Terrestrial Navigation Alternatives to Support PBN for Current and Future Aviation*

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BIOGRAPHY

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ABSTRACT

This paper recommends technologies for aviation authorities to consider to make Performance Based Navigation (PBN) services more resilient to GNSS Radio Frequency Interference (RFI) and other threats. Combining toughened GNSS with terrestrial Complementary Positioning, Navigation and Timing (CPNT) will enable seamless PBN services during GNSS degradation or loss, yielding many benefits to efficiency and airspace utilization, and ultimately for safety. The analysis here considers diverse, viable PNT alternatives to GNSS for both Conventional Air Transport (CAT) and Advanced Air Mobility (AAM) aviation and proposes 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 for CAT: Enhanced Distance Measuring Equipment (eDME), Enhanced Long Range Navigation (eLORAN), and L-Band Digital Aviation Communication System-Navigation (LDACS-Nav). For AAM the analysis indicates a different mix: eLORAN, LDACS-Nav, and possible developments in 5G Cellular, Commercial Pseudolites and new AAM/drone data links. 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.

1. 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 ground-base navigation aids (GBNAs) can support legacy performance requirements of basic enroute and terminal area traffic, but do not support the most stringent PBN levels needed for modern air traffic procedures. Some improvement is possible in the near term by increasing the density of legacy navigation aids like DME, but supporting wider PBN deployment will require terrestrial systems with higher performance.

GNSS positioning excels in providing PBN services to aviation users on a global scale, delivering better performance than most enroute and terminal operations require. However, it has become apparent that 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 (PNT Advisory Board, 2024), 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 how much GNSS can be toughened and there are 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 CPNT systems, i.e., the “Augment”

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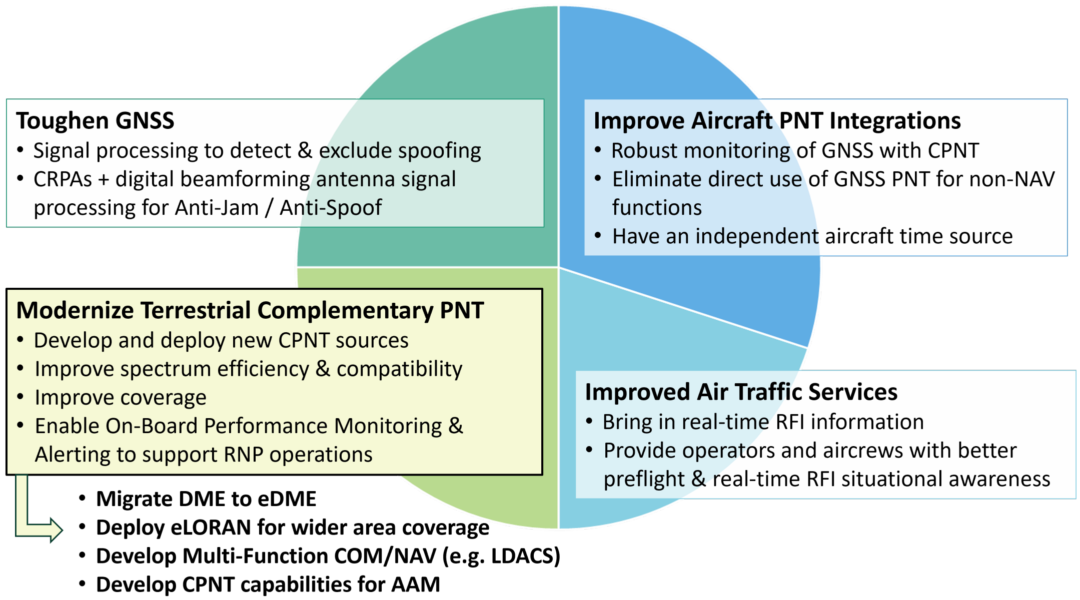

Figure 1: High-level summary of the recommendations of this paper for addressing the RFI challenge to PBN. These recommendations involve multiple areas, with a focus on modernizing terrestrial CPNT for Conventional Air Transport, recognizing the need for additional developments to support Advanced Air Mobility.

part of PTA. But as illustrated in Figure 1, "Toughen" and "Augment" are only half the battle in aviation: other areas, including improving how PNT information is integrated with other aircraft systems and providing better RFI situational awareness to operators and flight crews, are needed to fully exploit the capabilities provided by toughened GNSS and CPNT augmentation.

This paper considers a broad range of potential CPNT systems but does not claim to provide an exhaustive survey. Instead, the 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 have approval in process. While it must be acknowledged that no single terrestrial navigation system can possibly match GNSS performance globally, there are solutions that offer viable alternatives, especially to 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.

Combining toughened GNSS with terrestrial CPNT will enable maintaining seamless PBN services during GNSS degradation or loss, yielding many benefits to efficiency and airspace utilization, and ultimately on safety. Naturally, the degree of economic benefit of resilient PBN will depend on traffic loads and airspace configuration, and on the state of PBN implementation. However, with the increasing frequency of RFI events and growth in air traffic, the need to augment GNSS with modernized terrestrial CPNT is becoming ever clearer and urgent.

The analysis indicates that systems not developed by the aviation community such as 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 GBNAs, especially for CAT. Accordingly, our recommendations for the CAT sector 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 development of Enhanced LORAN (eLORAN) for aviation, as this system can provide coverage over larger areas with less infrastructure;
- 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 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

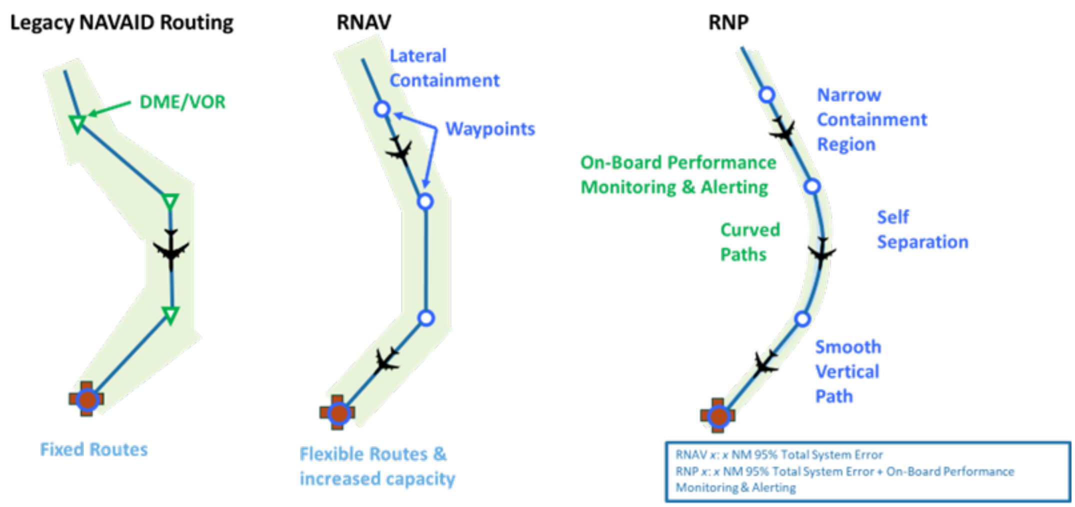

Figure 2: Benefits of PBN. Legacy routing requires the aircraft track to follow the physical layout of the NAVAIDs. RNAV enables a more flexible selection of the track, following database waypoints. RNP adds fixed-radius segments, plus OBPMA, which comes with the ability to "self-separate".

each system. Furthermore, eLORAN can also serve as a timing to aid in synchronizing eDME and LDACS ground stations.

For AAM, the recommendations are less definitive, as PBN standards for this segment have not been defined. However, it is likely that eDME will not be viable for AAM and some of the attributes of 5G cellular and/or commercial pseudolite systems that make them not suitable for CAT may not be as big an issue for AAM. Furthermore, there are data link developments for AAM (Becker and Schalk, 2024a,b) that may offer other potential CPNT candidates.

In addition, this paper does not consider precision approach and landing, as the Instrument Landing System (ILS) is an effective backup for GNSS approaches at larger airports, although often with a reduction in capacity. It also must be recognized that ILS does not address the needs for precision approach and landing for AAM.

2. BACKGROUND: PERFORMANCE-BASED NAVIGATION

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 (International Civil Aviation Organization (ICAO), 2023). The characteristics and benefits of PBN are summarized in Figure 2.

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

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

Note that the standard TSE equation often includes a term for the Path Definition Error (PDE), but with the development of GNSS-based geodesy, PDE is typically assumed to be The FTE is the control error that quantifies "the flight crew or autopilot's ability to follow the aircraft navigation system's defined path or track" International Civil Aviation Organization (2023). A large FTE can stem from a finite response time to control inputs, e.g., after a change in direction, or it can come from disturbances 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%.

The development of PBN has been heavily linked to GNSS navigation. However, GNSS is not the only system certified for RNAV, as discussed in later sections. For RNP, however, the situation is different as currently only GNSS can enable RNP. 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 GBNAs 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.

To support more complex airspace operations, RNP can be further enhanced 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.

3. ADAPTING PBN TO AAM

While PBN is a widely used tool in making airspace more efficient, with RNP in particular enabling more advanced operations, AAM applications had not been envisioned when PBN was introduced. As such, further development work is needed to fully realize the potential of PBN in AAM. As a simple example, RNP is based on the assumption that a user follows a ground track, given in pairs of latitude and longitude, but does not consider altitude directly. Instead, the aircraft receives an RNP clearance for a specific flight level, which in turn is an isobaric surface measured in height above mean sea level (MSL). AAM routing, by contrast, will likely be based on geometric altitude because it will be critical to maintain separation from terrain and barometric altitude would vary with meteorological conditions. Note that barometric measurements of height could be still be used, but they would need to be corrected by local surface pressure.

Key differences in how PBN is implemented in conventional airspace vs. AAM enroute airspace, stem from the nature of the air vehicles and their operating environments. Conventional aircraft, from mainline to general aviation (GA), fly well outside, or above, urban and suburban areas. On the relatively rare occasions that aircraft do enter populated areas, they do so under Visual Flight Rules (VFR), which require a pilot on board. The objective of many AAM developments is to operate without pilots, and so new services need to be defined and implemented. In addition, because of the needs of noise abatement and flying in and around built-up areas, it is expected that AAM corridors will require smaller RNP values than comparable CAT operations (Osechas et al., 2024). So instead of RNP 1 or greater for enroute CAT operations, AAM may need to meet RNP 0.3 or likely below to provide meaningful services above urban and sub-urban areas.

To achieve higher performance RNP for AAM, both the NSE and FTE will need to be addressed. In CAT it is common for PBN routes to accommodate a large variety of potential aircraft by using a standard allocation of 0.125 NM for the FTE, as required by the applicable standards (RTCA SC-227, 2025b), (EUROCAE WG-85, 2025a). The allocation is the same for a fully loaded four-engine jetliner as for an empty twin-engine regional jet; this may be conservative for the regional jet, but is assumed in the interest of simplicity. Applying that same buffer to an AAM vehicle, however, is both unrealistic and would also impede the definition of services with TSE below 0.125 NM. In terms of FTE, AAM vehicles will fly slower, with tighter turn radii and have higher thrust to weight ratio than conventional fixed-wing jet aircraft or even conventional helicopters, so their FTE is expected to be smaller as postulated by Geister et al. (2018). Whether the FTE can be made arbitrarily small is a question for future work. An example provided by Geister et al. (2018) quantifies the FTE of a 4 kg drone, powered by 400 N of thrust, which leads to FTE on the order of a few meters, under winds of up to 13 kts. The maximum FTE can be reduced by adequate design of the flight control system, by limiting the maximum wind speed for safe operation or by increasing the thrust-to-weight ratio of the aircraft.

In addition to the lateral component, defined by the TSE, PBN can also support vertical navigation and time-of-arrival services. These are less widely adopted in conventional aviation, but the standards support both, making PBN a full four-dimensional navigation standard. However, as with all PBN services, the operational assumptions behind the designs differ significantly from what AAM will likely require.

4. RFI THREATS TO AVIATION

A recent rise in RFI activity has highlighted the dependence of aircraft, and indeed the entire airspace system, on GNSS. The dependencies go well beyond navigation and impact the ability of aircraft to communicate, to recognize and stay clear of obstacles and Air Traffic Management (ATM) airspace surveillance. 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.

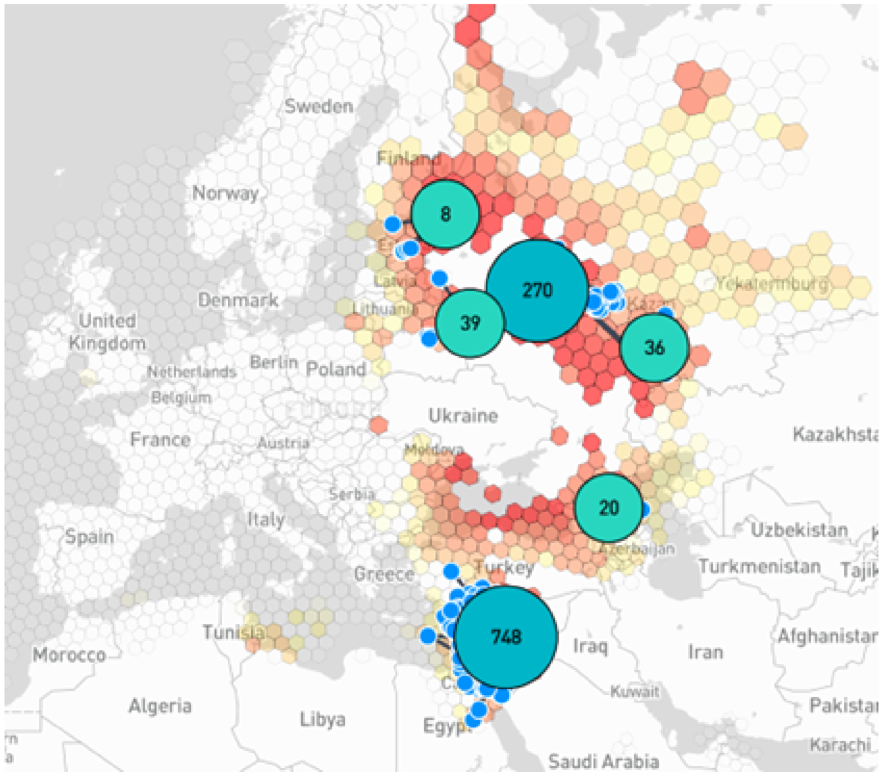

Figure 3: Flights are now regularly spoofed on daily basis and GNSS-based operations have become unavailable in many areas (Skai Data Services, 2024). This map is for a 24-hour period in the Summer of 2024; a circle with a number inside indicates the number of flights experiencing spoofing during that period. Different shades of orange or red indicate the likelihood of GNSS jamming.

4.1 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, 2024) and The Zurich University of Applied Sciences (ZHAW) (Skai Data Services, 2024) 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 a 24 hour period in the Summer of 2024. It shows that over one thousand flights were spoofed over this period. While the number of RFI events varies over time and where they occur, there is every indication that these incidents are ongoing. 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 multi-element 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. While there are pending changes to these export rules, introduction of CRPA technologies into aviation will be a lengthy process. In addition, appropriate GNSS integration with inertial and other sensors is another effective RFI-mitigation technique that also needs to be considered.

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.

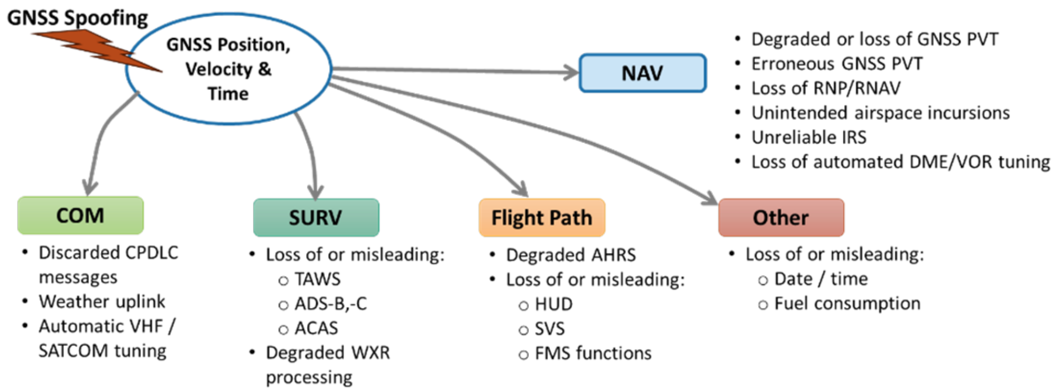

Figure 4: GPS spoofing has led to degradation to multiple aircraft systems, demonstrating that GPS has become a single point of failure. The dependence of some of the systems, failing during RFI, is not intuitive and should, arguably, not be happening. [Adapted from OPSGROUP (2024)].

4.2 RFI Impact on Aircrews and ATM

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 air traffic controllers, particularly when multiple aircraft are affected, has a profound impact on safety margins (OPSGROUP, 2024). 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 (European Union Aviation Safety Agency (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. RFI also impacts air-traffic controller workload in several ways. Loss of GNSS, currently considered primary navigation, will require a change in operations even when supported by current 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. Enhanced simulator training for cockpit crews for handling GNSS RFI would help in restoring safety margins that get eroded during interference events, but are not a long-term solution.

4.3 RFI 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 GBNAs 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 GBNAs. The US National Airspace System operates with a so-called Minimum Operational Network (MON). 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. GBNAs 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.

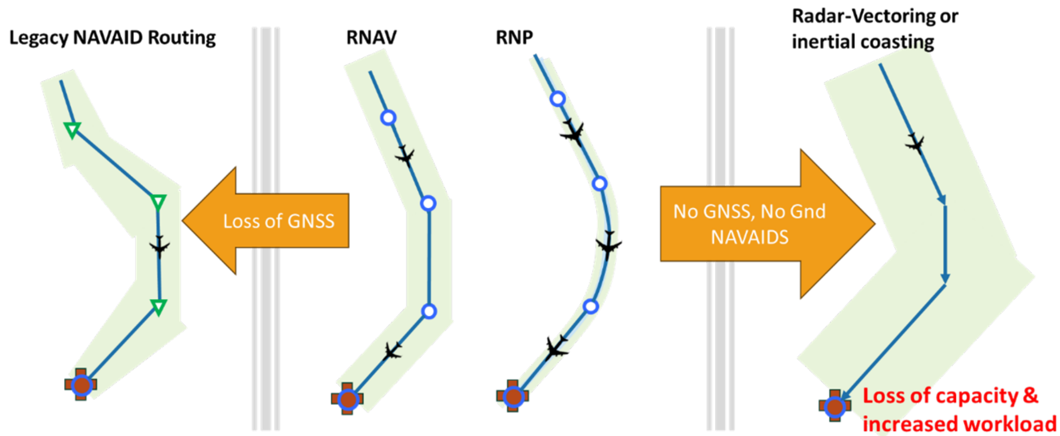

Figure 5: In areas with a strong infrastructure of GBNAs, RNAV can fall back on that during RFI. In some areas, PBN becomes completely unavailable, as RNP is lost.

4.4 AAM RFI Environment & Operational Impacts

For enroute flight, AAM will fly at relatively low altitudes, roughly 1000 - 4000 ft, so are more likely to be disrupted by ground-based RFI sources compared to CAT aircraft flying at higher altitudes. Most published AAM operational concepts generally assume the availability of GNSS and make no mention of GNSS loss or the need for CPNT (Federal Aviation Administration, 2023; Cozzens et al., 2024). As AAM moves from piloted towards remotely-piloted and eventually fully autonomous operation, the lack of a pilot onboard means that there will not be a human backup in the case of loss of GNSS navigation. Furthermore AAM will likely require more automated air traffic management (FAA, 2023), which implies the need highly reliable and redundant CNS capabilities. As conventional secondary surveillance radar may not be provide sufficient coverage in some AAM operational environments, automatic dependent surveillance based on the aircraft transmission of its navigation solution may be needed. All these factors point to the extreme vulnerability of AAM operations that dependence on GNSS entails.

5. MODERNIZATION OF CPNT INFRASTRUCTURE

5.1 Background

Current terrestrial infrastructure emits 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 also outdated. 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 unless 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 many of these concerns.

An added benefit of implementing resilient CPNT systems is that they will severely limit, and even in some situations 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.

5.2 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., the lowest RNAV or RNP value likely achievable.

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 Universal Coordinated Time (UTC).

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

5.3 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, 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 COM/NAV systems.

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 AAM. 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) and Tenny and 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.

5.4 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 illustrates. 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,b; RTCA SC-227, 2025a,b).

A second group of technologies is that of enhancing some of these legacy technologies, in particular: eDME (Li and Pelgrum, 2013; Lo et al., 2014; Lo and 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.

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 and 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. There are also emerging data links under early development to support air-to-air and command and control communications for drones and AAM applications (Becker and Schalk, 2024a,b) that may be future CPNT candidates. 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 present a number of new challenges. Many implementations rely on Doppler changes over an observation interval for positioning; on aircraft this might entail the need for tight integration with navigation-grade inertials. LEO satellites will operate within the ionosphere, which presents unique challenges with satellite orbit determination during solar storms along with ranging error compensation.

Another interesting class of GBNAs 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 and Yang, 2019). Some of these systems may have years of operational experience outside aviation applications. However, the certification process for these systems to be used by aviation will still be significant and their performance characteristics (accuracy, availability, integrity, continuity, and especially coverage) may not warrant their use in CAT aviation use cases, but their technical benefits could make them a workable solution for certain types of environments.

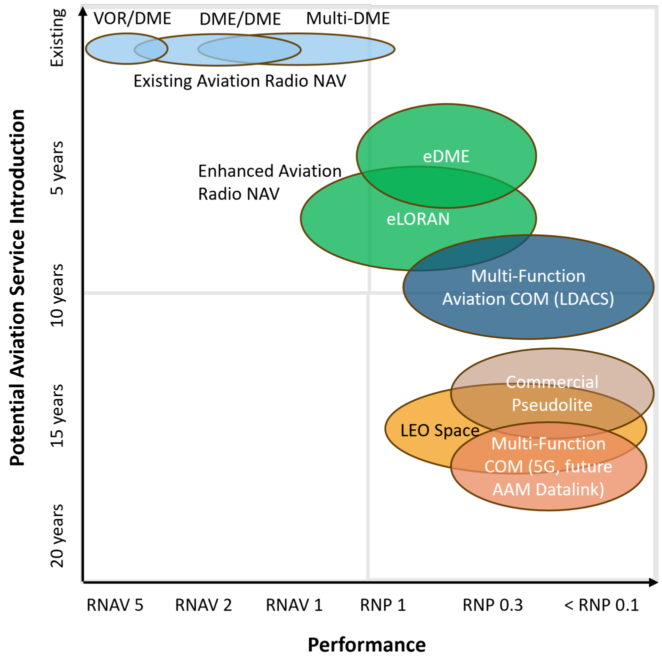

Figure 6: Candidate CPNT technologies, with potential performance and aviation service introduction. Existing NAVAIDS do not meet all the needs for PBN, pointing towards the need to modernize them. Existing and new pseudolite and multi-function COM systems may be able to meet the requirements for Advanced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

5.5 CAT CPNT Analysis

This section summarizes the analysis of the candidate CPNT alternatives against the criteria discussed above, which forms the basis for our recommendations. Figure 7(a) provides a graphical summary of the analysis for CAT, with the details of the evaluations provided in Osechas and McGraw (2024). Figure 7(b) provides a summary for AAM which will be discussed in the next section.

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. Signals with coherent carrier phase, like eDME and LDACS-NAV, can use carrier-smoothed code processing to mitigate multipath, providing improved ranging accuracy. Commercial pseudolite systems might offer wider bandwidth signals than aviation-specific systems and therefore provide better code ranging accuracy, but spectrum compatibility and availability become more challenging.

In terms of capacity limitations, some systems like DME use two-way ranging which necessarily has a maximum number of allowable users; others offer either full pseudoranging (PR) modes, like eLORAN, which is passive and has no limit on the number of users, or partial PR modes, like eDME and LDACS-NAV, with higher duty cycle for the ground-to-air link than the air-to-ground, enabling more aircraft to be supported by a ground station.

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.

In Figure 7(a), LDACS-NAV is given a more favorable evaluation over 5G Cellular or Commercial Pseudolites primarily based on the operational coverage offered, which is a particular concern for supporting large service volumes. Furthermore, LDACS will have a head start on certification for safety-of-life services. Similarly, the uncertainty of LEO SATNAV characteristics and

	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

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

(a) Evaluation for Conventional Air Transport

	Operations Supported	Operational Coverage	Deployment	Spectrum Compatibility	Capacity Limits	Provides Timing	Authentication
eLORAN	RNAV 1 – RNP 0.3	~1000 NM to <50 NM	New Gnd / Air Equip.	Not L-Band	Passive	<100 ns	Encrypted data channel
LDACS-NAV	< RNP 0.3	200 NM	New Gnd / Air Equip.	Shared with COM	Ranging, PR modes	< 100 ns	Two-Way COM Protocols
5G Cellular, AAM COM	<RNP 0.3 ?	<10 NM	New Air, Expanded Gnd	Shared with COM	Two-way COM	< 100 ns	Two-Way COM Protocols
Commercial Pseudolite	<RNP 0.3 ?	<20 NM ?	New Gnd /Air Equip.	Not ARNS spectrum	PR, ranging modes	<< 100 ns	Likely
LEO SATNAV	<RNP 0.3 ?	Potentially Global?	New SVs / Air Equip.	Shared with COM	Passive? Spot Beams?	< 100 ns	Likely

(b) Evaluation for Advanced Air Mobility

Figure 7: Summary of CPNT sources and evaluation. See Osechas and McGraw (2024) for details of the rationale for these evaluations.

performance lowers the evaluation as described in more detail in Osechas and McGraw (2024).

5.6 AAM CPNT Analysis

Given that AAM services have not yet been operationally deployed, nor PBN/RNP standards set for AAM operations, the analysis presented here is somewhat speculative. It is reasonable to assume that AAM vehicles will operate in both conventional controlled airspace, e.g., around airports, and dedicated airspace for AAM and possibly conventional helicopters. Therefore, AAM aircraft may need to be equipped with navigation equipment for both conventional airspace and AAM airspace operations. As discussed in Section 3, low altitude AAM enroute corridors will require smaller RNP values, possibly as low as RNP 0.05 (Osechas et al., 2024). For AAM vehicles there are numerous reasons to assume a reduction of the FTE is feasible (Geister et al., 2018). GNSS, particularly augmented with SBAS, can achieve the NSE required to meet these tight RNP values or less. In times of GNSS RFI, reducing the NSE will require highly accurate CPNT performance.

As indicated in Figure 7(b), conventional GBNA designed to support CAT airspace have been eliminated from detailed consideration for AAM, based primarily on inability to achieve reduced NSE. Legacy GBNA signals are unable to support RNP less than 0.3 NM, due to the possibility of large multipath errors. Furthermore conventional GBNAs are sited to serve CAT airspace, not AAM low altitude enroute operations. To cover new AAM routes, new GBNAs will need to be installed, which will be difficult for legacy GBNAs for a variety of reasons. Especially for DME, existing frequency channel congestion in high traffic areas would be a challenge. Even for eDME, the high peak power required makes siting sufficient numbers of ground transmitters difficult. On the air side, integration of eDME interrogators on small AAM aircraft would likely cause interference issues with other L-Band systems like TCAS. In contrast, LDACS requires less power and therefore needs less separation from other antennas.

Enhanced LORAN may address AAM operations in some instances, but achieving RNP under 0.3 NM means that the performance evaluation shown in Figure 7(b) is downgraded compared to the CAT evaluation in 7(a). This is due to the accuracy with which the so-called Additional Secondary Factors (ASF) can be corrected. With adequate compensation of ASF and all other propagation issues, it is possible that eLORAN could bring navigation benefits to AAM, but it will require careful analysis of the integrity case.

Another area where the AAM evaluation shown in Figure 7(b) differs from the CAT evaluation in Figure 7(a) is in the criterion of operational coverage. The relative short ranges of Commercial Pseudolites and 5G Cellular are less of a concern for AAM compared to CAT, so their evaluations in this aspect are upgraded. Similarly, full-power LDACS-NAV operational range would likely cover the entire operational radius for most AAM routes in a metropolitan area, although having more, lower-power ground stations may provide better solution geometry overall. Emerging air-to-air and command and control data links for drones and AAM (Becker and Schalk, 2024a,b) should also be evaluated for CPNT potential.

As discussed previously, the implementation of urban RNP services based on cellular signals is technically feasible but not necessarily straightforward to certify for safety-of-life operations. Deriving such critical navigation services from cellular infrastructure will require not only new technical capabilities, but also new business and regulatory models to deploy and maintain these capabilities.

Much like GNSS is subject to RFI, it should be noted that cellular signals are also known to be jammed. In fact, most established CNS systems can be jammed, certainly all established GBNA. The introduction of new airframes, therefore, also represents a rare opportunity to re-design the avionics architecture of the new entrants, without the burden of backwards compatibility. With changes to ITAR regulations, the introduction of AAM could also be an opportunity to introduce array antenna technology for many of the CNS radio systems on board, making AAM vehicles more robust to RFI, which will be key for migration to increasing autonomy.

6. RECOMMENDATIONS FOR MODERNIZING TERRESTRIAL CPNT

From the evaluation summarized in Figure 7, three technologies stand out as particularly attractive for achieving resilience in civil airspace for CAT: 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 carrier smoothing (Li and Pelgrum, 2013). Combining these enhancements with processing of multiple (more than two) observables per position fix (Liang et al., 2024) 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 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 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 recommendations for AAM CPNT build on the ones for CAT. LDACS-NAV and eLORAN are viable candidates to support AAM low altitude enroute operations and would enable operations in conventional airspace. Exclusion of DME/eDME in the

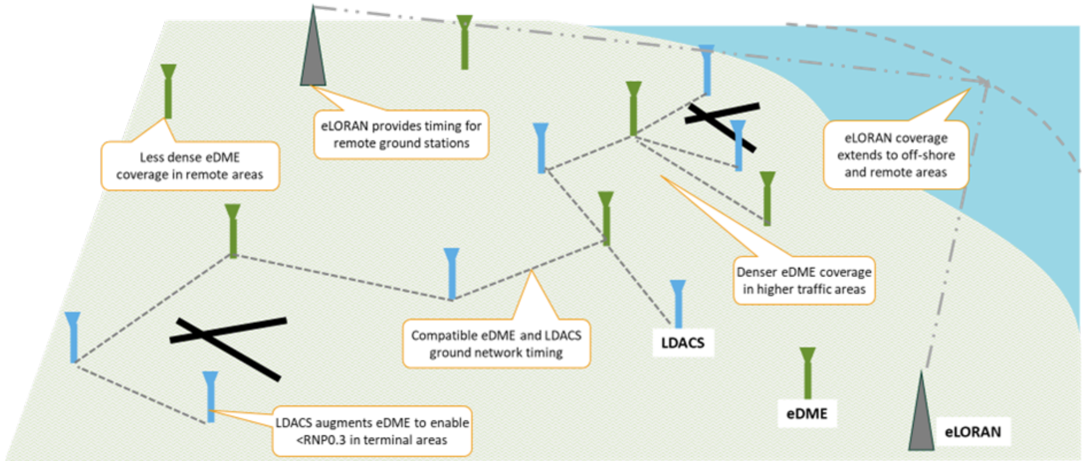

Figure 8: Conceptual operational view of long-term modernized CPNT deployment, with interoperable eLORAN, eDME and LDACS-NAV transmitters. Terrestrial fiber connections distribute timing in populated areas, whereas in remote areas, synchronization is provided by eLORAN.

AAM recommendation is due to spectrum compatibility concerns along with backwards compatibility not being a particular concern. In addition, 5G Cellular and Commercial Pseudolites, along with potential new AAM data links are potential CPNT candidates that should be considered.

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 address the the 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. Recently announced changes in export restrictions in the United States are welcome, but developing aviation standards around these technologies and widespread deployment on aircraft will be challenging.
- Dedicated services must be developed for AAM if this emerging market is to provide societal benefit. This includes designing the PBN services for low altitude enroute operations, as well as the navigation systems to complement GNSS. The introduction of new aircraft and capabilities represents an opportunity for clean-slate designs to specifically serve these aircraft types and operating environments.

7. CONCLUSIONS

This paper proposes performance criteria for terrestrial navigation aids and candidate technologies for consideration for both Conventional Air Transport and emerging AAM. High-level analysis based on the criteria identifies recommended candidates for CAT 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 timedistribution 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. For AAM, other technologies, such as 5G Cellular, Commercial Pseudolites, and new AAM data links should be considered in this tradespace.

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.

ACKNOWLEDGMENTS

This paper is a direct follow-on to work originally supported by the Resilient Navigation and Timing Foundation (Osechas and McGraw, 2024).

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