Alternative Position, Navigation, and Timing – The Need for Robust Radionavigation

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ABSTRACT

Positioning, Navigation, and Timing (PNT) services provide both essential (safety and security) and economically beneficial applications worldwide in the 21st century. Whether users are ground-based or sea-based or in the air, their primary source of P and N and T is a Global Navigation Satellites System (GNSS). The transition of various users/modes of transport from legacy PNT aids to GNSS is at varying stages of development. For all of these systems, we worry about the ability of users to revert back from GNSS to previous methods. After all, the previous methods may provide lower levels of performance, will require higher levels of user skills, knowledge, and abilities. These capabilities may no longer be available when needed without significant investment in equipment sustainment and upgrade and in-depth training and practice.

It is most necessary that the transition from GNSS-provided PNT services to an alternate means of achieving PNT require little change in the way operations are carried out. A robust PNT solution using an Alternative PNT (APNT) capability is needed. The Federal Aviation Administration (FAA) is initiating an APNT program to research various alternative strategies to support the US National Airspace System's (NAS) transition to the Next Generation Air Transportation System (NextGen). This paper discusses the scope of the problem, including the extent of known and predictable and unknown and unpredictable jamming, each of the alternative strategies identified so far, and their pros and cons.

INTRODUCTION

To properly address the need for *Robust Radionavigation*, it is prudent to first agree on what is *robust*. After exploring a number of sources, the most appropriate definition found, and one that applies to processes, organizations, or systems and that best promotes the theme of this discussion, is *the ability to withstand or overcome adverse conditions*. This then leads us to define robust radionavigation as *the provision of position, navigation, and timing (PNT) services that are strong, sturdy, and able to withstand or overcome adverse conditions.*

For radionavigation, the term *adverse conditions* implies situations where the accuracy, availability, integrity, or continuity of the data or information carried by a radionavigation signal is impacted so as to produce unacceptable, unsafe, or unsecure results that may also lead to significant losses in capacity and efficiency. This occurs in the presence of interference.

Interference comes in a number of different varieties. It can be intentional or unintentional. Many, if not most instances of radionavigation interference to date has been from sources that were totally unaware that they were causing a problem [reference Clatch, Brewin]. Interference can be predictable or unpredictable. For example, some radiofrequency interference (RFI) is actually planned and mitigations can be put in place to minimize, if not eliminate adverse effects. Interference can be both man-made and environmental. Recently much discussion has occurred on solar cycles and how increased sunspot activity has the potential for significant impacts to GNSS-provided services. Interference can be crude or sophisticated (sometime referred to as jamming or spoofing), the latter being more pernicious. Jamming denies service. Spoofing means that the user may not know that services have been lost and may rely on faulty data. Interference can either be widespread, affecting hundreds of square miles and thousands of feet of airspace, or localized, affecting only specific operators and operations. Finally, interference can be continuous or intermittent. While a constant-on jammer causes problems, locating one that randomly "pops up" and stays on for short periods of time can be much more disruptive to operations, as it promotes uncertainties in users – the "should I or shouldn't I" problem. In the case of safety and security operations, the answer is inevitably "I should not [rely on the system]," making the intermittent interferer as effective, but more deceptive than the constant interference source.

PNT systems differ with respect to their sensitivity to interference. When assessing whether a condition is adverse, one must consider the radionavigation system being employed. What is adverse for one may not be adverse for another, and that is a basis for determining an appropriate alternative PNT strategy that ensures safety and security and minimizes the impact to the economy. Some PNT systems rely on extremely low power signals while others employ high power transmissions. Some rely on line-of-sight signals, while others employ ground waves. Some have been designed from the start to work in *adverse conditions*, while others are more fragile.

The message of this paper is that the interference world is constantly changing. Interference occurs more and more often – from both predictable and unpredictable sources. The most prudent courses of action by both suppliers and users of radionavigation services are to ensure that they fully appreciate the potential for real-world interference and plan and design accordingly.

INCREASING SOURCES OF INTERFERENCE

Certainly the most *predictable* source of interference to GNSS-provided PNT are exercises conducted by military organizations, whose missions require them to be able to both deny services to opposing forces and to operate in GNSS PNT-denied environment. To ensure their readiness, a significant amount of testing is required. Figure 1 denotes the locations, extent, and duration of GNSS interference events originating from US Department of Defense (DoD) sources. To ensure that neither the FAA nor the DoD missions are impaired, FAA and DoD coordinate these exercises to ensure that the safety, security, and economic benefits of the US NAS are not adversely impacted and that the need for DoD readiness is properly supported.

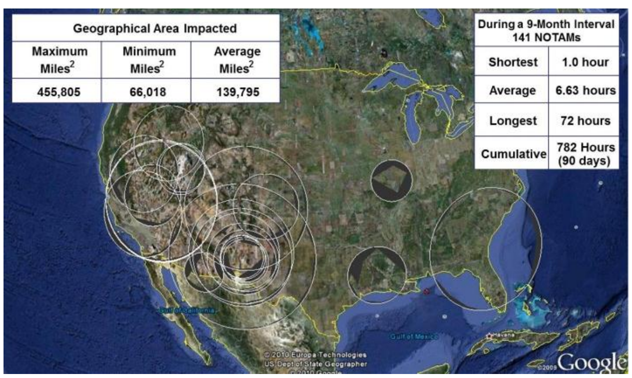

Figure 1: Adverse Condition: GPS Jamming Testing by DoD
[Slide courtesy of Innovative Solutions International (ISI)]

Personal Protection Devices (PPDs) respond to a growing awareness by the American public that the GNSS receiver in their car or mobile phone allows others to track their location In response, a number of manufacturers have produced PPDs which are small, compact jamming devices. Some interfere only with GNSS signals and others jam both GNSS and cellular telephone transmissions. Figures 2, 3, and 4 provide images of some of these devices that while illegal in most parts of the world, are easily obtainable on the Internet.

Figure 2: So-called "Personal Protection Device"

According to the specifications of the Personal Protection Device shown in Figure 2 (also available on the Internet) the jamming device is capable of transmitting 0.5W of power on the GPS L1frequency (1575.42 MHz). While it claims to be effective for only 2 – 10 meters, in actuality its range can extend hundreds of meters and cause significant disruption to other GNSS users – even those involved in providing safety and security services. Its price on the Internet is listed as $33.

Figure 3: A few more "Personal Protection Devices"

For a bit more, personal protection devices are available that will jam multiple GNSS and mobile telephone frequencies. Some of these jammers can produce interference signal that exceed 5 Watts (W).

A recent addition to the jammers available on the Internet is shown in Figure 4. While it does not profess to operate on GNSS frequencies, the ability of this device to do so given the frequency ranges for which it does operate is clear. One can only imagine the effect of these devices if carried aboard airplanes, trains, ships, or buses.

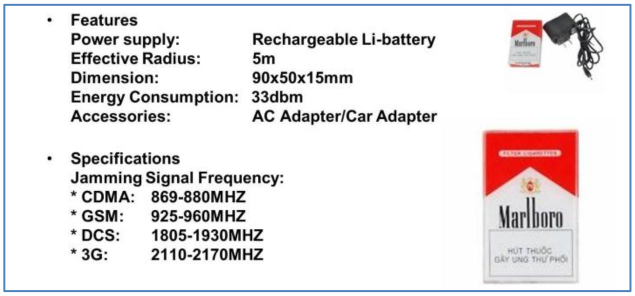

Figure 4: So-called "Super HOT Jammer Cell Phone Jammer"

As a provider of safety and security radionavigation services, the FAA is keenly aware of the PPD problem along with all other sources of intentional and unintentional jamming. The FAA is also well aware of the dangers associated with jamming. That is the first step – to be aware that as a GNSS service user or supplier you are operating in a potentially hostile signal environment. As shown in Figure 5, the FAA has installed a Local Area Augmentation System (LAAS), the US Ground-Based Augmentation System (GBAS), at

Figure 5: In Harm's Way -- FAA GBAS Installation at EWR

Newark Liberty International Airport (EWR) – an airport that it ringed by major highways. The system's extremely sensitive GNSS antennae are located close to the New Jersey Turnpike, where literally millions of trucks and automobiles pass by each week – a location dictated by siting criteria based on runway configuration. Being aware of the potential problems, the LAAS program is implementing system enhancements to mitigate the effects of interference sources and to maintain safe and secure services. It has been a valuable lesson – one that it is hoped will be taken up by PNT users and suppliers worldwide.

ALTERNATIVE POSITION NAVIGATION & TIME (APNT)

The FAA, in compliance with US national policy must maintain aviation operations indefinitely in the event of a GNSS interference event or outage. Outages have the potential to impact aviation safety, security, capacity, and efficiency. From the FAA's perspective, a key aspect of any alternative is that NAS air traffic control services can be continued without significant impact throughout an interference event. Waiting for the source of the interference to be located and turned off is not an acceptable alternative. Therefore, the FAA continues to develop procedures and refine technologies that have the potential to minimize the impact of a loss of GNSS-provided PNT.

As the FAA migrates today's NAS to NextGen, the reliance on GNSS-provided PNT services will only grow. As NextGen evolves from a ground-based system of air traffic control to a satellite-based system of air traffic management GNSS-technology applications become more important in managing capacity and demand. These applications will allow more aircraft to safely fly closer together on more direct routes, thus reducing delays and providing unprecedented benefits for the environment and the economy.

To maintain safety and security and minimize impact to the economy, an alternative means of providing position, navigation, and timing services must be developed. The FAA has, therefore, initiated an APNT program to research various alternative strategies that will ensure that the PNT services necessary to safely, securely, and effectively support today's NAS and its transition to NextGen will be assured. An important realization is that today's air traffic control system cannot simply be scaled up to handle the predicted 2X traffic in the future. Nor can air traffic controllers handle such an increase using radar vectors. Automation and surveillance systems requiring PNT services will need to separate aircraft performing trajectory based operations (TBO) based on area navigation (RNAV) and Required Navigation Performance-based (RNP) operations. In the NextGen Concept of Operations controllers will need to intercede only to provide "control by exception."

The performance increases that can be obtained from widespread use of RNAV/RNP can be seen in Figures 6 and 7. Figure 6 shows the number of aircraft that can be safely "fit" into a 10-nautical mile (nm) airspace depending on the navigation performance available. The navigation performance is a combination of the navigation service provided, the navigation capability of the aircraft avionics, and the ability of the pilot and onboard systems to fly the intended path. As you can see the number of aircraft capable of safely using the airspace increases dramatically as the capability reaches RNP 0.3. The reason for this increase is explained by Figure 7.

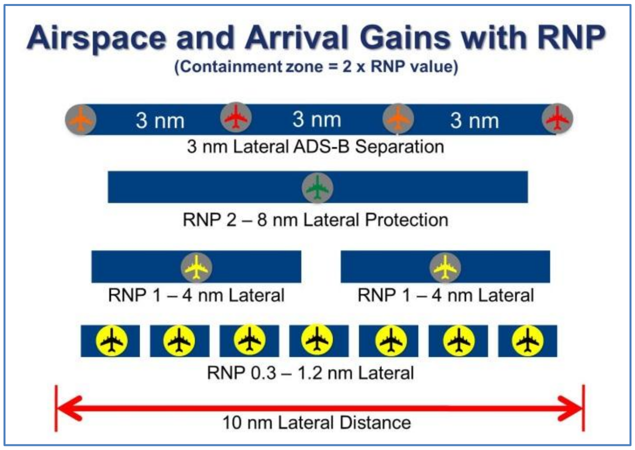

Figure 6: The Value of RNP to Airspace Capacity

A radionavigation/avionics system providing only RNP 1.0 capability would not be sufficient to allow aircraft to safely maintain a 3-mile lateral separation standard – the standard envisioned to support better airspace utilization in congested, high density airspace and support of advanced procedures under NextGen. With RNP 0.3 capability, not only can 3-mile separation be safely achieved, but it should also support RNP operations for parallel runway operations. Therefore, the PNT services that support the safe, secure, and efficient operation of the NAS cannot be significantly impaired by interference. To this end, an APNT system must be developed so that in the event of interference, safety, security can be sustained and air traffic demand regulated to reach an economically affordable alternative that sustains most flight operations consistent with the airspace user's need for continued operations.

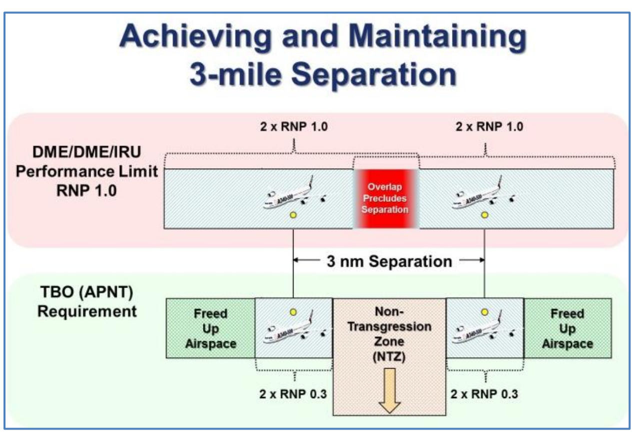

Figure 7: The Benefit of Providing RNP 0.3

TRADE-OFFS

The problem statement is fairly simple – NAS operations now and in the future will rely heavily on PNT. Most PNT to date and more in the future will be derived from GNSS, and GNSS-provided PNT services are vulnerable to *adverse conditions* (i.e., radio frequency interference). Figure 8 denotes the possible trade-space of solutions.

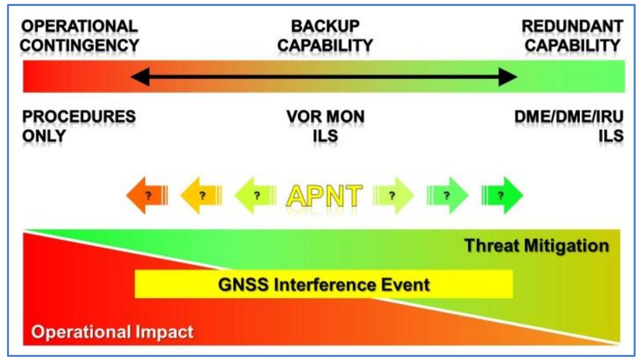

Figure 8: APNT Trade-space

On the left of the trade space are the operational contingencies that rely on procedural air traffic control. These alternatives cannot support the "normal" capacity of the NAS, so many aircraft will not be able to fly their intended routes – or in many cases, fly at all. Safety and security will be maintained, but economic impact will be great. On the right are redundant capabilities, which provide all aspects of the systems – in the air and on the ground PNT services equivalent to that provided by GNSS. Safety, security, and economic benefit is maintained for these alternatives as well, but the costs and resources associated with their implementation may not be realistic – especially in an industry where the refresh period for avionics and infrastructure is measured in decades rather than years. In the prudent middle-ground are found alternatives that provide a backup capability. While not totally eliminating potential economic impact, a well-designed APNT solution would minimize the impact to an acceptable level while ensuring safety and security is maintained.

Therefore, the goal of the FAA's APNT research is to provide a cost effective Alternative PNT service that:

- Ensures continuity of operations in NextGen;
- Provides Performance Based Navigation (PBN) – RNAV/RNP;
- Supports Dependent Surveillance Operations (Automatic Dependent Surveillance – Broadcast, (ADS-B) both Out and In);
- Supports Trajectory-Based Operations (TBO) and Four Dimensional Trajectories (4DT);
- Supports all users (GA, Business, Regional, Air Carrier, Military);

- Minimizes Impact on User Avionics Equipage by leveraging existing or planned equipage as much as possible;
- Supports backward compatibility for legacy users;
- Minimizes the need for multiple avionics updates for users; and
- Provides long lead transition time (circa 2020 transition)

The FAA also wishes to avoid the potential $1.0B costs of having to recapitalize the existing Very High Frequency Omnidirectional Radio Range (VOR) system that currently supplies a non-GNSS position and navigation capability that most operators now use only as a backup, albeit not to the accuracy of GNSS and without area navigation capability. The current VOR network does not support RNAV/RNP and does not provide a GNSS-independent timing capability. The FAA hopes to disestablish all VORs by 2025.

ALTERNATIVE PNT REQUIREMENTS

In order to determine the viability of alternative solutions, the FAA first assessed the minimum PNT requirements that an acceptable alternative would need to provide. These requirements are shown in Figure 9.

		Navigation (≥ 99.0% Availability)		Surveillance (≥99.9% Availability)			Positioning
		Accuracy (95%)	Containment (10^{-7})	Separation	NACp (95%)	NIC (10^{-7})	GNSS PNT (99.0 – 99.999%)
APNT	En Route	*10 nm	20 nm	5 nm	308m (7)	1 nm (5)	GPS
		*4 nm	8 nm				
		*2 nm	4 nm				
	Terminal	*1 nm	2 nm	3 nm	171m (8)	0.6 nm (6)	DME Only Gap
	LNAV	*0.3 nm	0.6 nm				
	RNP (AR)	*0.1 nm	**0.1 nm	2.5 nm DPA	171m (8)	0.2 nm (7)	SBAS
	LPV	16m/4m	40m/50m	2.5 nm DPA	171m (8)	0.2 nm (7)	
	LPV-200	16m/4m	40m/35m				
	GLS Cat-I	16m/4m	40m/10m	2.0 nm IPA	121 m (8)	0.2 nm (7)	GBAS
	GLS Cat-III	16m/2m	40m/10m				

* Operational requirements are defined for total system accuracy, which is dominated by fight technical error. Position accuracy for these operations is negligible.
** Containment for RNP AR is specified as a total system requirement; value representative of current approvals.

Figure 9: Performance-Based Navigation and Surveillance Requirements

The leftmost column lists the various airspace domains, i.e., en route, terminal, LNAV (lateral navigation/non-precision approach), LPV (Localizer with Precision Vertical), and GBAS-enabled Cat I and Cat III landings. The rightmost column lists the systems that provide the necessary capabilities to support these operations. In the middle are the navigation and surveillance requirements required for each operation. Navigation is measured in accuracy and containment with integrity. Surveillance is measured by Navigation Accuracy Category (NAC) and Navigation Integrity Category (NIC). After much analysis and discussion, the requirements for an APNT system were set at the level shown, i.e., an acceptable APNT system will need to support navigation and surveillance down through LNAV/non-precision approach.

ALTERNATIVE PNT COVERAGE REQUIREMENTS

Where does an APNT system need to provide *what* performance? The US NAS is not homogenous. There are key locations where higher capacity and efficiency requirements exist. In the US, the FAA has identified 135 terminal areas where significant capacity is required and where a loss of capacity due to GNSS interference would cause significant economic impact. Figure 10 denotes these areas as seen from Flight Level (FL) 180 (18,000 feet).

Figure 10: High Capacity Need Areas in Conterminous US (CONUS)

The FAA has categorized the airspace into three zones. Zone 1 is the airspace at FL 180 and above – all the way to FL 600 (60,000 feet). Zone 2 is the airspace that is below FL 180 and above 5000 feet above ground level (AGL). Zone 3 is the airspace that supports terminal operation in high-density areas. It is defined as starting 500 feet above the ground and extending out to 5 statute miles (sm) from the airport, and then going up at a 2 degree angle to 18,000 feet above mean sea level (MSL). Figure 11 shows these three different zones.

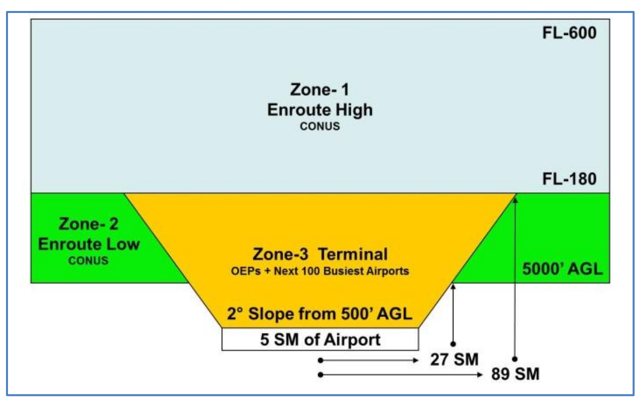

Figure 11: PNT Performance Zones

Definition of these zones and the PNT requirements within these zones was necessary to be able to appropriately bound solutions that will most likely rely on ground-based and line-of-sight assets. Throughout the FAA's analysis of alternatives and selection of solution(s), safety and security will always be ensured and services provided where economics warrant.

In looking for potential solutions, the FAA has concentrated on the availability of systems onboard aircraft and how to leverage existing and future equipage to facilitate an acceptable solution with a reasonable transition time. Figure 12 shows the various systems on the aircraft and where APNT solution(s) might best fit in.

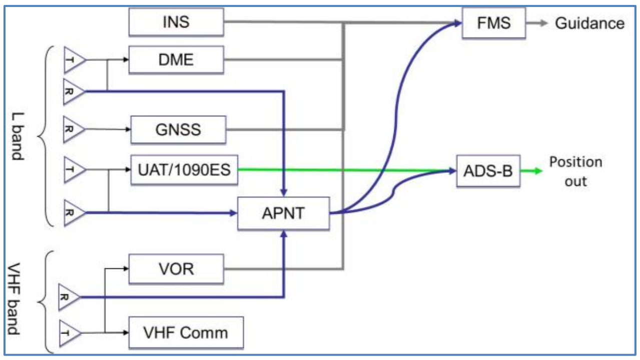

Figure 12: Potential APNT Solutions on Aircraft

ALTERNATE PNT ALTERNATIVES

The FAA has concentrated on three categories of solutions that appear promising, while inviting input from the public and industry at meetings, symposiums, and conferences on other potential areas of research. The three categories currently being considered are an *Optimized Distance Measuring Equipment (DME) Network, Wide-Area Multi-lateration, and a DME Pseudolite Network*. Each will be described below, along with the pros and cons associated with each potential solution.

OPTIMIZED DME NETWORK

Historically DMEs provide pilots with slant range distance from their aircraft to the DME site. DMEs that are collocated with VORs provide pilots with their slant range distance to the end of an airway, while DMEs that are co-located with landing systems at airports provide pilots with their slant range to runway ends. Years ago, avionics engineers recognized that because aircraft at altitude could see a number of DMEs, a system using multiple DME ranging sources could provide pilots with their geographic position (this usage is termed "DME/DME"). However, since the DME network was not designed or laid out for this function, gaps in service coverage exists – caused by lack of DMEs or lack of necessary geometry between available DMEs to derive a position solution. The current population of DMEs in the conterminous United States (CONUS) is show in Figure 13, many of which are associated with military Tactical Navigation (TACAN) facilities. DMEs provide high power transmissions, typically 1000 W.

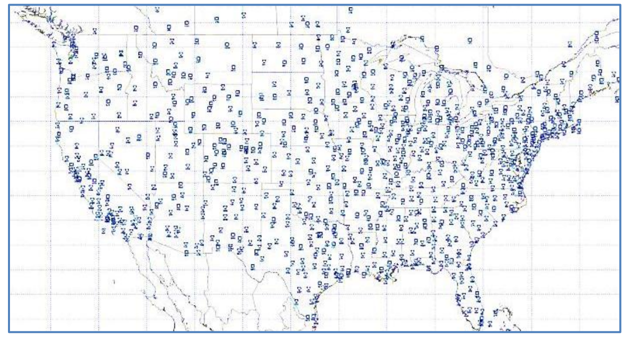

Figure 13: 1100 DMEs in CONUS

A DME network solution leverages existing technology and systems, and would have the least impact on avionics for air carriers. However, it would have a significant impact on most general aviation, where DME avionics are not carried.

The FAA is planning to fill gaps in the DME coverage at FL 180 and above as part of the NextGen initiative. Use of the DME Network for RNAV assumes that aircraft will be equipped with inertial reference units (IRU) that allow them to coast through any remaining gaps in coverage. Aircraft with DME/DME/IRU (DDI) are not authorized to conduct a published approach procedures requiring less than RNAV/RNP-1.0 and aircraft using DME/DME without IRUs are not authorized to fly RNAV/RNP routes. There is also a concern that a significant increase in use of the DME network could cause interrogation saturations and impact service delivery. Finally, unless general aviation can be equipped with DME RNAV capability, there may be a need to retain and recapitalize a large number of the VORs at a substantial cost.

WIDE AREA MULTI-LATERATION

Wide Area Multi-lateration (WAM) utilizes signals that are transmitted frequently from an aircraft equipped with ADS-B to determine the aircraft's position. Figure 14 denotes the sequence of events that occur that would allow an aircraft to learn its position in the event of a loss of GNSS-provided PNT.

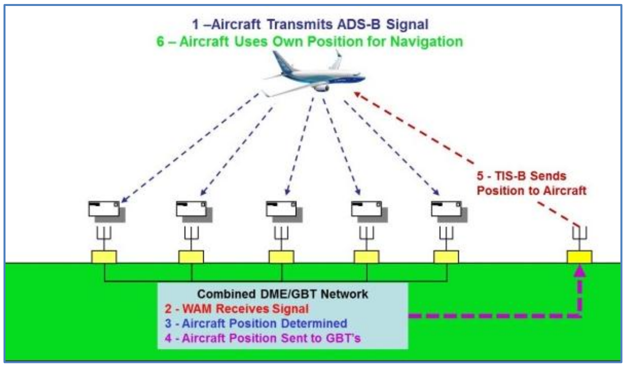

Figure 14: Passive Wide Area Multi-lateration

Ground-based transceivers (GBTs) being installed to support ADS-B can utilize this technology to determine aircraft position in the event that the aircraft cannot. The planned system of ADS-B GBTs is shown in Figure 15.

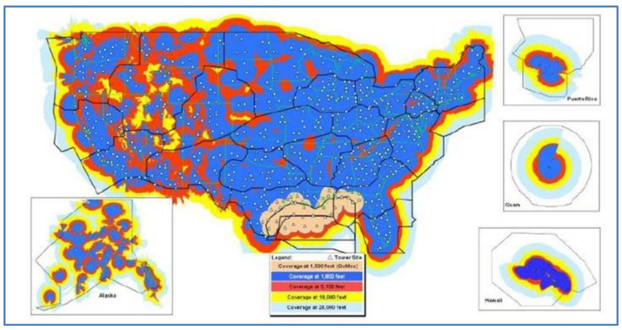

Figure 15: ~800 GBTs to be Installed Nationwide

By leveraging the DME installed base and the planned GBT installations, coverage across CONUS would be greatly improved. Figure 16 shows this combined infrastructure.

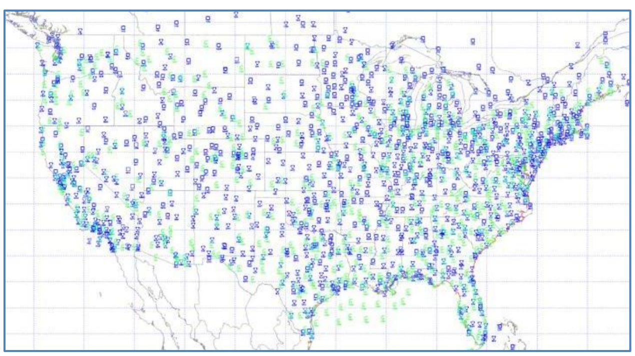

Figure 16: Combined DME and GBT Network

The WAM solution has minimal impact on existing avionics for surveillance. Accuracy has been demonstrated to be within target levels and it is compatible with existing WAM systems. However, integrity monitoring and meeting the required time-to-alert for navigation may be very challenging. While ADS-B's Universal Access Transceiver's (UAT) 978 MHz frequency appears to have sufficient capacity, there are some concerns regarding the availability of bandwidth on the 1090 MHz channel used by air carriers in high density environments. Use of WAM for navigation will likely require changes to existing avionics.

WAM also requires that each of the ground stations maintain a common time reference as WAM is a time-of-arrival system. Current WAM system utilize a common beacon that can "be seen" by all systems as the synchronizing mechanism. Wider area system may encounter issues, and certainly additional costs, if beacons were the only means to maintain synchronization.

DME PSEUDOLITE NETWORK

DMEs broadcast in the L-band, the same area of the spectrum as GNSS. They work by receiving interrogations from aircraft and replying after a fixed delay, thus allowing the aircraft to determine its slant range to the DME. The fundamental DME signal is a pulse pair. The pulse pairs required to serve one aircraft occupy a very small duty cycle. When a DME is not being interrogated, it maintains a "heartbeat" awaiting the next interrogation. Thus, all DMEs could overlay a continuous "heartbeat" on top of the normal pulse pairs. The DME Pseudolite (DMPL) solution would include a transmission on the DME heartbeat, which would be maintained continuously, identifying the particular DME, its location, and the time-of-day. The aircraft, using the same methodology employed by GNSS and WAM systems, would determine its position. Since the aircraft would receive the "raw" data, it would also determine the integrity of the derived information.

The DMPL alternative provides unlimited capacity and an aircraft-based position and integrity solution, and could leverage use of existing DMEs and GBTs. However, it would require modifications to DME operations and/or signal and a minimum of 3 sites to compute aircraft position (unless the DMEs interrogation/reply capability were also utilized, and then two would suffice). The DMPL alternative would also require a common GNSS-independent timing reference similar to that needed by the WAM solution. While it would have the greatest impact to aircraft avionics and be the most costly, it could potentially provide the most benefit. There is the potential to include position calculation and integrity monitoring functions in ADS-B-In avionics applications; however, it is the least mature concept, and so no avionics are yet developed and no standards have been established. If used alone, it would also require the retention and recapitalization of nearly half the VORs unless general aviation equipped with pseudolite avionics.

TIME SYNCHRONIZTION

The need to provide time synchronization for both the WAM and DMPL alternatives, as well as the need to provide frequency services for telecommunication applications caused the FAA to research alternative time and frequency provision as part of the APNT effort. During the problem analysis phase, the FAA determined that if the source of GNSS interference were so great as to preclude the use of any satellite in any direction, such a situation would be outside the FAA's means to mitigate the time service interruption. Therefore, the FAA assumed that the interfering source would arrive from at most a few directions and that by using a steerable null antenna, the jammer could be substantially eliminated and a source of good time and frequency reinforced. Figure 17 shows how this concept would work.

Steerable null antennas located at ground facilities (either DME or GBT) should be able to sufficiently null out interfering signals while reinforcing the time and frequency signals from a satellite – whether it be in GEO, Medium, or Low Earth orbit. This would allow GBTs or DMPL or both to continue providing multi-lateration services despite a GNSS service interruption.

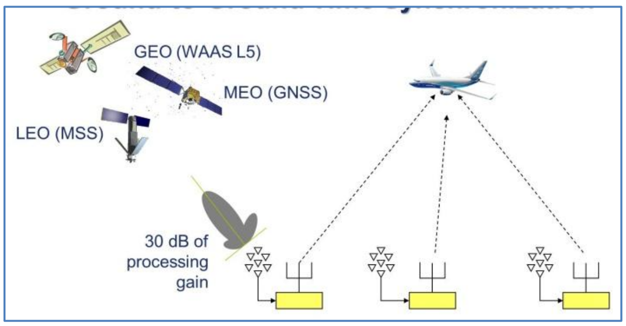

Figure 17: Ground-based Time Synchronization

NEXT STEPS

In pursuit of the best APNT solution(s) the FAA is developing a Project Plan for Full Investigation, the means to validate backup requirements, and performing appropriate system engineering analyses. The FAA intends to develop R&D Prototypes along with cost schedule estimates while it completes the analysis of alternatives. The schedule for accomplishing these actions is show in Figure 18.

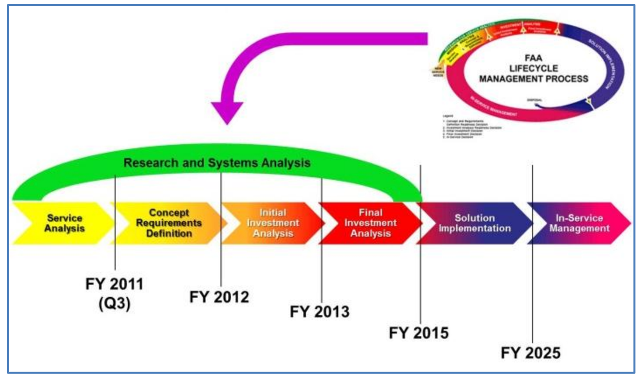

Figure 18: APNT Program Life Cycle

The FAA remains committed to the transition from a ground-based to satellite based air traffic control system. First and foremost, the APNT remains a research endeavor. The "best" answer is still, as they say *to be determined*. Most importantly, the potential problems and impacts due to interference have been recognized and steps are being taken to ensure the safety, security, and efficiency of the US NAS will be maintained in the event of a loss of GNSS-provided PNT.

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