Zurich University
of Applied Sciences

School of Engineering
Centre for Aviation

Complementing GNSS for Resilient Performance Based Navigation

December 2024
Dr. Okuary Osechas, ZHAW, Switzerland
Dr. Gary A. McGraw, Consultant, USA

Executive Summary

GNSS positioning excels in providing Performance Based Navigation (PBN) services, both Area Navigation (RNAV) and Required Navigation Performance (RNP), to aviation users on a global scale, delivering better performance than most enroute and terminal operations require. However, it has become apparent that radio frequency interference (RFI) makes sole reliance on GNSS untenable. As depicted in Figure 1 and in the spirit of the "Protect, Toughen and Augment" (PTA) paradigm promoted by the National Space-Based PNT Advisory Board (*GPS.Gov: PNT Advisory Board*), ensuring aviation PBN capabilities will require action on multiple fronts.

GNSS receiver technologies exist that would make GNSS more resilient to RFI, i.e., "Toughen", but there are limits to how much GNSS can be toughened and other threats to GNSS that must be considered, so this can only be a piece of the solution. A key aspect of making PBN resilient to RFI and other GNSS threats is modernization of Complementary Positioning, Navigation and Timing (CPNT) systems, i.e., the "Augment" part of PTA. But as illustrated in Figure 1, "Toughen" and "Augment" are only a part of aviation's problem: other aspects, like improving how PNT information is integrated with other aircraft systems and how better RFI situational awareness will be provided to operators and flight crews are needed to fully exploit the capabilities provided by toughened GNSS and CPNT augmentation. Note that while RFI situational awareness is an important aspect of "Protect" in PTA, such situational awareness relies on having interference detection and dissemination capabilities that are not currently standard.

This report focuses on the "Augment" aspect of PTA. While it considers a broad range of potential CPNT systems, it lays no claim to being an exhaustive survey. Instead, its focus is on CPNT systems that have the greatest potential to meet the needs of aviation, with an emphasis on the evolution of systems that are either currently approved for civil aviation, have previously been approved, or already in an approval process. While it must be acknowledged that no single terrestrial navigation system can possibly match GNSS accuracy and coverage performance, there are solutions that offer viable alternatives, especially to over-land enroute and terminal area users, preserving the PBN capabilities that currently only GNSS can provide. A set of performance criteria are proposed to evaluate the candidate CPNT sources. Applying these evaluation criteria to the list of proposed CPNT technologies yields our recommendations for future-proofing resilient PNT for aviation, with consideration given to other applications as well.

The analysis indicates that systems not developed by the aviation community, e.g., 5G cellular, Low Earth Orbit (LEO) systems, signals of opportunity, or commercial beacons, and pseudolites, lack some of the basic functions and provider commitments at the core of safety-critical applications requiring high integrity. Because of the high costs and likely lengthy timelines for adapting these technologies for aviation CPNT, the focus should be on modernizing terrestrial aviation current RADIONAV. Accordingly, our recommendations are:

- Accelerate development of Enhanced DME (eDME), as eDME can help to address intra-system interference issues with current DME, as well as offer performance improvements;
- Support the continued development of Enhanced LORAN (eLORAN) for aviation, as this system can provide coverage over larger areas with less infrastructure, as well as timing for aviation and other users;

- Continue to develop a navigation capability in the L-band Digital Aviation Communications System (LDACS-NAV), which is capable of providing higher performance ranging than either eDME or eLORAN.

The analysis here also suggests that there are synergies between these different systems. For example, eDME and LDACS-NAV measurements could be integrated together in airborne solutions, reducing the required number of ground installations needed in a region for each system. Furthermore, eLORAN can also serve as a timing aid to eDME and LDACS ground stations. In addition, LDACS could disseminate differential eLORAN corrections with very low latency.

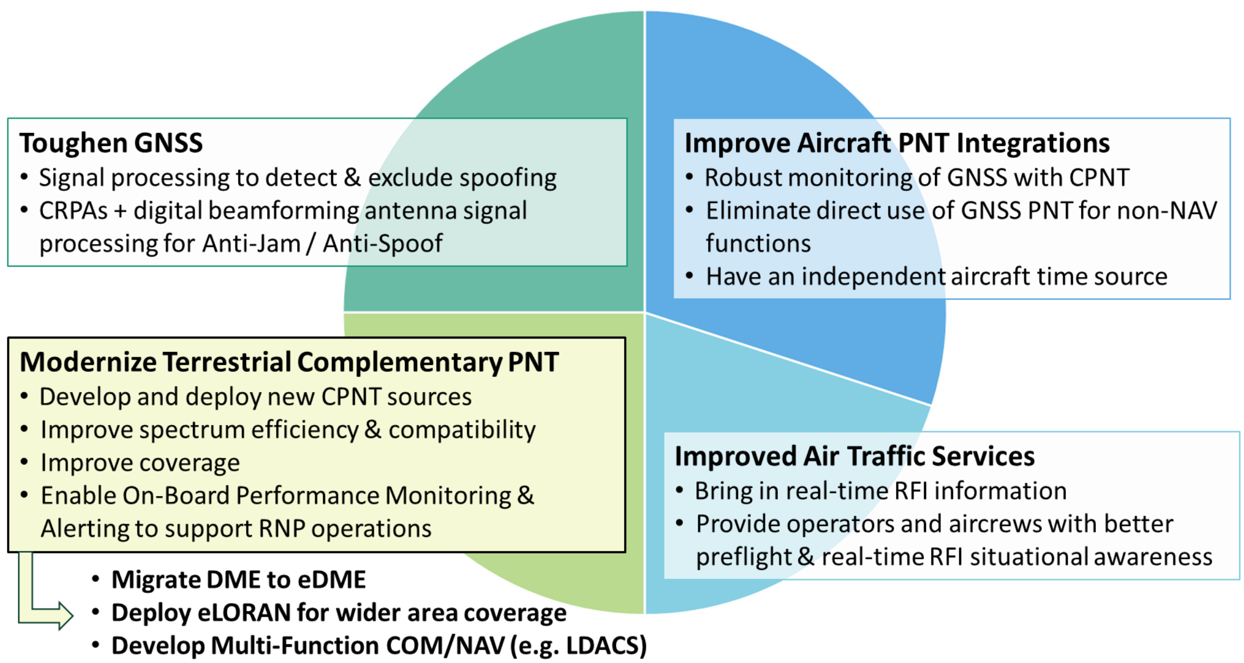

Figure 1: High-level summary of the recommendations of this paper for addressing the RFI challenge to PBN. These recommendations involve multiple areas, with a focus on modernizing terrestrial CPNT.

Introduction

Growing demand for air travel, along with the need to meet environmental and operational objectives, is leading to the increasing use of advanced PBN operations that currently rely on GNSS-based navigation. Existing terrestrial radio NAVAIDS can support the legacy RNAV performance requirements of enroute and terminal area traffic, but they currently do not support the more stringent RNP levels needed for increased airspace efficiency and capacity. Some improvement is possible in the near term by increasing the density of legacy navigation aids like DME, but supporting RNP will require new systems with new technologies that can provide this higher performance.

This report recommends technologies for aviation authorities to consider improving PBN services and to make them resilient to GNSS RFI and other threats. Combining toughened GNSS with improved, state-of-the-art terrestrial CPNT will enable maintaining seamless PBN services during GNSS degradation or loss, thus maintaining to a significant extent the desired benefits to efficiency and airspace utilization, and most importantly, to safety. While the degree of economic benefit of resilient PBN will depend on traffic loads and airspace configuration and on the state of PBN implementation, the increasing frequency of GNSS RFI events and the growth in air traffic highlights the critical need to complement GNSS with modernized terrestrial CPNT.

Throughout the report it is important to distinguish between conventional, "air transport" aviation and new entrants like "Advanced Air Mobility" (AAM) users. The US Federal Aviation Administration (FAA) defines AAM as an "emerging ecosystem of new aircraft" and "an array of innovative technologies" (Federal Aviation Administration, 2023b), which will combine to provide new levels in efficiency, sustainability and more equitable options for transportation. This report focuses on conventional air transport, as currently regulated by the FAA or by the European Union Aviation Safety Agency (EASA). In contrast, AAM will refer to those kinds of users that are not currently regulated, but in the experimental phase, usually featuring autonomous or unpiloted operation, electric propulsion and Vertical Takeoff and Landing (VTOL) operations. As such, AAM users are expected to operate outside the conventional enroute and terminal area airspace, currently occupied exclusively by air transport, with concepts for mixed use being discussed by regulators (Federal Aviation Administration, 2023a).

For the air transport category, the focus of this report is larger aircraft, i.e., airliners, regional aircraft, and cargo and business aviation, but the needs of general aviation are also taken in consideration. This report also does not consider precision approach and landing, as the Instrument Landing System (ILS) is an effective backup for GNSS approaches at larger airports. It also must be recognized that ILS does not address the needs for precision approach and landing for AAM and at smaller facilities.

The analysis here considers diverse viable PNT alternatives to GNSS for aviation applications and consolidates performance criteria by which to evaluate them. Applying these criteria to the systems under consideration results in a set of three technologies with the most promise for development and implementation: eDME, eLORAN, and LDACS-Nav. This work can also inform national decision makers who must take a view broader than aviation and reinforce their PNT architectures to serve other modes of transportation, critical infrastructure, and essential applications.

PBN Background

Performance-Based Navigation is a concept for improving airspace efficiency, reliability and safety. Compared to the conventional sensor-specific airspace route design, PBN makes operations more flexible, eases the transition to new (non-GNSS) navigation technologies and makes the airspace more efficient (ICAO, 2023). The characteristics and benefits of PBN are summarized in Figure 2.

The essence of PBN is that it relies on ascertaining that the Total System Error (TSE) is commensurate with the operation to be executed (ICAO, 2023). The TSE is made up of two components, root-sum-squared; the Navigation System Error (NSE) and the Flight Technical Error (FTE):

$$\mathrm{TSE}^2 = \mathrm{NSE}^2 + \mathrm{FTE}^2$$

Note that the standard TSE equation often includes a term for the Path Definition Error (PDE), but with the development of GNSS-based geodesy, that is typically assumed to be negligible compared to NSE and FTE. The NSE is the 95% horizontal position error. NSE can be improved with better measurements, but also with redundant navigation sources. The FTE is the control error, associated with having an aircraft adhere to a procedure center line. The FTE increases during track angle changes, but also during disruptions like wind gusts.

PBN distinguishes between two different types of operations: Area Navigation (RNAV) and Required Navigation Performance (RNP). The key difference is that RNP includes On-Board Performance Monitoring and Alerting (OBPMA), i.e., the ability of the on-board navigation system to monitor its own navigation performance. Both RNP and RNAV services are accompanied by a number that indicates the 95% TSE specification in nautical miles (NM). For example, an RNP 1 operation requires the navigation solution to be accurate to 1 NM in the horizontal, with a confidence of 95%.

It should be clear to experienced readers that GNSS navigation is ideally suited for PBN. However, it is not the only system certified for RNAV; other systems have been certified, as discussed in later sections. For RNP, however, the situation is different as currently only GNSS can enable RNP.

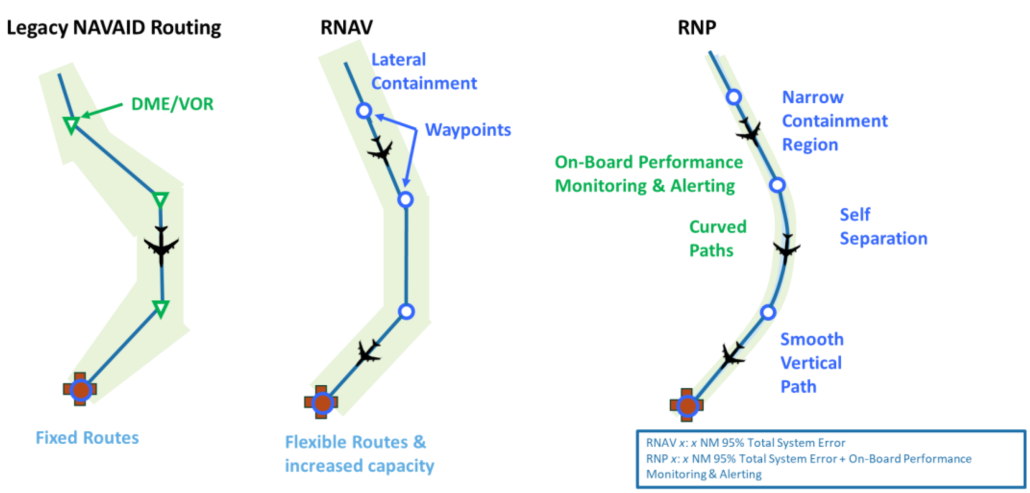

Figure 2: Benefits of PBN. Legacy routing requires the aircraft track to follow the physical layout of the NAVAIDs. RNAV enables a more flexible selection of the track, following database waypoints. RNP adds fixed-radius segments, plus OBPMA, which comes with the ability to "self-separate".

In short, GNSS is critical for some RNAV routes, where the ground infrastructure does not support useful values of TSE, and currently essential to all RNP, largely because other Ground-Based Navigation Aids (GBNA) have not received the same level of focus and funding. Two factors play in favor of GNSS: greater redundancy in ranging sources and a more benign radio propagation environment. Redundancy refers to the fact that in most cases, far more than the four required GNSS satellite signals are available to compute a position fix, while for terrestrial systems such measurement redundancy has been challenging, due to both ground infrastructure and avionics limitations. The relatively benign propagation for GNSS stems from the fact that in most aviation situations, there is an unobstructed view of the sky. Furthermore, the measurement errors induced by GNSS radio propagation can be modeled and mathematically over-bounded, whereas for terrestrial ranging, over-bounding errors has been challenging due to complex multipath environments and terrain blockages.

In complex airspace, RNP can be further developed to Advanced RNP (A-RNP), which relies on the lowest levels of TSE, such as RNP-Authorization Required (RNP-AR), RNP-Approach (RNP-APCH), and additional features like Time of Arrival Control and automated holding.

Threats to Aviation PBN

A recent rise in RFI activity has highlighted the dependence of aircraft, and indeed the entire airspace system, on GNSS. The dependences go well beyond navigation and impact the ability of aircraft to communicate, to recognize and stay clear of obstacles, as much as Air Traffic Management (ATM) to surveille the airspace. Some of these are discussed below. This section describes the threat of RFI to aviation and its impact, more specifically, on PBN, which often becomes unavailable during such interference events.

RFI Environment

The frequency of RFI events has risen sharply in the 2020s, with jamming becoming commonplace and spoofing recently a daily occurrence. A number of online services monitor RFI activity in real time, typically by analyzing ADS-B feeds provided by third-party operators. Among them, GPS Jam (gpsjam.org, n.d.) and The Zurich University of Applied Sciences (ZHAW) (Skai Data Services, n.d.) have provided the aviation community and the public more generally with evidence of consistent growth in RFI incidents. For example, Figure 3 shows the ZHAW/SkAI compilation of flights that were spoofed during the Summer of 2024. It shows that over one thousand flights were spoofed every day. As of the date of this report, there are no indications that these incidents are decreasing. Many observers cite the lack of meaningful disincentives as an indication it will continue indefinitely and may well increase (OPSGROUP, 2024).

This continuing impact on aviation safety, security, and efficiency illustrates the fragility of unprotected GNSS and, therefore, the threats its sole use poses to modern ATM which relies so heavily upon it. GNSS is a very faint radio signal, with a received power below thermal noise, so unhardened receivers are easy to jam or spoof. Hardening GNSS receivers against interference has been an important feature in military receivers and is receiving increasing attention in the commercial world as well. There are many receiver signal processing and measurement consistency techniques that have been used to counter RFI (Scott, 2021). These can be particularly effective against spoofing.

Among the most powerful anti-jam technologies are Controlled Reception Pattern Antennas (CRPAs), which combine multielement antenna arrays along with associated nulling and beam-steering techniques. CRPAs, with appropriate manifold calibration, could make aircraft highly resistant to GNSS jamming while still meeting navigation performance requirements, but export restrictions in the United States have limited their use. Appropriate GNSS integration with inertial and other sensors is another effective RFI-mitigation technique.

While GNSS hardening measures should be adopted in aviation, they do not address all threats. It may be possible for jamming or spoofing threats to overwhelm whatever GNSS hardening technologies are employed. And there are more system-wide threats like cyber-attacks and space weather effects that GNSS receiver hardening are unlikely to cope with. Providing non-GNSS navigation sources will help mitigate many of these threats.

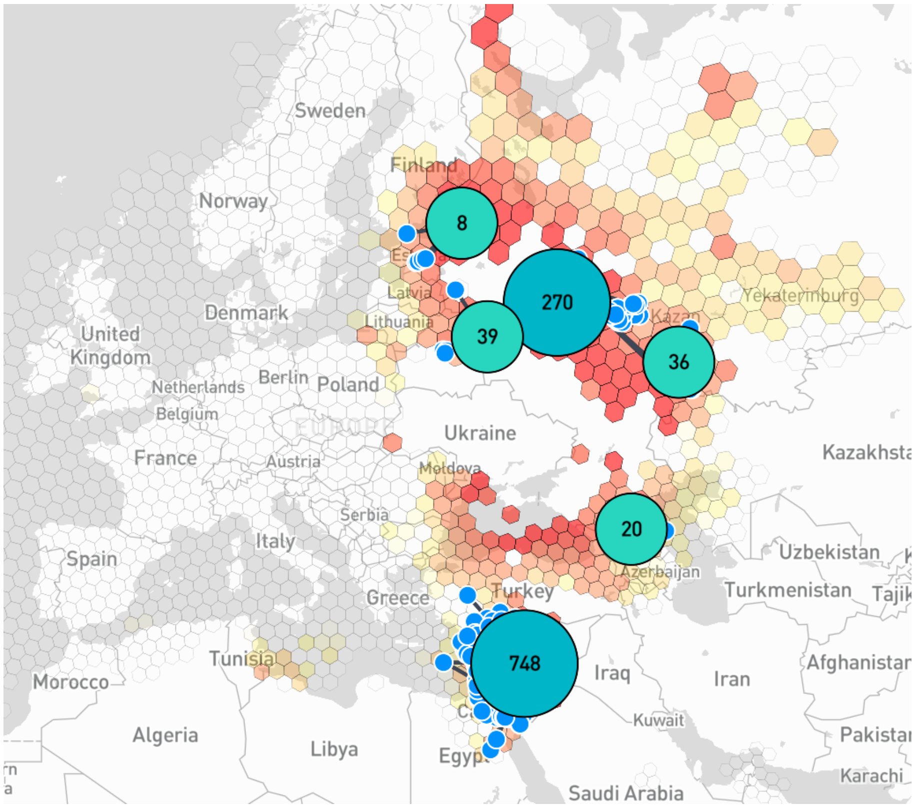

Figure 3: In some parts of the world, thousands of flights are spoofed daily and GNSS-based operations have become unavailable (Skai Data Services, n.d.). A circle with a number inside indicates the number of flights experiencing spoofing on the given day. Different shades of orange or red indicate the likelihood of GNSS jamming.

Impact on Aircrews and on Controllers

The threat to aviation does not always receive the attention it deserves, as redundancies in systems enable most operations to comply with navigation standards. The increased workload on both flight crews and controllers, particularly when multiple aircraft are affected, has a profound impact on safety margins (OPSGROUP, 2024). Enhanced simulator training for cockpit crews, specifically in response to GNSS RFI, would go a long way in restoring these safety margins that get eroded during interference events.

Recent increases in RFI, particularly spoofing, have highlighted how GNSS PNT data has been incorporated into numerous critical aircraft functions, leading to often unexpected consequences as detailed in (EASA, 2024) and (OPSGROUP, 2024). These effects are summarized in Figure 4, illustrating that communications (COM), surveillance (SURV) and flight control all have critical dependencies on GNSS. This highlights the need for updates in other avionics and better aircraft integration, including that GNSS be monitored by independent PNT sources.

While pilots, dispatchers and controllers have found workarounds that appear safe enough for normal operations, these are still exceptions to desired and best practices to enable continued operations in the face of adversity. For the most part, there is no safety case yet behind these workarounds, because of the difficulty of developing aviation performance standards to contend with a rapidly evolving RFI environment, and the slow acknowledgment by authorities and operators of GNSS vulnerabilities. Aside from economic losses caused, for example, by having to use less favorable routing, RFI could well lead to serious mishaps given the thousand or more significant jamming and spoofing events that impact aviation each day.

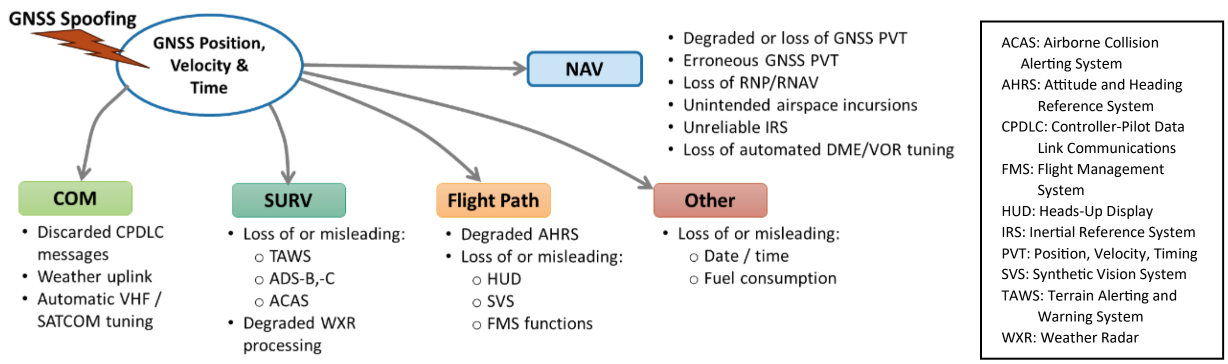

Figure 4: GPS spoofing has led to degradation to multiple aircraft systems, demonstrating that GPS has become a single point of failure. The dependence of some of the systems, failing during RFI, is not intuitive and should, arguably, not be happening. [Adapted from (OPSGROUP, 2024)].

GNSS RFI impacts air-traffic controller (ATC) workload in several ways. Loss of GNSS, currently considered primary navigation, will require a change in operations as supported by GBNA. With that comes increased air-ground communications and may even necessitate controllers providing radar vectors to pilots. The events also impact the workload of cockpit crew, who deal with false alerts like ground-proximity warnings while cruising at 40,000 ft above mean sea level. RFI has been shown to lead to increased rates of aborted landings, go arounds, traffic conflict alerts, and other stressors which all create additional distractions and add to the ATC burden.

Impact on PBN

As illustrated in Figure 5, loss of GNSS requires ATM to fall back on RNAV routes, as they are supported by GBNAs, while RNP becomes unavailable. Most RNAV 1 or 2 operations rely on GNSS for navigation. Alternatively, they resort to GBNA and inertial navigation, where available. When the ground network does not support the required performance, crews revert to legacy routing, which is based on procedural, rather than numeric solutions, and results in loss of efficiency. RNP, on the other hand, relies entirely on GNSS for navigation, as per ICAO and RTCA/EUROCAE standards. This dependency is changing and will eventually be removed, but current standards make it clear that only GNSS can support RNP. In the absence of GBNA, the flight must be operated with inertial coasting with radar vectors from ATC.

The U.S. and Europe have different approaches to terrestrial NAVAIDS. The US National Airspace System operates with Minimum Operational Network (MON), likely structured to minimize costs to the federal government. This concept is centered on VOR/DME and is incapable of delivering better than RNAV 5 broadly, with RNAV 1 only supported by DME in select areas and the best service available to users of DME integration with inertial navigation. In continental Europe, most RNAV 1 routes can be supported by DME/DME.

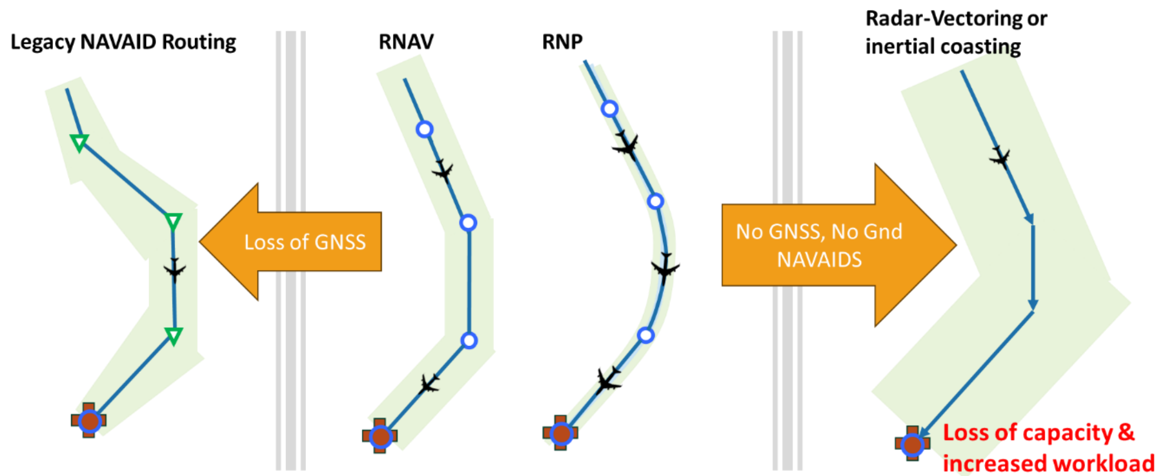

Figure 5: In areas with a strong infrastructure of terrestrial NAVAIDS, RNAV can fall back on that during RFI. In some areas, PBN becomes completely unavailable, as RNP is lost.

NAVAIDS are crucial in maintaining capacity during GNSS disruption. This is especially true in areas with high traffic density, at lower altitudes, and in the vicinity of large Terminal Maneuvering Areas (TMAs). Work to develop non-GNSS RNP is currently ongoing, but reliance on legacy DME will not support projected significant increases in traffic.

Modernization of CPNT Infrastructure

Current terrestrial infrastructure emit high power signals at a range of frequencies in both the VHF and UHF bands, making them resilient to the kind of RFI that disrupts GPS/GNSS. These GBNA also support RNAV in both the enroute and terminal areas. However, existing GBNA are, for the most part, dated; they require upgrading or replacing, to take advantage of state-of-the-art technology. The signals that GBNA currently use are outdated, too. A full modernization program will have to update both the GBNA and the signals they use for navigation.

Such a modernization effort would also allow CPNT sources to transition to support lower RNAV values and, more importantly, to support RNP. A variety of new navigation modalities and evolutions of older, established systems have been proposed to complement GNSS. However, fielding any completely new or improved navigation and timing solution is problematic, as the costs for development, certification and deployment are significant. To achieve resilient time and frequency services for all users will likely exceed the capacity of any one agency, stakeholder, or even groups of stakeholders. On the other hand, evolutionary solutions, developed from existing technology and multi-domain systems that can serve sectors beyond aviation or even beyond transportation, will have significant advantages in both development and deployment timelines and cost-effectiveness. Another challenge in designing navigation systems for aviation is to accommodate legacy users. Airplanes remain in service for many decades and the avionics are rarely updated, until a business case can be made, or when regulations require it. Integrating CPNT onto aircraft in a way that minimizes complexity for flight crews will also be a challenge; ideally, transitions from GNSS-based guidance to CPNT would be both simple and seamless.

Historically, significant change in aviation has often come as a result of a system failure, or of an aviation accident leading to tragedy. Rather than waiting for a tragic event to occur, the authors encourage the aviation community to promptly begin orderly, measurable, and systematic changes in both the ground infrastructure and onboard the aircraft. Ensuring safety, security, and airspace efficiency, regardless of the presence of GNSS RFI, is a matter of due diligence and in the best interests of the aviation and navigation communities. Given the current severity and extent of GNSS RFI threats, the safety and efficiency of the airspace system has been called into question (EASA, 2024; OPSGROUP, 2024) and the development of resilient CPNT systems will address all concerns.

An added benefit of implementing resilient CPNT systems is that they will severely limit, and even in some systems eliminate any impacts due to disruption of GNSS signals, thus making it “less attractive” to malicious actors. If use of resilient CPNT is widely adopted, belligerents may find interfering with navigation and timing systems so difficult, they will target other vulnerabilities instead.

Evaluation Criteria

This section proposes a non-exhaustive list of considerations to help identify the best technical solutions from a list of candidate technologies.

Achievable Performance: The RNAV/RNP type that the system is expected to support. Navigation performance depends on a number of factors, including the inherent ranging accuracy of the waveform and assumptions about the geometry and density of infrastructure. The analysis here generally assumes sufficient infrastructure is deployed to support the best levels of performance, i.e., lowest RNAV or RNP value.

Operational Coverage: The operational volume provided by the network of ranging sources. Unlike GNSS that have global coverage, terrestrial systems have service volume limitations of one form or another, such as line of sight (LOS) range to one or more GBNA.

Deployment Complexity / Cost: A qualitive measure of the relative cost and complexity of deploying a given system. It considers changes to ground sites and avionics and whether these changes would be upgrades or replacements to existing deployed equipment, or completely new infrastructure.

Backwards Compatibility: The ability to support existing aircraft installations until they can be upgraded.

Spectrum Compatibility: The ability of a new or modernized CPNT system to operate without interfering with GNSS and other established or emerging systems. Operating outside the GNSS frequency band is also attractive, as the band is highly congested. Multi-function applications of radio links, such as use of COM systems for NAV, is considered here as having good compatibility.

Capacity Limits: The number of simultaneous users. One-way pseudoranging systems like GNSS can support unlimited numbers of passive users. Two-way ranging systems are limited on the number of users depending on the multiple access method employed.

Support for Other Applications: The ability of a system specific to support other ground, maritime, air, and perhaps infrastructure applications.

Support for Time Transfer Services for Aviation Systems: The ability of a system to provide airborne or ground users time and timing information traceable to UTC.

Support for Source Authentication: The ability of a system to assure the validity of measurements and other information being transmitted.

Expectations

The goal of establishing one or more CPNT systems is to ensure PBN during degradation or loss of GNSS, especially where RNP is critical to maintaining efficiency. The eventual solution should minimize losses in airspace capacity, as well as avoiding increases in controller and pilot workloads. The development of terrestrial CPNT should, therefore aim to:

- Provide RNP during GNSS RFI;
- Improve spectral compatibility and efficiency;
- Fill in gaps in terrestrial RNAV;
- Support emerging applications;
- Support autonomous operations;
- Have few to no common failure modes with GNSS, including operation at different frequency bands.

The availability of Resilient PBN – both RNAV and RNP, means that GNSS RFI will no longer cause disruptions of air traffic enroute or on precision and non-precision approach. For this to happen, a terrestrial system will have to support OBPMA, in the same way GPS does, to guarantee observability and alarming in the event of out-of-tolerance PNT performance.

Improved spectral compatibility is becoming a crucial metric in the hotly contested world of radio spectrum, especially in the L-band. In this sense, multi-domain signals and systems can help relieve spectrum pressure. One salient example is LDACS: a communication system that supports RNP would provide two important functions on every single radio link. There are, of course, further concerns that an outage of a multi-function radio link would lead to simultaneous COM and NAV outages, but such concerns can be addressed with system architecture, like requiring multiple threads.

To bridge gaps in RNAV coverage, an adequate network of terrestrial NAVAIDS must be deployed. For airspace operators this means more carefully designed ground networks. For any given RNAV or RNP level, there exists a minimum density and optimum geometry of ground stations required to support that operation. The required density depends on the technological implementation and the ruggedness of the local terrain.

Modernized CPNT should also support emerging applications, like Advanced Air Mobility. This means it will need to support operations, distinct from today's conventional and mainline airspace. Autonomous operation will simply not be feasible without terrestrial CPNT. As discussed by (Osechas et al., 2024; Tenny & Humphreys, 2022), exclusive reliance on GNSS for navigation is infeasible for truly autonomous systems, where no safety or remote pilots are engaged. A fundamental difference between fully autonomous vehicles and piloted vehicles is the ability to operate under Visual Flight Rules (VFR). A human pilot usually has that ability, which provides an additional defense against RFI that is proving difficult to bridge with automation.

Finally, adequate systems integration needs to be an important consideration. The sheer amount of non-intuitive or "surprising" dependencies of aircraft systems on GNSS, as cited by (EASA, 2024) and (OPSGROUP, 2024) and sketched out in Figure 4, is evidence of the lack of appreciation of GNSS vulnerabilities. Adequate testing of system integrations must become a part of certifying critical hardware on any aircraft; in fact, it may become necessary to re-engineer some of the integration architectures in the existing fleet. GNSS position solutions are neither perfect nor foolproof.

Candidate CPNT Technologies

From the many possible technologies that have the potential to support PBN services, this paper considers a subset of both aviation systems and commercial, non-aviation systems, as Figure 6 indicates. The analysis starts with the existing technologies that already support some PBN operations: DME and VOR can be used in various combinations to support anywhere between RNAV 5 and RNAV 1 (EUROCAE WG-85, 2025a, 2025b; RTCA SC-227, 2025b, 2025a).

A second group of technologies is that of enhancing some of these legacy technologies, in particular: eDME (Li & Pelgrum, 2013; Lo et al., 2014; Lo & Chen, 2020) and eLORAN (Federal Aviation Administration, 2004; International LORAN Association, 2007). So long as the developments retain some essential features of their parent technologies, the adoption could be simpler than for other systems, although LORAN is no longer an ICAO Annex 10 recognized system. It is believed that these technologies have a schedule advantage, as questions like frequency compatibility and known failure modes have extensive experience behind them.

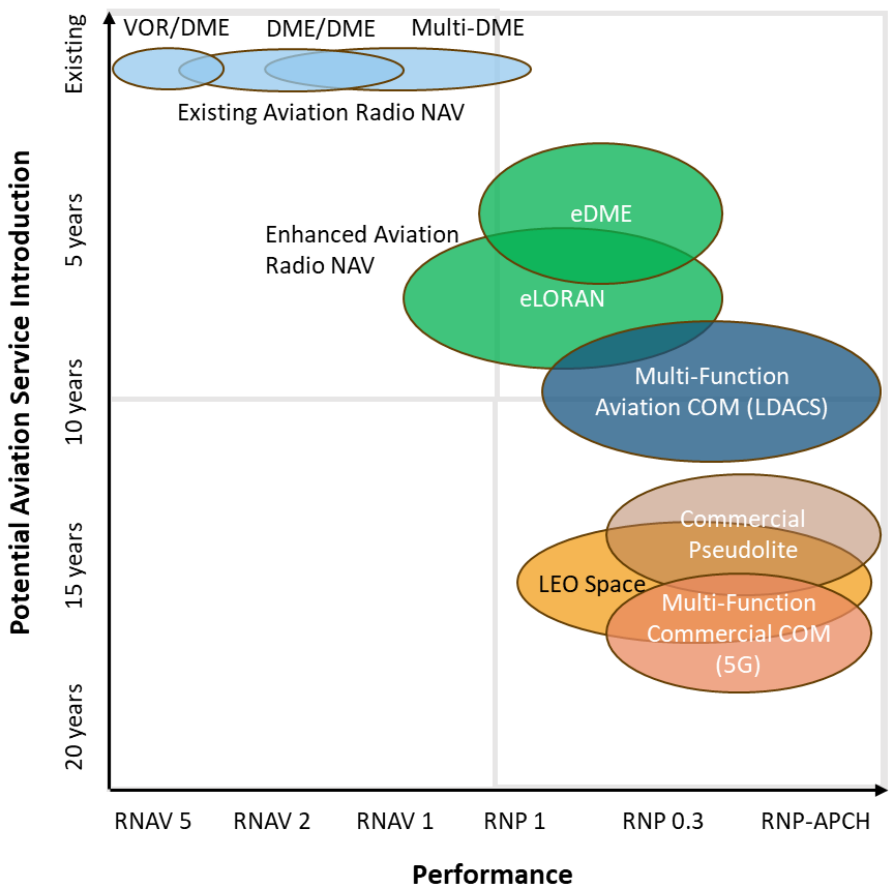

Figure 6. Candidate CPNT technologies, with potential performance and aviation service introduction. Existing NAVAIDS do not meet all the needs for PBN, pointing towards the need to modernize them. Existing operational commercial systems may be able to meet the requirements for Advanced RNP, and may provide better accuracy than modernized aviation NAVAIDS, but they would likely face lengthy standardization timelines.

The notion of dual-purposing communication systems for aviation is behind the efforts of developing a navigation capability for LDACS (LDACS-NAV) (Osechas et al., 2019; Schneckenburger et al., 2013), as is the use of other signals, designed for land mobile communications (4G/LTE, 5G, etc.) (Del Peral-Rosado et al., 2024; Shamaei & Kassas, 2018). The technical arguments may be similar for these types of systems, but the approval processes are different. LDACS would be derived from a certified aviation system, compliant with ICAO Standards and Recommended Practices (SARPs) and other industry standards, while the others would not. It should also be acknowledged that for these "multi-function" systems, loss of COM would entail loss of CPNT, so these systems should only be used in conjunction with other COM and NAV capabilities.

Extending further into commercial and proprietary systems, a new family of navigation services is emerging based on LEO satellites. These technologies show great potential, especially considering their global reach, but given the long lead times usually involved in certifying new systems for aviation, this could prove to be a complicating factor. LEO systems also have the challenge of providing enough satellites in view at any given location and time to yield good solution geometry.

Another interesting class of systems is what is called here "commercial pseudolite" services that have been designed for indoor and urban positioning such as NextNav (Meiyappan et al., 2013) and Locata (Rizos & Yang, 2019). These systems can often show years' worth of operational experience outside aviation applications. However, the certification process for these systems to be used by aviation will still be a significant and their value (accuracy, availability, integrity, continuity, and especially coverage) may not warrant their use by many aviation use cases, but their technical benefits could make them a workable solution for certain types of environments.

Analysis

This section summarizes the analysis of the candidate CPNT alternatives against the criteria discussed above, which forms the basis for our recommendations. Both, the candidate systems in the left-most column and the performance criteria in the first row, come from the preceding sections. Figure 7 provides a graphical summary of the analysis, with the details of the evaluations provided in the Appendix.

	Operations Supported	Operational Coverage	Deployment	Backwards Compatibility	Spectrum Compatibility	Capacity Limits	Other Applications	Provides Timing	Authentication
VOR/DME	RNAV 1 - 5	75 NM	Deployed / Certified		High PAPR	Ranging	Designed for Aviation		Morse code IDENT
DME/DME	RNAV 1	140 NM	Deployed / Certified		High PAPR	Ranging	Designed for Aviation		Morse code IDENT
Multi-DME	RNP 1	140 NM	Deployed / Certified		High PAPR	Ranging	Designed for Aviation		Morse code IDENT
eDME	RNP 0.3	140 NM	New Gnd / Air Equip.	Yes: 100%	High PAPR	PR mode	Designed for Aviation	~100 ns	Includes data channel
eLORAN	RNAV 1 – RNP 0.3	~1000 NM to <50 NM	New Gnd / Air Equip.	New Aviation NAVAID	Not L-Band	Passive	Maritime & Timing	<100 ns	Encrypted data channel
LDACS-NAV	< RNP 0.3	200 NM	New Gnd / Air Equip.	New Aviation COM	Shared with COM	Ranging, PR modes	Potential for AAM	< 100 ns	Two-Way COM Protocols
5G Cellular	<RNP 0.3 ?	<10 NM	New Air, Expanded Gnd	New System	Shared with COM	Two-way COM	Potential for AAM, GND	< 100 ns	Two-Way COM Protocols
Commercial Pseudolite	<RNP 0.3 ?	<20 NM ?	New Gnd /Air Equip.	New System	Not ARNS spectrum	PR, ranging modes	Potential for AAM, GND	<< 100 ns	Likely
LEO SATNAV	<RNP 0.3 ?	Potentially Global?	New SVs / Air Equip.	New System	Shared with COM	Passive? Spot Beams?	Land/Sea/Air	< 100 ns	Likely

Poor/High Cost	Marginal/Costly	Fair/Moderate Cost	Good	Excellent	N/A

Figure 7: Summary of CPNT sources and evaluation. See the Appendix for the rationale for the evaluations in this table.

The most significant criterion is the best-case performance: systems that do not support RNP 0.3, and preferably RNP-APCH or better, are not worth the development effort involved in reaching full certification. In terms of capacity limitations, some systems like DME use two-way ranging which necessarily has a maximum number of allowable users, while others offer pseudoranging (PR) modes, which is passive and has no limit on the number of users. In terms of spectral compatibility, some systems, like LDACS-NAV have continuous ground-to-air waveforms and rely on coherent signal processing to achieve high accuracy measurements. Others, such as DME, rely on narrow pulses with high Peak to Average Power Ratio (PAPR); systems with high PAPR can be more challenging for ground station siting and aircraft installations.

In the particular case of eLORAN, the coverage from a single station is on the order of 1000 NM, so with sufficient coverage from multiple stations baseline performance likely supports RNAV 1 or RNP 1. However, to achieve the RNP 0.3 performance, a local differential station with limited coverage is required, which might require the use of another data link to provide these corrections. The differential information decorrelates with the distance between user and reference station, depending on a variety of geographical factors, like ground conductivity. The value of 50 NM, listed in Figure 7, represents an estimate of a typical radius for this coverage zone.

The improvements offered by eDME compared to current DME technology, includes coherent carrier phase, enabling carrier-smoothed pseudorange processing, which extends eDME performance to support lower levels of RNP. From a spectral compatibility and capacity limitation perspective, eDME has the ability to function in a partial PR mode, enabling more aircraft to be supported by a ground station. In addition, eDME has a data transmission capability on the order of between 8 and 16 kbps. As a point of comparison, the data rate of a single LDACS station is 291 kbps – 1.32 Mbps, depending on mode.

Recommendations for Modernizing Terrestrial CPNT

From the detailed evaluation summarized in Figure 7, three technologies stand out as particularly attractive for achieving resilience in the civil airspace: eDME, eLORAN, and LDACS-NAV. The selection of these PNT systems is based on the following considerations and the concept depicted in Figure 8:

- Modernizing and evolving an existing aviation radio NAVAID like DME to eDME while ensuring backwards-compatibility with legacy DME users enables a safe, secure and cost-effective roll-out of new capabilities while, at the same time, modernizing the infrastructure that will be continued to be used by legacy users. The replacement of DME ground transponders could be prioritized for high-traffic areas where more demanding performance (e.g., RNP vs. RNAV) is required. These areas are typically where spectrum congestion and intra-system interference is an issue and additional channels are unavailable or would require significant spectrum engineering redesign and re-channelization. Enhanced DME would enable pseudoranging and coherent detection (Li & Pelgrum, 2013), as well as processing of multiple (more than two) observables per position fix (Liang et al., 2024), which can lead to RNP 0.3 performance or better. These benefits will help incentivize operators to upgrade their airborne equipment.
- There are places where it is not feasible or cost-effective to install sufficient ground infrastructure to support line of sight limited systems like DME/eDME, e.g. along a coastline or in challenging, mountainous terrain. In these areas, eLORAN could provide the most cost-effective means to deliver RNAV and/or RNP. Additionally, eLORAN has been shown to support maritime and other

transportation applications, as well as precise time and frequency to all users. eLORAN can support up to RNAV 1 over remote areas and offshore and with proper reference station infrastructure, can also provide RNP 0.3 to support terminal area procedures, non-precision approach (NPA), and LNAV/VNAV approaches when used with barometric altimeter. In addition, eLORAN could also serve as a wide-area synchronization service for other terrestrial pseudoranging systems, like eDME or LDACS-NAV (International LORAN Association, 2007).

- As aviation traffic increases, there will be the need to support RNP-APCH/RNP 0.3 and continuity of ADS-B services even when GNSS is unavailable. Currently, aircraft ADS-B squitter only use position information from GPS augmented by Space Based Augmentation Systems (SBASs). Being able to utilize complementary PNT systems to support ADS-B transmissions would provide both continued situational awareness and help to alert ATC to the loss of GNSS. Furthermore, spectrum compatibility considerations will likely limit the deployment of more eDME ground stations in high traffic areas. Multi-function COM systems like LDACS could play a key role here. LDACS-NAV, particularly in conjunction with eDME, could meet future airspace terminal area needs. The combined system could also take advantage of the authentication capabilities inherent in LDACS and use LDACS-COM to transmit information like tropospheric correction information, to further improve ranging accuracy for eDME as well as LDACS-NAV.

The introduction of GNSS to aviation was a game changer and, as such, no single technology will be able to replace or adequately complement all the functions it provides to aviation. It has become evident that aviation needs to sustain, replace, and improve its terrestrial navigation services, and that airframe manufacturers need to clean up their current deep integration of GNSS in the cockpit. In some cases, GNSS has become the sole means of navigation, and it is time to change that. Most importantly, aviation needs to work together to design, develop, certify, and implement multiple radionavigation technologies that can be used concurrently, complement each other, and ensure PNT resilience.

While this effort has focused on CPNT technologies for aviation, the authors want to highlight related issues critical to future aviation safety:

- Aircraft PNT integration must be improved. GNSS and future CPNT sources must not constitute single points of failure that ripple through multiple aircraft systems. Cross-checking between dissimilar sources must be pursued. A related need is to enhance flight simulators to include RFI scenarios, so that pilots get trained for these situations.
- Air traffic services must include RFI monitoring, prediction and reporting. Analogous to weather forecasts, providing RFI information to operators and air crews as part of the pre-flight briefing, along with updates in-flight, would give air crews additional situational awareness that allow them to more effectively cope with the RFI challenge.
- GNSS receivers should be hardened against interference. Multiple technical solutions can mitigate the impact of RFI on aviation-grade GNSS receivers. They range from smarter signal processing and data-level consistency checks to arrays of receiving antennas for adaptive beamforming and Direction-of-Arrival authentication. A combination of these techniques could prove sufficient in many instances. Export restrictions in the United States need to be changed to enable aviation use of these systems.

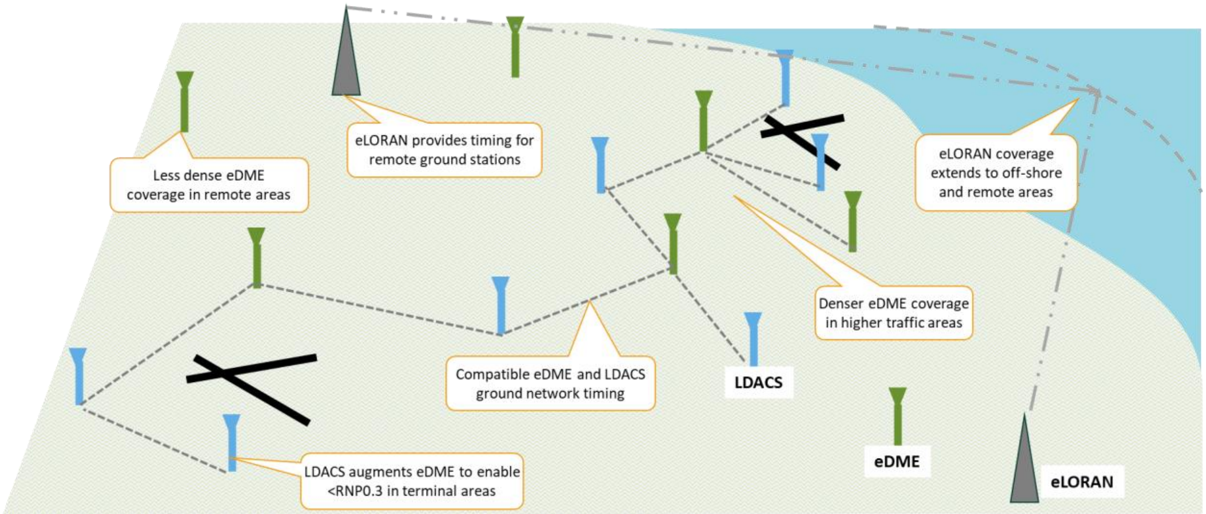

Figure 8. Conceptual operational view of long-term modernized CPNT deployment, with interoperable eLORAN, eDME and LDACS-NAV transmitters. Terrestrial fiber connections distribute timing in populated areas, whereas in remote areas, synchronization is provided by eLORAN.

Conclusions

This report proposes performance criteria for terrestrial navigation aids and candidate technologies for consideration. High-level analysis based on the criteria identifies recommended candidates for governments and industry to pursue: eDME, eLORAN and LDACS-NAV, which have the commonality that they have excellent navigation performance at a lower expected lead time into the cockpit than other systems. The recommendation to modernize CPNT infrastructure also includes a concept for how the systems will interplay, by having eLORAN as a time-distribution service for pseudoranging based on eDME and LDACS-NAV, while also providing service to remote and coastal regions that LOS-limited systems cannot. By implementing the recommendations, the airspace will regain some of the safety margins lost to GNSS RFI. It will also become more resilient to potential future disruptions, maintaining efficiency during incidents that would cripple air traffic, if they were to occur today.

The specific CPNT implementation adopted by each country or region will be dependent on a large number of considerations. For example, a region with dense DME infrastructure might want to prioritize eDME transition, whereas a region with little or no existing DME may want to prioritize LDACS-NAV, particularly if they need to upgrade aeronautical COM. More sparsely populated regions may find eLORAN most effective. All this points to the need for additional system engineering trade studies to be conducted to provide more specific cost/benefit information to policy makers.

Modernized CPNT will require public and private infrastructure investment. But just as important, there needs be a sense of urgency in government and industry to address these issues that go beyond funding. Implementing modernized CPNT in a timely fashion necessitates breaking down institutional barriers. Improved cooperation is needed between different government agencies, industry and government regulators, and internationally, to develop technologies, create industry standards, and deploy infrastructure.

Acknowledgements

The views expressed herein are solely those of the authors alone and do not reflect the views of the Zurich University of Applied Sciences. We thank the Resilient Navigation and Timing Foundation for their support. We also thank Dana Goward, Logan Scott, John Betz, Charles Schue and Mitch Narins, who reviewed and commented to improve this work.

Biographies

Dr. Okuary Osechas is a researcher at the Zurich University of Applied Sciences. He received a PhD from Tufts University, where he was sponsored by the FAA to develop new concepts for integrity monitoring in GBAS. He worked at the German Aerospace Center, where he led efforts to make air traffic more resilient to GNSS RFI. He leads the standardization Working Group 85 at EUROCAE, which together with RTCA Special Committee 227, maintains the RNP standards. He is an Associate Editor with IEEE Transactions on Aerospace and Electronic Systems.

Dr. Gary McGraw is a PNT consultant with Genova Technologies. He is retired from Collins Aerospace (formerly Rockwell Collins), where he was instrumental in the development of several significant PNT technologies for civil aviation and military applications. He is currently leading research in Complementary PNT technologies and supporting development of DFMC GBAS. Dr. McGraw received his PhD from UCLA. He is a Fellow of the ION and an Associate Editor for NAVIGATION.

Appendix: CPNT System Analysis

The appendix presents the details of the analysis at the core of the report. The findings, summarized in Figure 7, are the basis for the recommendations on modernizing terrestrial radionavigation. The proposals for three specific systems (eDME, eLORAN, LDACS-NAV) recommended, are derived directly from this appendix.

VOR/DME

Achievable Performance and Coverage: The cross-range positioning accuracy of VOR degrades with increasing distance between user and GBNA, whereas DME ranging accuracy is almost independent of that distance. As specified in FAA AC 20-138D (Federal Aviation Administration, 2016) a single VOR/DME, depending on the flight path relative to the station, can support RNAV 1 performance out to 12 NM, RNAV 2 to 30 NM and RNAV 5 to 75 NM. While the maximum operational range for VOR is about 100 NM, at these longer ranges performance would not support RNAV 5 (FAA, 2016), therefore in our high-level summary in Figure 7, we use 75 NM as the operational range. Furthermore, as stated in RCTA DO-236E (RTCA SC-227, 2025a), VOR/DME is not approved for RNP procedures.

Deployment Status / Ease of Deployment: VOR and DME are legacy systems likely found on any Part 25 (transport class) aircraft. That makes VOR/DME automatically backwards compatible, but due to VOR limitations, it cannot be considered a viable candidate for modernized CPNT. A single VOR/DME installation can support RNAV 5 at best.

Spectrum Compatibility and Capacity Limitations: DME is a high-power pulsed system, with high peak-to-average power ratio (PAPR), occupying 1 MHz channels, with strong potential for inter- and intra-system interference on aircraft installations, thus we evaluate it as having poor spectral compatibility. Furthermore, because of the two-way ranging mode of operation (aircraft interrogation and ground station response), there are definite capacity limits on the number of aircraft that a single DME ground station can support.

Support for Timing and Other Applications: VOR/DME is an aviation-specific system and does not provide timing.

Authentication: VOR and DME signals include Morse Code Identifications (IDENTs), yielding a rudimentary authentication capability. In addition, their high power levels make them harder to jam or spoof.

Recommended Use Cases: VOR/DME is a legacy system that is unable to support RNP. Except if there is a need to service older aircraft and general aviation, it is recommended that over the long-term VOR be phased out and replaced with modernized terrestrial CPNT sources.

DME/DME

Achievable Performance and Coverage: As specified in FAA AC 20-138D (2016) an aircraft equipped with a DME/DME can support RNAV 1 performance out to about 140 NM, although DME/DME usage is permitted out to 160 NM.

Deployment Status / Ease of Deployment: DME/DME is an existing system, widely used around the world (International Civil Aviation Organization, 2023), so is automatically backwards compatible.

Spectrum Compatibility and Capacity Limitations: As explained above, DME has poor spectral compatibility and suffers from capacity limits on the number of aircraft that can be supported. Spectral crowding has led to the number of available DME channels dropping to zero in some parts of Europe. That means: no new DME ground transponders can be installed.

Support for Timing and Other Applications: DME/DME is an aviation-specific system and does not provide timing.

Authentication: As explained above, DME provides rudimentary authentication, and DME power levels make it harder to jam or spoof.

Recommended Use Cases: DME/DME is a legacy system that is unable to support PBN procedures with low TSE, although with RNAV 1 it supports most existing non-precision approaches. As discussed below, it is recommended that DME be modernized to support RNP.

Multi-DME

Achievable Performance & Coverage: Because of the measurement redundancy provided by using three or more DME ranges in a solution, multi-DME has the potential to support OBPMA, thus could support RNP instead of RNAV. Similar to the discussion for DME/DME, we assess that multi-DME may support RNP 1 out to about 140 NM (RTCA SC-227, 2025b).

Deployment Status / Ease of Deployment: Multi-channel, scanning DME avionics are available today, though upgrading older aircraft may require an FMS upgrade, along with the upgraded DME, which might be cost-prohibitive.

Spectrum Compatibility and Capacity Limitations: The capacity limitations of multi-DME are worse than DME/DME, since as the airborne system is interrogating three or more DME ground stations, the overall signal traffic increases. There are indications that this is already causing interference issues in high-traffic areas.

Support for Timing and Other Applications: Multi-DME is an aviation-specific system and does not provide time.

Authentication: There is no authentication included in the DME waveform.

Recommended Use Cases: Multi-DME is an existing system that is able to support modern PBN procedures at a level of RNP 1. Multi-DME can serve as a beginning for evolved CPNT.

Enhanced DME (eDME)

Achievable Performance and Coverage: Similar to multi-DME, eDME avionics would range to three or more ground stations and therefore would support OBPMA. In addition, the eDME signal-in-space includes coherent carrier phase, enabling carrier smoothing of ground-to-air DME pseudoranges which will greatly mitigate multipath, which is the dominant error in DME. With the improvements in ranging accuracy, it is predicted that eDME could support RNP 0.3, with an operational radius from the eDME ground station of about 140 NM (RTCA SC-227, 2025b).

Deployment Status / Ease of Deployment: eDME will require both new ground and airborne equipment. However, as ground stations are upgraded, they would still be able to support legacy DMEs making eDME fully backwards compatible.

Spectrum Compatibility and Capacity Limitations: eDME includes a pseudoranging mode of operation, reducing the frequency at which the airborne radio would need to interrogate ground stations. Depending on the accuracy of the GS network synchronization, the frequency of interrogations could be much less than 1 Hz, after initial acquisition. Thus, eDME should have much improved capacity compared to existing DME. However, the waveform would still be less than optimal from a PAPR perspective.

Support for Timing and Other Applications: Depending on whether ground stations are synchronized, it is possible that eDME could support timing. However, eDME would still be an aviation-specific system and would not support other applications.

Authentication: eDME is expected to have improved data communications capability, so some form of authentication will be included, although the low data rate would likely limit the authentication reliability.

Recommended Use Cases: eDME would be able to support modern PBN procedures to a level of RNP 0.3, making eDME a prime candidate to support terminal area and non-precision approach operations. The relatively long range of DME means that eDME could support domestic enroute operations in higher traffic areas at a level of RNAV2 with perhaps only modest increase in ground station deployment.

eLoran

Achievable Performance and Coverage: A major advantage of eLORAN is that it is a very high-power ground wave operating at 100 kHz, thus its propagation is well beyond line of sight, up to 1000 NM, so operations can be extended to remote continental and coastal areas with relatively sparse ground installations. With ground monitoring providing real-time ground conductivity measurements in the vicinity of the user, eLORAN can provide precise time and positioning. Along with the accuracy and integrity provided via the eLoran data channel, RNP 0.3 is achievable. (International LORAN Association, 2007). At longer ranges without ground monitors in the vicinity, it is expected RNAV 1 could be supported, although over saltwater propagation errors are much less, so RNP 1 or better might possible, with enough measurement redundancy.

Deployment Status / Ease of Deployment: While there are some eLORAN stations deployed or planned, new ground infrastructure will be required to provide widespread service. Furthermore, certified eLORAN airborne receivers do not presently exist, nor are there any industry design standards for such equipment. Therefore, deployment of eLORAN for aviation will be a years-long process.

Spectrum Compatibility and Capacity Limitations: eLORAN operates at 100 kHz, far from GNSS L-band frequencies, which is why we evaluate it highly on the spectrum compatibility criterion. Furthermore, eLORAN is a passive system, so is not capacity limited.

Support for Timing and Other Applications: eLORAN is capable of disseminating timing at a level of 100 ns or better, more than adequate for most aviation applications. eLORAN also can support maritime, ground mobile, and network timing applications, so investment in eLORAN infrastructure could be quite cost-effective.

Authentication: Authentication is supported in the eLORAN data channel, which includes encryption, but the low data bandwidth means that this will be limited in the level of sophistication. On the other hand, the high transmit power of eLORAN and it 100 kHz broadcast frequency would be challenging, this making transmission of a similar signal capable of jamming or spoofing very unlikely.

Recommended Use Cases: eLORAN could be used for enroute and terminal area navigation down to RNAV 1 and also support NPA with minimal ground monitoring and considerably less ground infrastructure than other systems. In many areas, ground monitoring capability installed for maritime harbor entrance navigation could also be used to support RNP 0.3 at nearby airports. Another key potential use of eLORAN would be a means to synchronize ground stations for other CPNT sources, like eDME or LDACS.

LDACS-NAV

Achievable Performance and Coverage: As LDACS is still undergoing development and standardization, the performance of a future LDACS-NAV is speculative. However, under assumption of adequate multiple ground station coverage and ground network synchronization, simulated LDACS-NAV results show support for RNP 0.3 or better and ADS-B NACp = 8 (Zampieri et al., 2023). While LDACS transmits at 1% or less of the peak power of a DME, the strong forward error correction coding enables reception at ranges that equal or exceed DME, although still LOS-limited.

Deployment Status / Ease of Deployment: LDACS-COM is currently undergoing ICAO standardization, but the LDACS-NAV standardization process has not started. Furthermore, LDACS will require new avionics and ground installations, and initial deployment would likely occur in areas with high air traffic density, where legacy VHF datalinks do not provide sufficient capacity. Therefore, early LDACS-NAV capability would likely be limited to terminal areas and would likely require additional ground stations to be deployed beyond the needs of COM if it is to be a standalone CPNT source. LDACS is designed to be compatible with existing L-band avionics, although it is likely that older surveillance equipment may need to be replaced with newer units that have better out of band signal rejection characteristics.

Spectrum Compatibility & Capacity Limitations: The low transmit power of LDACS (relative to DME) and the dual COM/NAV use makes for excellent spectral compatibility. as does the fact that it matches improves on the navigation performance of DME at 0.1 % of the peak power. But it is capacity limited as any two-way COM system.

Support for Timing and Other Applications: LDACS has a defined system time definition that is traceable to GNSS time standards/UTC (ICAO DCIWG PT-T, 2024). LDACS is being developed for aviation applications, but its multifunction capabilities would make it useful for emerging AAM applications.

Authentication: The LDACS COM implements state-of-the-art multi-layered data security, encompassing both the control and data planes, to address modern cyber threats (ICAO DCIWG PT-T, 2024). These capabilities can benefit CPNT security as well.

Recommended Use Cases: Around airports and terminal control areas it may be cost effective to deploy LDACS to provide both high-capacity COM and CPNT. In places where LDACS coverage is limited to one or two stations at a time, LDACS ranging measurements could serve as an augmentation to eDME measurements, thus an area where eDME can only provide LNAV 1, might be able to support RNP 1 or RNP 0.3.

LEO PNT

Achievable Performance and Coverage: It does not seem likely that aviation authorities would accept use of signals of opportunity from LEO-SATCOM signals absent some sort of performance guarantees. Thus, even though considerable attention has been garnered from demonstrations of PNT from massive LEO-SATCOM constellations like Starlink, it is our position that they are not suitable for safety-of-life applications. There are other LEO systems that are intended for PNT, such as the deployed Iridium/STL system and the proposed constellations from Xona Space Systems and TrustPoint. Iridium does not provide snapshot positioning solutions, but instead relies on accumulated Doppler observables over minutes. This is fine for static positioning or on slow-moving platforms like ships, but for aviation high-rate positioning would require integration with stable inertial navigation systems. This might be acceptable for some classes of users but cannot be assumed for all users. The concepts from Xona and TrustPoint propose to provide snapshot positioning. While coverage from these systems might be global, it is hard to assess what kind of integrity case can be made for these services, so we can only speculate what operational service level can be obtained.

Deployment Status / Ease of Deployment: Iridium/STL is deployed, and aviation receivers for the basic Iridium COM services are available, but these would have to be upgraded for the Iridium/STL PNT capability, and these radios would likely need to meet higher design assurance levels. Other systems would need new satellites, avionics and ground control installations. The certification complexity implies it would take many years for standards and equipment to be developed.

Spectrum Compatibility and Capacity Limitations: To the extent these systems would operate outside the GNSS bands they can be regarded as spectrally efficient. Some of these systems will have capacity limits if they involve two-way communication, like Iridium.

Support for Timing and Other Applications: It is likely that these systems would all be able to provide timing and definitely could support other applications.

Authentication: Presumably some sort of security features could be built included, but this is difficult to evaluate.

Recommended Use Cases: LEO PNT could be used for synchronizing ground infrastructure particularly over longer distances.

5G Cellular

Achievable Performance and Coverage: While cellular systems have been widely used in different ways for pedestrian and ground vehicle navigation, the standard protocols would likely not apply to fast-moving aircraft flying at thousands of feet above the ground. There have been many demonstrations using cellular signals of opportunity for drone positioning, but as discussed above, absent some sort of performance guarantees, this would likely not be acceptable for civil air transport. The relatively short range of current cellular systems implies that a combination of new signal structures and more ground infrastructure would likely be needed to provide coverage.

Deployment Status / Ease of Deployment: The fast-paced development cycles of mobile applications can be incompatible with aviation and fundamental questions remain open, such as whether mobile operators are willing to subject their systems to the rigorous certification processes that are customary for aviation systems.

Spectrum Compatibility and Capacity Limitations: The use of spectrum outside of GNSS bands would make mobile cellular spectrally efficient from the aviation perspective. While the high bandwidth of 5G systems implies many users can be supported, individual ground stations would have capacity limits and it is questionable how aviation could be supported at the same time as terrestrial users.

Support for Timing and Other Applications: It is likely that these systems would all be able to provide timing and definitely could support other applications.

Authentication: As a two-way communication system some security features are built in. The benefits of such features for a CPNT service need to be quantified.

Recommended Use Cases: 5G cellular is a good candidate for emerging AAM applications that will fly at lower altitudes and slower speeds than air transport aircraft.

Commercial Pseudolites

Achievable Performance and Coverage: Most of these systems have short range as they are intended for urban or indoor environments. Locata (Rizos & Yang, 2019) has been used at longer ranges at DoD test ranges for truth positioning during GPS jamming and is able to achieve well below meter-level accuracy. NextNav has been demonstrated as a GNSS backup for low-altitude drones (Tenny & Humphreys, 2022), but it is unclear how it would perform at the altitudes associated with air transport aviation.

Deployment Status / Ease of Deployment: It is unclear if the owners of these systems would be willing to subject their systems to the rigorous certification processes that are customary for aviation systems.

Spectrum Compatibility & Capacity Limitations: The use of spectrum outside of GNSS bands would make most of these systems spectrally efficient from the aviation perspective. Some systems are passive, whereas others are two-way, so it is an open question on how well aviation could be supported.

Support for Timing and Other Applications: It is likely that these systems would all be able to provide timing and definitely could support other applications.

Authentication: Presumably some sort of security features could be built included, but this is difficult to evaluate.

Recommended Use Cases: Possible candidates for emerging AAM applications that will fly at lower altitudes and slower speeds than air transport aircraft.

Bibliography

Del Peral-Rosado, J. A., Schlötzer, S., Ince, E., Nolle, P., Kaltenberger, F., Sirola, N., Garlaschi, S., Canzian, L., Lapin, I., & Flachs, D. (2024). Sub-Meter Hybrid Positioning with Flying 5G Networks and Synchronization Corrections. *37th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2024)*, 2487–2494. https://doi.org/10.33012/2024.19942

EASA, (European Union Aviation Safety Agency). (2024, July 5). *Safety Information Bulletin 2022-02R3: Global Navigation Satellite System Outage and Alterations Leading to Communication / Navigation / Surveillance Degradation*. easa.eu. https://ad.easa.europa.eu/ad/2022-02R3

EUROCAE WG-85. (2025a). *ED-75F - Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation*.

EUROCAE WG-85. (2025b). *ED-323—Minimum Operational Performance Standards for Required Navigation Performance for Area Navigation*.

Federal Aviation Administration. (2004). *Loran's Capability to Mitigate the Impact of a GPS Outage on GPS Position, Navigation, and Time Applications*. Federal Aviation Administration.

Federal Aviation Administration. (2016). *Advisory Circular 20-138D, Change 2, Airworthiness Approval of Positioning and Navigation Systems*. https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_20-138D_with_Change_1__2.pdf

Federal Aviation Administration. (2023a, April 26). *Urban Air Mobility (UAM) Concept of Operations Version 2.0*.

Federal Aviation Administration. (2023b, July). *Advanced Air Mobility (AAM) Implementation Plan: Near-term (Innovate28) Focus with an Eye on the Future of AAM, Version 1.0*.

GPS.gov: National Space-Based Positioning, Navigation, and Timing Advisory Board. (2024). https://www.gps.gov/governance/advisory/

gpsjam.org. (n.d.). *GPSJAM GPS/GNSS Interference Map*. Gpsjam.Org. Retrieved November 18, 2024, from https://gpsjam.org

ICAO. (2023). *Performance Based Navigation (PBN) Manual (Doc 9613)* (5th ed.). https://store.icao.int/en/performance-based-navigation-pbn-manual-doc-9613

ICAO DCIWG PT-T. (2024). *LDACS Manual—Part A: Functionalities, Capabilities, and Performance* (10172). (Draft)

International Civil Aviation Organization. (2023). *Annex 10 to the Convention on International Civil Aviation, Aeronautical Communications. Volume I: Radio Navigation Aids. Eighth Edition*.

International LORAN Association. (2007). *Enhanced LORAN (eLoran) Definition Document v1*. https://rntfnd.org/wp-content/uploads/eLoran-Definition-Document-0-1-Released.pdf

Li, K., & Pelgrum, W. (2013). Enhanced DME Carrier Phase: Concepts, Implementation, and Flight-test Results: eDME: Concepts, Implementation, and Flight-tests. *Navigation*, *60*(3), 209–220. https://doi.org/10.1002/navi.42

Liang, X., Milner, C., Macabiau, C., Estival, P., & Zhao, P. (2024). Performance-Based Multi-DME Station Selection. *IEEE Transactions on Aerospace and Electronic Systems*, *60*(5), 6299–6312. https://doi.org/10.1109/TAES.2024.3407049

Lo, S., & Chen, Y.-H. (2020). Message Design for a Robust Time Signal using Distance Measuring Equipment (DME) Pulse Pair Position Modulated (PPPM) Pseudo lite. *2020 European Navigation Conference (ENC)*, 1–10. https://doi.org/10.23919/ENC48637.2020.9317492

Lo, S., Chen, Y.-H., Segal, B., Peterson, B., Enge, P., Erikson, R., & Lilley, R. (2014). Containing a Difficult Target: Techniques for Mitigating DME Multipath to Alternative Position Navigation and Timing (APNT). *Proceedings of the 2014 International Technical Meeting of The Institute of Navigation*, 413–423.

Meiyappan, S., Raghupathy, A., & Pattabiraman, G. (2013). Positioning in GPS Challenged Locations—The NextNav Terrestrial Positioning Constellation. *26th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2013)*, 426–431.

OPSGROUP. (2024, September 6). *GPS Spoofing, Final Report of the GPS Spoofing WorkGroup*. https://ops.group/blog/gps-spoofing-final-report/

Osechas, O., Felux, M., & McGraw, G. (2024). Navigation Needs for the Unpiloted Airspace. *2024 International Technical Meeting of The Institute of Navigation*, 177–185. https://doi.org/10.33012/2024.19576

Osechas, O., Narayanan, S., Crespillo, O. G., Zampieri, G., Battista, G., Kumar, R., Schneckenburger, N., Lay, E., Belabbas, B., & Meurer, M. (2019). Feasibility Demonstration of Terrestrial RNP with LDACS. *32nd International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2019)*, 3254–3265. https://doi.org/10.33012/2019.17119

Rizos, C., & Yang, L. (2019). Background and Recent Advances in the Locata Terrestrial Positioning and Timing Technology. *Sensors*, *19*(8), Article 8. https://doi.org/10.3390/s19081821

RTCA SC-227. (2025a). *DO-236E - Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation*.

RTCA SC-227. (2025b). *DO-283C - Minimum Operational Performance Standards for Required Navigation Performance for Area Navigation*.

Schneckenburger, N., Elwischger, B., Shutin, D., Suess, M., Belabbas, B., & Circiu, M.-S. (2013). Positioning Results for LDACS1 Based Navigation with Measurement Data. *26th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2013)*, 772–781.

Scott, L. (2021). Interference: Origins, Effects, and Mitigation. In J. Morton, F. Diggelen, F. Spilker, & B. Parkinson (Eds.), *Position Navigation & Timing Technologies in the 21st Century* (1st ed., Vol. 1). Wiley.

Shamaei, K., & Kassas, Z. M. (2018). LTE receiver design and multipath analysis for navigation in urban environments. *NAVIGATION*, *65*(4), 655–675. https://doi.org/10.1002/navi.272

Skai Data Services. (n.d.). *Live GPS Spoofing and Jamming Tracker Map*. Retrieved November 18, 2024, from https://www.spoofing.skai-data-services.com/

Tenny, R., & Humphreys, T. E. (2022). Robust Navigation for Urban Air Mobility via Tight Coupling of GNSS with Terrestrial Radionavigation and Inertial Sensing. *35th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2022)*, 1599–1609. https://doi.org/10.33012/2022.18469

Zampieri, G., McGraw, G. A., Osechas, O., Weaver, B., & Meurer, M. (2023). LDACS APNT Service Area Analysis with Barometric Altimeter Augmentation and Ground Station Selection Constraints. *Proceedings of the 36th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2023)*, 727–738. https://doi.org/10.33012/2023.19230