable aviation. *Energy* 188:115945. <https://doi.org/10.1016/j.energy.2019.115945>
- Rodrigues RG, Fulindi JB, Oliveira DBPD, Moraes ADO, Marini-Pereira L (2022) Safety analysis of GNSS parallel runway approach operation at Guarulhos International Airport. *J Aerosp Technol Manag* 14:e1622. <https://doi.org/10.1590/jatm.v14.1260>
- Sadou AM, Njoya ET (2023) Applications of artificial intelligence in the air transport industry: a bibliometric and systematic literature review. *J Aerosp Technol Manag* 15:e2223. <https://doi.org/10.1590/jatm.v15.1312>
- Silva PR, Bruno MGS, Moraes AO (2024a) Cooperative-based augmentation system using Bayesian filtering. *IEEE Trans Veh Technol* 73(7). <https://doi.org/10.1109/TVT.2024.3363679>
- Silva PR, Bruno MGS, Moraes AO (2024b) Cooperative localization under ionospheric scintillation events. *EURASIP J Adv Signal Process* 2024(1):64. <https://doi.org/10.1186/s13634-024-01140-4>
- Silva P, Bruno MG, di Santis V, Moraes A, Sousasantos J, Marini-Pereira L (2025) An alternative approach for pseudorange variance estimation under scintillation environments using Markov-Rao-Blackwellized particle filtering. *IET Radar Sonar Navig* 19(1):e70017. <https://doi.org/10.1049/rsn2.70017>
- Sousasantos J, Marini-Pereira L, Moraes ADO, Pullen S (2021) Ground-based augmentation system operation in low latitudes – Part 2: Space weather, ionospheric behavior and challenges. *J Aerosp Technol Manag* 13:e4821. <https://doi.org/10.1590/jatm.v13.1237>
- Tariq M, Maswood AI, Gajanayake CJ, Gupta AK (2017) Aircraft batteries: current trend towards more electric aircraft. *IET Electr Syst Transp* 7(2):93-103. <https://doi.org/10.1049/iet-est.2016.0019>
- Taylor C, Vargo E, Manderfield T, Heitin S. Teaching artificial intelligence good air traffic flow management. *J Air Transp* 32(4):184-196. <https://doi.org/10.2514/1.D0414>
- Timmons D, Terwel R (2022) Economics of aviation fuel decarbonization: a preliminary assessment. *J Clean Prod* 369:133097. <https://doi.org/10.1016/j.jclepro.2022.133097>