The Need for Robust and Resilient Position, Navigation, and Timing for the US National Airspace System

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ABSTRACT

Positioning, Navigation, and Timing (PNT) services are key enablers of essential safety and security applications and economically beneficial capacity and efficiency applications worldwide. Whether users are ground-based, sea-based, or in the air, their primary/go-to source of PNT has become a Global Navigation Satellites System (GNSS), with the US Global Positioning System (GPS) being the most widely used. Starting in 2001, with the publication of the landmark Volpe Transportation Systems Center's GPS Vulnerability Report and leading up to the Department of Homeland Security sponsored GPS Interference Testing in 2012, the world has become much more aware of the vulnerability of GNSS-based services – especially during 2011, as the result of significant interest in using the spectrum directly adjacent to GPS for mobile communications services. This was an important wake up call to the world. While users of GNSS positioning and navigation services are usually at least cognizant of the source of their services, many users of GPS precise time and frequency are oblivious to both the source of these services and their inherent vulnerability. Many time and frequency users are not even aware of how GNSS-provided time is crucial to their operations. The US Federal Aviation Administration (FAA) has initiated an Alternate Position, Navigation, and Timing (APNT) program to research various alternative strategies that can ensure a safe, secure, and effective transition of the US National Airspace System (NAS) to the Next Generation Air Transportation System (NextGen) and from a GNSS-available to a GNSS-non-available/impaired environment. This paper discusses the various aspects of the FAA's APNT program, including its concept of operations, the alternative strategies being explored, research and development activities associated with both ground-based and avionics equipment, signal-in-space design considerations, and timeframe are discussed.

INTRODUCTION

To discuss "robust and resilient position, navigation, and timing" we must first define what is meant by "robust" and "resilient." For the purposes of this paper, robust is used to describe a system *having the ability to overcome adverse conditions*, while resilient describes a system *having the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions – including from deliberate attacks or naturally occurring threats or incidents*.[1] Therefore *Robust and Resilient Position, Navigation, and Timing* denotes the provision of strong, sturdy precise services that are able to both withstand or overcome adverse conditions and recover rapidly from disruptions. As we are dealing with radionavigation signals, the adverse condition and disruption we must overcome and recover from is radio frequency interference (RFI), which we define as *any electromagnetic disturbance that interrupts, obstructs, or otherwise degrades or limits the performance of user equipment*.

Radio frequency interference (RFI) comes is many "flavors." It can be intentional or unintentional; predictable or unpredictable, manmade or environmental, crude or sophisticated (jamming or spoofing); and/or widespread or localized. We define jamming as *intentional* interference and spoofing as *the surreptitious replacement of a true signal with a manipulated signal*. When we speak of a harsh radionavigation environment, we envision one in which we must overcome some type of interference to arrive at the accuracy, availability, integrity, continuity, and coverage required by our specific applications, so that these applications can continue in the presence of interference.

The FAA's aviation transition of the US NAS to NextGen will rely on widespread use of precision PNT services provided by GPS to maintain safety, increase capacity, and improve efficiency. GPS sourced PNT services are the primary enablers of performance-based navigation (PBN) and Automatic Dependent Surveillance – Broadcast (ADS-B) services that, in turn, enable Trajectory-Based Operations (TBO), area navigation (RNAV), Required Navigation Performance (RNP), precision approach, Closely Spaced Parallel Operations (CSPO), and other planned operational improvements. In accordance with US National Policy, the FAA needs to ensure a sufficient backup PNT capability is present to mitigate risks to aviation users if the PNT services provided by GPS become unavailable. The FAA's NextGen APNT program

[1] US Presidential Policy Decision 21, February 12, 2013

will ensure that alternate PNT services will be available to support flight operations, maintain safety, minimize economic impacts from GPS outages, and support air transportation's timing needs. Delivery of these alternate services must be able to sustain safe flight operations and reduce the impact of loss of GPS to capacity and efficiency.

NEXTGEN APNT CONCEPT OF OPERATIONS

As US aviation transitions to NextGen with increased emphasis on performance-based navigation (PBN) and TBO, RNAV/RNP will become the norm for operations. Using airways and arrival and departure procedures designed around the limitations of a ground-based infrastructure will no longer be beneficial or efficient for the traffic volume anticipated in NextGen. Growth in air traffic will drive the need for increased precision in navigation to support more efficient use of airspace and increased capacity – especially in high-density airspace and at high-activity airports.

NextGen APNT will need to support key capabilities described within the NextGen Concept of Operations (CONOPS), including:

- Network-centric operations – where information is shared with stakeholders in near-real time, providing common situational awareness and greater strategic planning – users need to know the status of GNSS outages;

- Collaborative Air Traffic Management (CATM) – where information collected and shared is used to guide decisions on flows and system performance – so that air traffic controllers can strategically manage an outage event;

- Precision Navigation and Surveillance – where precision use of RNAV with RNP becomes a matter of routine so as to open up more airspace trajectories and support increased arrival and departure rates in high-density airspace and airport operations – where pilots can continue to use RNAV and RNP in the presence of a GNSS outage event; and

- Trajectory-based Operations – where the 4 D trajectory is used by automation (both on the aircraft and at the ANSP) to merge, sequence, and separate aircraft – without significant impact to controller and pilot workload.

Recognizing the role that APNT must play, the APNT CONOPS was developed based on four guiding operational principles, or pillars:

- Safe recovery (landing) of aircraft flying in Instrument Meteorological Conditions (IMC) under Instrument Flight Rule (IFR) operations;

- Strategic modification of flight trajectories to avoid areas of interference and manage demand within the interference area;

- Continued dispatch of air carrier operations to deny an economic target for an intentional jammer; and

- Continued flight operations without a significant increase in workload for either the pilot or the Air Navigation Service Provider (ANSP) during an interference event.

The APNT operational pillars are shown in Figure 1.

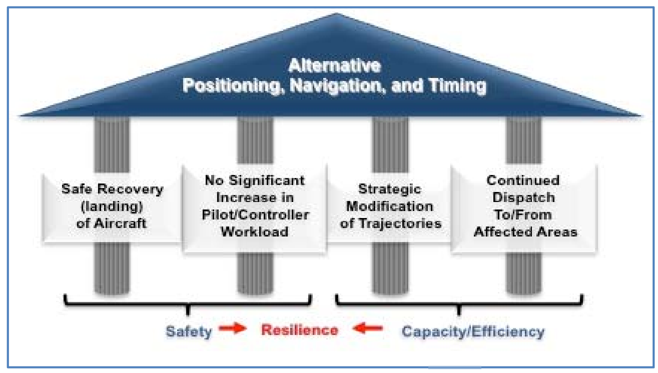

Figure 2 APNT Pillars

Most importantly, NextGen APNT must ensure that these capabilities will be supported seamlessly as the FAA transitions from *NAS Normal* to *NAS Nominal* operations in the presence of RFI – with the goal that the capacity and efficiency of *NAS Nominal* be as close to that of *NAS Normal* as feasible while ensuring safety.

Today, terrestrial based navigation is provided by a mix of different historical systems (e.g., Distance Measuring Equipment (DME), Tactical Navigation (TACAN), and Instrument Landing Systems (ILS)) that provide GNSS-independent signals-in-space that are used by aircraft avionics, as shown in Figure 2a. While today's non-GNSS alternatives

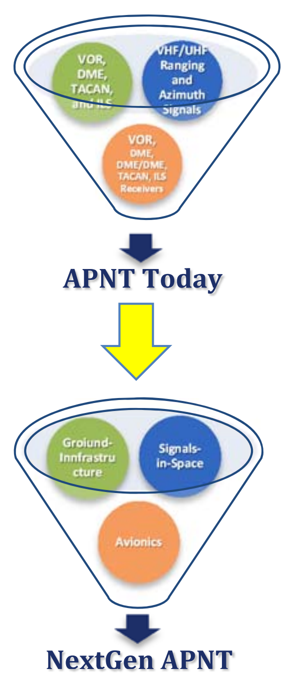

Figure 1a/b APNT Evolution

ensure safety and continued operations, they will not be able to support the required off-airway operations and the efficiency and capacity necessary for NextGen. The FAA will need to migrate from today's alternative means of positioning, navigation, and timing to NextGen APNT.

The development of NextGen APNT requires the identification of multiple potential solution sets that can serve diverse NAS users. These NextGen APNT solution sets, as shown in Figure 2b will be comprised of ground-based infrastructure transmitting non-GNSS signals-in-space to avionics that may vary by user and the signals-in-space must support legacy users as well as emerging user communities (e.g., Unmanned Aerial Systems). Robustness/resilience is paramount, i.e., safety of operations must be maintained ***and*** operations must continue at a nominal level.

The majority of risk associated with a GNSS outage is economic, principally capacity and efficiency losses, as delays are incurred. However, there is also a safety risk element that must be addressed. This safety risk element is tied to two functions. The risks associated with the transition from one aircraft state to another, and the risk associated with changing aircraft separation spacing, discontinuing paired flight activities, the delegation of separation, and self-separation.

Before one can propose alterative solutions, requirements must be established in order to assess the capabilities and value of any alternative. Because NextGen APNT will need to support not only navigation services within the US NAS, but also the ability of aircraft to report their position via ADS-B, consideration of both navigation and surveillance metrics is crucial. The APNT CONOPS also considers the surveillance capabilities Air Traffic Services requires for separation.

In today's NAS, surveillance is evolving from secondary surveillance radar (SSR), backed up by primary radar to a fused product that includes position information from ADS-B. For IFR operations, there are three types of separation operations: 1) procedural, where there is no surveillance coverage and position reports are used for separation, 2) radar coverage (SSR or Primary) that may include fused positions from both radar and ADS-B, and 3) ADS-B-only surveillance coverage, where ADS-B is dependent on GPS for the position information. This ADS-B-only operation becomes procedural separation at the time of GPS failure. In every case where GPS is providing the position source for ADS-B and fails, there is a need to re-establish the separation distances for the means used. In the case of ADS-B using 3-nautical mile (NM) separation the aircraft must be increased in separation to 5 NM separation beyond 40 NM from the SSR site. Likewise, radar-like separation services using ADS-B in airspace with no radar coverage must revert to procedural separation procedures.

Figure 3 provides a comparison of navigation and surveillance metrics, a table that the FAA APNT Team has dubbed "The Rosetta Stone," as it helps the navigation and surveillance communities to understand their requirements intersections.

		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
APNT		*4 nm	8 nm				
APNT		*2 nm	4 nm				
APNT	Terminal	*1 nm	2 nm	3 nm	171m (8)	0.6 nm (6)	DME Only Gap
APNT	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 flight 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 3 NextGen APNT Navigation and Surveillance Metrics

As the figure shows, to support 3 NM aircraft separation the required navigation metrics are 0.3 NM 95% and containment of 0.6 NM with 10^{-7} integrity. Similarly, the surveillance metrics needed to support 3-NM separation are a Navigation Accuracy Category (NAC) of 8 (equivalent to 171 meters (m) 95%) and a Navigation Integrity Category (NIC) of 6 (equivalent to 0.6 NM with 10^{-7} integrity).

While the APNT CONOPS is neutral to technical solutions, it must recognize existing aircraft avionics configurations to compare and contrast the impacts of the outages and effectiveness of proposed alternatives. The CONOPS identifies three groups of aircraft: (1) aircraft having a flight management system (FMS) with an inertial reference unit (IRU) and a scanning Distance Measuring Equipment (DME) transponder (DME-DME), referred to as DDI-aircraft; (2) aircraft with an FMS and DME-DME, but no IRU. Referred to as DD-aircraft; and (3) aircraft that have no FMS or DME-DME and are equipped with GPS as a primary source of positioning and navigation, referred to simply as GPS-only aircraft. Additionally, in general these aircraft are not equipped with any type of DME because FAA policy currently permits GPS to be used in lieu of DME.

APNT REQUIRED COVERAGE/CAPABILITIES

The airspace where APNT is deemed necessary to support continued capacity and efficiency is shown in Figure 4. This APNT service volume within the Conterminous US (CONUS) extends from the top of the US NAS at FL 600 (60,000 feet above Mean Sea Level (MSL)) down to FL

180 (18,000 feet MSL) to serve the En Route High airspace – identified as Zone 1 in the figure, and from FL 180 down to 5,000 feet Above Ground Level (AGL) to serve the En Route Low airspace – identified as Zone 2 in the figure. In more congested and challenging terminal airspace located near major airports APNT will need to ensure service down to 1,500 feet AGL to support terminal operations and down to 500 feet AGL to support Standard Terminal Arrival Routes (STARs) and Special Instrument Departures (SIDs).

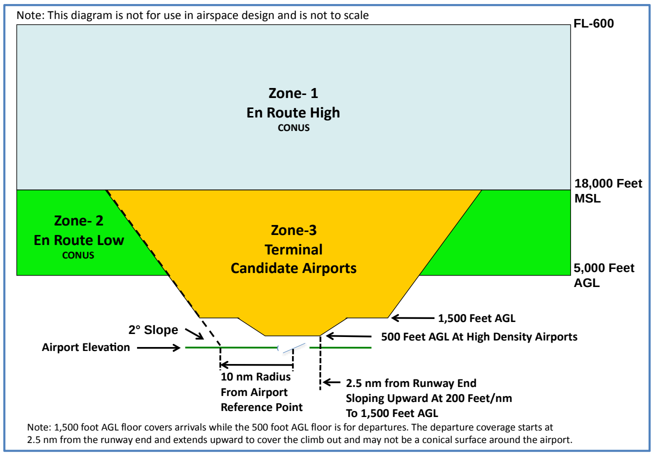

Figure 4 Required APNT Service Volume

The focus of APNT research, to maximize benefits of current avionics and ground-based infrastructure, is to extend the current coverage of DME to provide most commercial aircraft with an RNAV capability independent of GPS, define a minimum operating network of ground-based navigation aids to safely recover aircraft in the presence of interference, and examine the feasibility of being able to derive position based on the use of precision timing, independent of the GPS performance to minimize the economic impact of the loss of GNSS to aviation.

Precision time and frequency stability are critical to navigation and positioning and is the basis of all GNSS performance. Precision time from GPS is used extensively in transportation and other segments of critical infrastructure for purposes beyond aviation and other modal navigation and positioning. As the FAA looks to the future, alternative timing sources will be required for not only navigation and positioning, but for networking, efficient use of spectrum, and improvements in automation. For APNT, the requirements for time and frequency stability are driven by the navigation alternatives being considered and the system and node synchronization required to maintain precise Coordinated Universal Time (UTC).

CURRENT TERRESTRIAL NAVIGATION CAPABILITIES AND SUPPORTED OPERATIONS

Today's NAS and its airspace structure are built on ground-based navigation aids to create aircraft routings, arrival and departure paths. The aircraft's flight trajectory is restricted to the service volumes of the navigational aids. To operate off airways requires area navigation, where an aircraft derives its RNAV position based on a network of DMEs or GNSS. Several legacy ground-based systems are used to provide position and navigation services today, which allow aircraft relying on GPS for navigation to transition to an alternate means of navigation when GNSS services are unavailable. However, these systems do not allow for seamless transition to APNT operations that necessarily support RNAV operations in all domains (e.g., non DDI aircraft will not be able to continue RNAV operations and DDI RNAV operations may be limited at lower altitudes due to line-of-sight constraints).

Also, the FAA plans to eliminate a portion of these aging legacy systems because they only support pre-defined route structures driven by line-of-sight coverage. NextGen operations, based on performance-based navigation, positioning, and surveillance will "open up" the airspace by removing flight track constraints and allow aircraft to operate off these constraining airways. This freedom to operate off the route structures will add capacity and efficiency to the NAS, provide users with more options in selecting flight tracks, and support dynamic re-routing when required to avoid weather or other events. Legacy navigation and surveillance systems used today include:

- *DME* - During a GPS outage the DME/DME-derived position allows the aircraft position to be known, and navigation to continue, at reduced levels of performance. Use of DME-DME RNAV is currently limited to DDI aircraft due to gaps in DME coverage.

- *VOR / NDB* – Before flight crews can rely on the VOR or NDB for Legacy APNT; they must tune and confirm reception of the desired VOR or NDB. However, VOR and NDB cannot support RNAV or RNP operations, which prevent them from being a viable option for maintaining operational capabilities in a NextGen operating environment.

- *Radar* - For aircraft not capable of utilizing the Legacy APNT system but are within radar coverage, air traffic controllers can utilize secondary surveillance radar and provide radar vectoring and altitude assignments in the presence of outages.

- *ILS* – The Instrument Landing System (ILS) is retained in the APNT concept of operations to provide the ability to recover aircraft in the presence of weather and GPS interference.

This allows APNT to be less robust than and not redundant to the operational capabilities of GPS.

As shown in Figure 5, the economic loss risk associated with a GNSS interference event increases with each new set of NextGen capabilities. As such, the value of APNT as an "insurance policy" against adverse economic impacts and protector of safety increases over time.

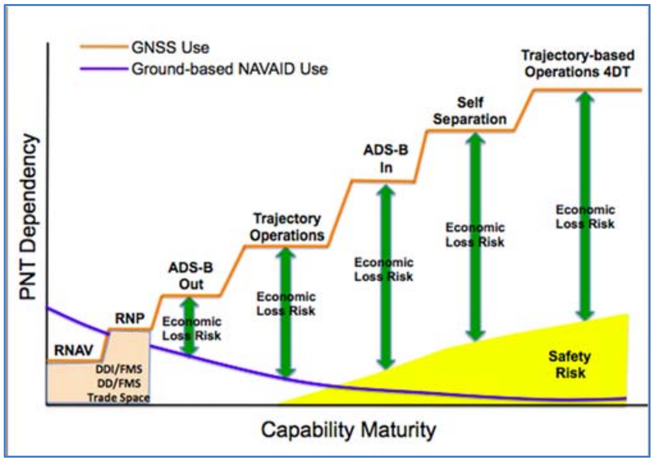

Figure 5 Increased PNT Dependency vs Capability Maturity

An element of the APNT strategy is the retention of a selected number of instrument landing systems that would provide precision guidance for landing. Not all current ILSs would need to be retained as their purpose shifts from the primary means of aircraft approach guidance and landing to an alternative means, where RNAV/RNP approaches with vertical guidance support normal operations and the ILS provides a means of recovering aircraft in weather in the event of interference. Both a DDI and a DD-aircraft will be able to navigate to an ILS localizer intercept and execute an approach; however, a GPS-only aircraft would require vectors to the ILS or use

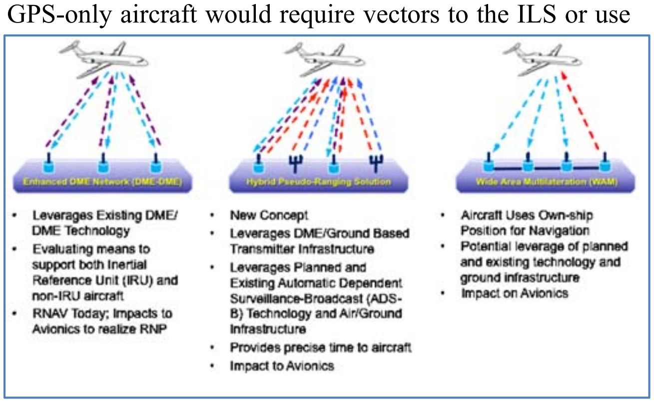

Figure 6 APNT Alternative Solutions

a VOR to fly a course to an ILS intercept. The NextGen APNT solution will need to support navigation in en route and many terminal airspace to support transition to an ILS or VOR approach for safety, as well as RNAV and RNP capabilities to support the capacity and efficiency required in more challenging airspace (i.e., Figure 4, Zone 3).

APNT ALTERNATIVE SOLUTIONS

The FAA is currently investigating three categories of alternative solutions, as shown in Figure 6: First, the enhancement of the current DME network to provide better accuracy to support RNAV 0.3 and the development of new DME-DME avionics to support RNP 0.3. Second, the use of both DMEs and ADS-B Radio Transceivers (RTs) as the source of hybrid ranging signals (i.e., true ranging from DMEs and pseudo-ranging from DMEs and ADS-B RTs). Lastly, the use of DME and ADS-B sites to determine aircraft position through multilateration and provide that position to aircraft to support continued navigation. Each of these alternatives is explored below.

Active Two-way Ranging Solutions (True Range)

Aircraft equipped with DME/DME receivers combined with IRU, complying with FAA Advisory Circular 90-100A, can operate in the US NAS today on RNAV routes and utilize SIDs and STARs. The incorporation of the IRU into the navigation avionics allows for the aircraft to "coast" for a limited time through airspace where line-of-sight availability of DMEs in *good* geometry may be insufficient because of altitude or ground infrastructure constraints. Figure 7 denotes the distribution of DME services used within CONUS that are provided by either DMEs or TACANs.

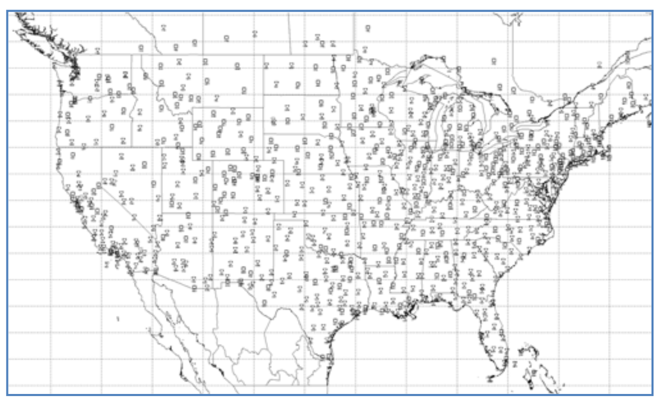

Figure 7 DME Service Locations Used in CONUS

An aircraft receives DME services by interrogating the DME and listening for the reply transmitted by the DME after a fixed (50 μs) delay. Replies from two DMEs in *good* geometry ($30° \leq \alpha \leq 150°$ to ensure acceptable dilution of precision (DOP)) produces two true slant ranges, which the aircraft's FMS converts into an actual position based on barometric altitude. The current DMEs and DME/DME/IRU avionic systems can support RNAV 1 (one nautical mile (nm)) or RNAV 2, but cannot support RNP, and certainly not the desired target of RNP 0.3. This allows APNT to not be as robust as augmented GPS. APNT is not redundant to the operational capabilities of GPS. While the FAA has been investigating the means to "tighten up" ground-based DME operations to achieve better accuracy while not impacting legacy DME/DME avionics, advanced APNT avionics to achieve the accuracy, availability, integrity, and continuity to support RNP 0.3 will be needed in the future.

A benefit of the true ranging solution is also the number of ground stations required. While *good geometry* is essential, only two stations are required for the aircraft to determine its position (altitude being provided via barometric altimeter). This ability to limit ground infrastructure helped in development of the third alternative solution.

One-Way Ranging Solution

The FAA is exploring Multilateration as a passive, one-way ranging solution. The multilateration concept of operations is that multiple ground-based stations in *good geometry* will receive the same transmission from an aircraft, determine its position, and transmit it to the aircraft in the event that it loses navigation. The concept is depicted in Figure 8.

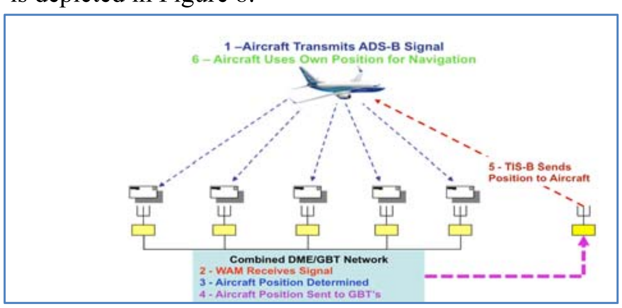

Figure 8: Multilateration Alternative

The FAA has already deployed multilateration at a number of sites to fill gaps in surveillance coverage. Using ADS-B RTs as the ground-based infrastructure and the Mode-S squits from aircraft as the aircraft transmissions, the FAA's Wide Area Multilateration System (WAM) currently supports reduced separation standards in areas where lack of surveillance would preclude such procedures. The challenges of a multilateration solution for CONUS would be to ensure the required geographical and altitude coverage and determine the means whereby the integrity of the aircraft's position solution could be ensured. This could lead to a significant cost disadvantage for the FAA in terms of the number of ground stations needed for coverage, but there is no additional avionics cost.

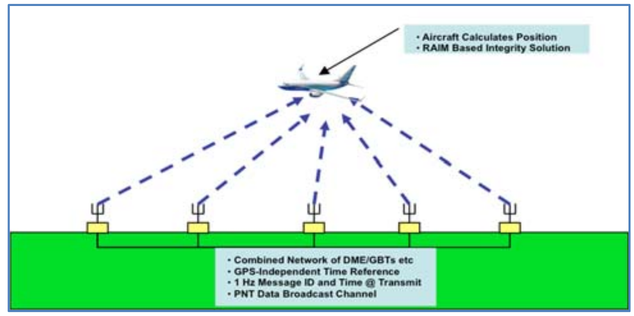

Figure 9 Pseudolite Alternative

Instead of receiving the same aircraft transmissions from multiple ground sites, one way ranging can also be implemented using signals from multiple ground locations received by the aircraft to allow determination of position and, with enough signals in *good geometry*, a position solution with the required integrity. This concept, labelled the Pseudolite Alternative, is shown in Figure 9. It should be noted that the use of the term *pseudolite* does not imply that these transmissions would occur on GNSS frequencies; however, it is interesting to note that both DME and ADS-B services are all provided by L-band signals, as shown in Figure 10. This commonality is valuable when considering what avionic antenna and receiver characteristics will be needed to implement an APNT solution.

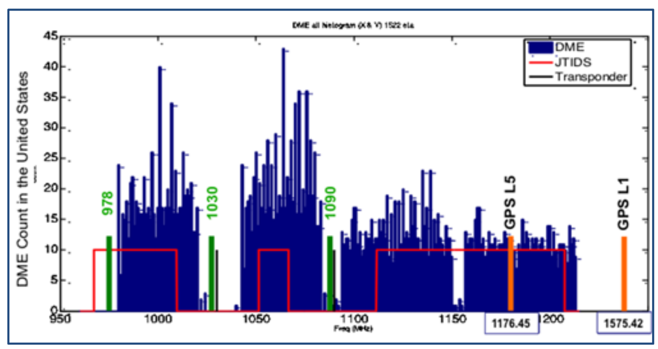

Figure 10 L-Band Aeronautical Services

APNT has examined and designed terrestrial based pseudolite is to send a passive ranging or pseudo range signal in a manner similar to GNSS satellite ranging signals. Many signals are possible for this purpose with the primary signals currently examined based on:

- Distance measuring equipment (DME)
- Universal access transceivers (UAT)
- Transponder/Mode S/1090 MHz signals
- L-band digital aviation communication systems (LDACS)
- A new spread spectrum-based signal [such as that used in Ultra-High Accuracy Reference System (UHARS)]
- Other FAA signals of opportunity

The APNT team determined that pseudoranging signals based on DME and ADS-B (1090 MHz Mode S ES and UAT) transmissions seem most reasonable for the US airspace. DME-based pseudolites would use the existing DME signals to create a pseudo-ranging and data capability [ref]. This new system thus would provide capabilities that currently do not exist on DME. UAT has the built-in pseudo-ranging and data capability in its ground segment transmission. The benefit of these first two signals is that they utilize broadcasts that already exist in the NAS without any changes to their signal or message structure [6]. Transponder signals, specifically Mode S ES, already exist but will need modifications to provide a pseudo ranging capability. LDACS and UHARS are systems in development [ref] [ref]. LDACS may make sense as a pseudo ranging signal for APNT in European airspace as Europe does not use UAT.

A common thread between all candidates is that they all have some data capacity. This is important for precise time as providing users time information such as time of week requires additional bits beyond the basic timing needed to support pseudo ranging. The take-away is that while all pseudolite signals need to be able to indicate time of transmission relative to some common time frame (e.g., UTC second), the candidate signals have the capability to provide information specific for precise time.

The benefits of transmitting pseudolite signals based on signals emanating from these facilities to compliment GNSS is twofold: (1) The combination of DME, TACAN, and ADS-B RT sites provides better geometry – especially at lower altitudes; (2) the signals emanating from these facilities are at a much, much higher power than GNSS signals, making them more resilient to RFI; and (3) like GNSS signals, there is no capacity limitation on the number of potential users as there is for current DMEs. As the signal is terrestrial, the coverage per transmitter is much less due to line-of-sight restrictions, but ionospheric effects need not be considered. APNT pseudolites can also be designed with data capability that can be used to strengthen or provide added benefits for GNSS such as improving accuracy or robustness, or to provide the means to validate the authenticity of the source of the data.

Pseudolite signals over existing DMEs would be encoded to allow aircraft to determine the transmitter location and time of transmission, allowing users to calculate total travel time (and hence pseudo range) by measuring the time of arrival. Pseudolite location could be provided in this the transmission directly or with unique pseudolite identifiers and a stored lookup table. Additional data can include integrity information. Another benefit of pseudolite is its unlimited capacity whereas DME is capacity limited.

Additionally, while the primary requirements driving the design and development of APNT pseudolites are based on positioning and navigation needs, pseudolites can also serve as distribution points for precise time and frequency. By their very nature, APNT pseudolites must be precisely time synchronized. While APNT can synchronize to any time base, synchronizing to a common standard could allow for interoperability with other systems and use by other modes or users. The most common standard is Coordinated Time Universal (UTC). GPS time is synchronized to UTC) while WAAS Network Time (WNT) is synchronized to GPS time (and hence UTC).

A common time base results in having a common clock bias between all pseudolite stations and the aircraft. This enables the calculation of horizontal position with three pseudo ranges to solve for the two-dimensional coordinates and the common clock bias. Thus, all of the pseudolites in view must be in the same time reference frame for the measurements to be valid and the determined position to be reasonably correct – Remember, a nanosecond of error is approximately equivalent to a foot of error. So, if the pseudolites must broadcast their time of transmission for an aircraft to determine its position and use the information to establish its position and navigate, this transmission of time is a most import ancillary product. Of even greater interest is the fact that non-aviation users could also use these high power pseudolite signals, providing significant multi-modal benefit from this robust time information service in the event of GNSS outages. The location of these pseudolite signals – both geographically and spectrally is key to providing the position and navigation, as well as the timing essential services. Figure 8 shows the potential locations of both multilateration sites and/or pseudolites that could be co-located with existing DME and ADS-B GBT sites – over 1000 locations within the Conterminous US (CONUS).

Both the multilateration and pseudolite solutions require that the ground network be precisely synchronized in time – every nanosecond of time error being equivalent to approximately 1 foot in distance error. However, like in GNSS, the aircraft's clock is generally not synchronized with the ground transmitters, the calculated total travel time is biased by the difference between its clock and the multilateration/pseudolite system clock. This clock time difference generally termed *clock bias*. Hence the range is a pseudo rather than a true range. With passive ranging, three ground stations, with reasonable geometry, are needed to simultaneously solve for horizontal position and the clock ambiguity between the user and the ground system. This is a major detriment to coverage, especially near the ground where terrestrial signals are hard to come by due to line-of-sight (LOS) limitations. While pseudolites provide many benefits, the coverage limitation would require significantly more infrastructure and led the APNT team to develop the Hybrid APNT solution.

Hybrid APNT Solution

The Hybrid APNT (H-APNT) Alternative seeks to capture the major benefits of pseudolites and DME. In H-APNT, both one-way (pseudolite) and two-way (DME) ranging is used. This concept is depicted in Figure 11. The key observation is that with DME, there is a single

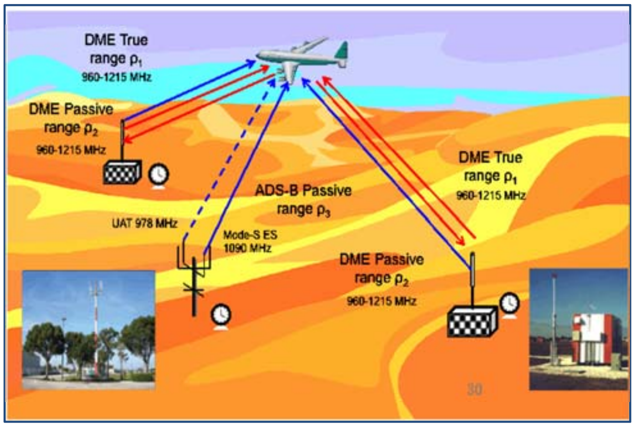

Figure 11 H-APNT: True and Pseudoranging

source of both forms of ranging and the combination of these two measurements can be used to solve for the *clock bias* without an additional station. DME true range solution entails the timing of a "round-trip" (interrogation, established ground delay reply) and captures the true distance to the station. The DME pseudo ranging signal provides time of transmissions. These two measurements can be used to solve for the true time of arrival (TOA) and then the clock bias (difference between the true TOA and the estimated TOA based on the aircraft clock).
Having knowledge of the clock bias, pseudolite ground stations effectively provide true range. And so the avionics can provide horizontal position with two ground

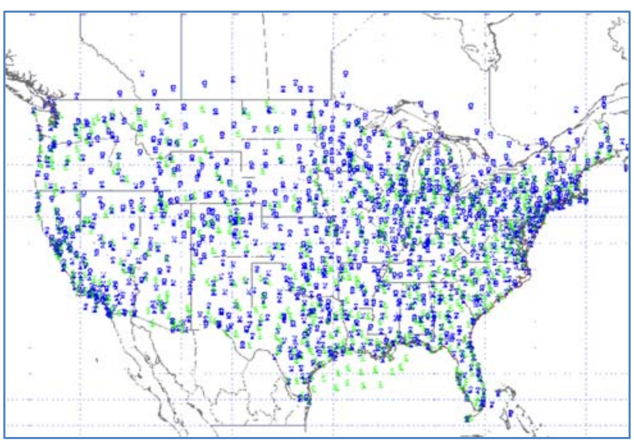

Figure 11 Potential H-APNT Ranging Locations: DMEs & ADS-B RTs

stations in good geometry. If the clock bias is known *a priori* (e.g., previous calculated and maintained with a good on-aircraft clock), any two stations (pseudolite or DME) may be used. Otherwise, one DME station will be needed for determining the clock bias. The result is the same geometry benefits as DME with more possible ranging sources. Hence, the hybrid refers the fact that pseudolite and DME ground stations can be used almost interchangeably providing geometry benefits. Moreover, the pseudolite timing and data benefits are retained. Furthermore, DME only and pseudolite only operation is also possible which is attractive to legacy DME/DME and power constrained aircraft operators, respectively. The basic infrastructure providing hybrid APNT is made up of a combination of DME, TACAN, and ADS-B RT facilities and is shown in Figure 11.

THE CHALLEGES OF PRECISE TIME AND FREQUENCEY DISTRIBUTION

Given that we are able to deliver precise time to GBTs and/or pseudolites, (as an undeniable requirement) the challenge is how to provide this information reliably and with high integrity to aircraft and other users. For at least one of the GBT multilateration options the answer appears obvious – utilize the UAT transmission protocol to provide time of transmission to the aircraft from multiple GBTs based on "GBT System Time" derived from a reliable UTC source. Similarly, pseudolites could employ the same time transmission message to provide their time of transmission to aircraft, thus enabling the aircraft with multiple sources of precise time in view, an over-determined solution, and thus high integrity.

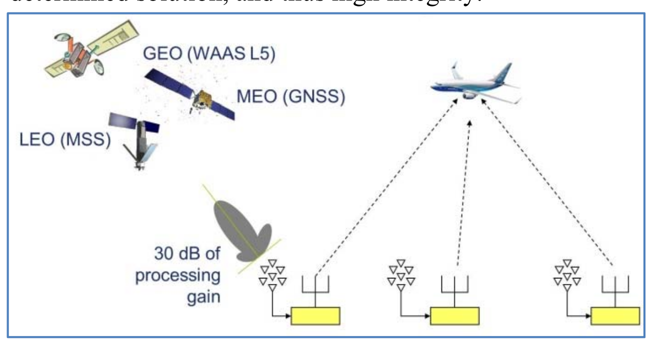

Figure 12 Ground-Based Time Synchronization

Three primary potential solutions have been considered for time synchronization of the multilateration sites and pseudolites. The first would leverage robust, wireless, space-based time synchronization methods, while the second and third options would use wired (network) and wireless terrestrial solutions.

The robust space-based timing solution would use satellite signals from the WAAS geostationary (GEO) satellites, GPS/GNSS medium Earth orbit (MEO) satellites, and low Earth orbiting (LEO) satellites, along with an adaptive beam forming, null steering controlled reception pattern antenna (CRPA) array to significantly mitigate RFI and provide anti-jam (A/J) performance. It should be noted that WAAS is an FAA system designed to support aviation needs in compliment with GPS. It operates with and provides signals similar to GPS. So WNT is steered to GPS time with WAAS maintaining its own master clocks that can operate independent of the GPS clocks. This provides the potential for operations even if GPS is unavailable. Space-based time transfer is already the most popular means of precise time transfer due to its accuracy and cost effectiveness. For example, GPS accuracy relative to UTC is specified to less than 1 microsecond (µs) (without UTC offset), though in actuality accuracies better than 15 nanoseconds (ns) have been routinely achieved. One-way space-based methods are cost effective as they derive time only from reception of satellite broadcasts. However, satellite broadcast signals are susceptible to interference due to their low received signal power.

CRPA technology allows for the use of satellite signals for precise timing and synchronization even in the presence of strong RFI by 1) making outages much more difficult and 2) limiting outages to a small, local area. CRPA enable beam steering and adaptive null forming which focuses more of the desired signal energy while rejecting more interference than conventional antennas. Coupled with other anti-jam technologies, jam resistance can be improved by a factor of 1000 or more over conventional GPS receivers.

Network timing provides time synchronization using standardized protocols developed and supported by network equipment. Two candidates are precise time protocol (PTP) described in the IEEE 1553 standard and J.211. PTP is a protocol being developed and built in router and switching hardware to enable precise time transfer over Internet connections using Internet Protocol (IP). While there are many flavors of PTP, the most stringent current target for a wide area network (WAN) is 1 µs aimed at supporting telecommunications. PTP timing performance is limited by its use of Ethernet lines that operate different lines for the incoming and outgoing traffic. These incoming and outgoing lines will typically have small percentage differences (0.15%) in length that result in timing errors. For example, over 50 km, 0.15% error equals 75 m or 250 ns of error. The error increases over distance and cannot be easily corrected with PTP. To improve performance, J.211 mandates that incoming and outgoing traffic use the same lines to eliminate this difference. However, this requires dedicated lines and has currently only been implemented over relatively small geographic regions. Table 1 summarizes the key characteristics for the major network timing protocols.

Terrestrial techniques use land based RF transmissions for timing. Two techniques are being considered – the use of long-range signals, such as low or very low frequency (LF, VLF), and line-of-sight (LOS). LF and VLF signals are useful as they can propagate along the earth for very long ranges. One broadcast, such as the WWVB time

	NTP	PTP	J.211
Deployment	All networks	Precision networks	Cable industry
Layer	Software (SW)	PHY (physical layer), MAC (media access control), SW	Hardware, PHY, MAC, SW
Precision	1-10 ms	100 ns-10 µs	100 ps-5 ns
Transport	Any, software	Ethernet preferred	CAT 5 cable
Scale	Network (WAN), Internet	Network (WAN and LAN)	Local/ dedicated

Table 1 Summary of Network based Protocols Requirements & Capabilities: Network Time Protocol (NTP), PTP, J.211

signal from Fort Collins, CO, can cover much of the CONUS. The time accuracy of the signal is affected by variations in ground propagation delay and skywave multipath that changes throughout the day. This makes sub-microsecond timing over a large area using the signal quite challenging. Line-of-sight time synchronization using reference transmitters (RefTrans) is being used in the FAA multilateration (MLAT) system implemented in Steamboat Springs, Colorado, and in commercial pseudolite systems, such as Locata's Locatalites (the basis for UHARS) and Saab-Sensis Closed Loop Transmitter (CLT). These systems can perform very precise time synchronization, especially using two-way closed loop control. However, LOS is only viable over short distances and does not provide absolute time synchronization (unless there is a master that relies time traceable to a primary reference source/master clock such as the US Naval Observatory (USNO) or the National Institute of Standards and Technology (NIST)). Table 2 summarizes the accuracy levels of the methods discussed in this section.

Method	Accuracy (to UTC)
GPS Timing Receiver	40 ns (< 15 ns)
WAAS (with WNT-UTC offset corrections)	29 ns
Iridium	1 µs (20 picosecond (ps) for 1 sat)
Radio - Dedicated	10 ns - 10 ms
Radio - WWVB (60 kHz)	0.1 - 10 ms
PTP	1 µs (target)
J.211 (DTI)	< 5 ns

Table 2: Summary of the Accuracy of Precise Time Technologies

NEXT STEPS

The FAA is continuing to pursuing "the best APNT solution(s) and continues to research APNT. Currently, an initial investment decision (IID) is planned in 2016 and a final investment decision in 2017.

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