The Benefit of Alternative Position, Navigation, and Timing (APNT) to Aviation and Other User Communities for Precise Time and Frequency Services

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INTRODUCTION

Positioning, Navigation, and Timing (PNT) services are the key basis for the provision of 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/go to source of P and N and T is a Global Navigation Satellites System (GNSS). While the transition of various users/modes of transport from legacy PNT aids to GNSS is at varying stages, it is of concern that the ability of users to revert from the highly accurate positioning, area navigation (RNAV), and precise time provided by GNSS back to previous methods, which may provide lower levels of performance, will require higher levels of user skills, knowledge, and abilities – capabilities that may no longer be available when needed without significant investment in equipment sustainment and upgrade and in-depth training and practice.

GNSS signals are extremely weak and highly susceptible to radio frequency interference (RFI). It is, therefore, extremely important that an alternative means of providing PNT services be implemented that ensures safety and security and precludes significant loss of economic in the event of a GNSS service outage. The Federal Aviation Administration (FAA) has initiated an Alternative Position, Navigation, and Timing (APNT) program to research various strategies that can provide the necessary PNT services to support the US National Airspace System's (NAS) transition to the Next Generation Air Transportation System (NextGen). Under APNT, three alternative strategies are being considered – (1) continuation and potential improvement of current Distance Measuring Equipment (DME)-based area navigation (DME-DME), (2) aircraft position determination using ground-based multilateration and information uplink via the ADS-B network, and (3) aircraft position determination by means of ground-based pseudolites. The DME-DME alternative is currently used by aircraft in the NAS to fly area navigation (RNAV) routes in the NAS per FAA's Advisory Circular 90-100A; however, it is the two "newer" alternatives that are the concentration of this paper because of their ability to support the robust distribution of precise time and frequency in addition to supporting position determination. This paper focuses on these two alternatives and specifically of this time/frequency capability. It enumerates both the challenges and potential methodologies for implementing a multi-modal precise time and frequency service (tens-of-nanoseconds as well as real time information) to all user communities through the broadcast of a high power signals in protected spectrum.

GROWING SOURCES OF INTERFERENCE

Before exploring potential solutions, it is important to fully understand the motivations behind this effort. Despite its enormous worldwide utility as a source of precise PNT, GNSS is vulnerable to RFI.

Interference is real – it is a daily occurrence that many users have had to face in operational environments – in the NAS and other parts of our critical infrastructure. And the problem is growing. The message is clear – the world has already changed and is still changing. Interference is occurring more and more often.

Certainly the most *advertised* source of interference to GNSS-provided PNT are the exercises conducted by military organizations, whose missions require them to be able to both deny services to opposing forces and operate in GNSS PNT-denied situations. 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 mission is impaired, FAA and DoD coordinate these exercises to ensure that the safety, security, and economic benefits of the US NAS are not impaired and that the need for DoD readiness is properly supported.

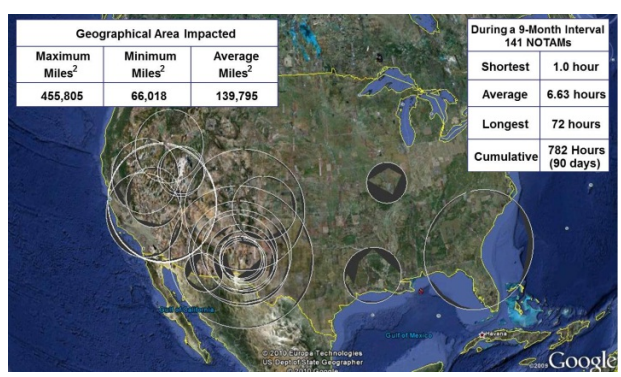

Figure 1: Adverse Condition: GPS Testing by DoD

The more troubling problem is that more and more, interference is becoming more insidious, driven in part by peoples' awareness that the GNSS receiver in their car or mobile phone allows others to track their location In

response to this awareness, a number of manufacturers have produced what they call *personal privacy devices (PPD)*, small, low cost compact jamming devices that are sold to either interfere only with GNSS signals or to jam both GNSS and cellular telephone transmissions. Figures 2 and 3 provide images of just some of the devices that are readily available on the Internet, despite being illegal in most parts of the world.

According to its specifications, also available on the Internet, the jamming device shown in Figure 2 is capable

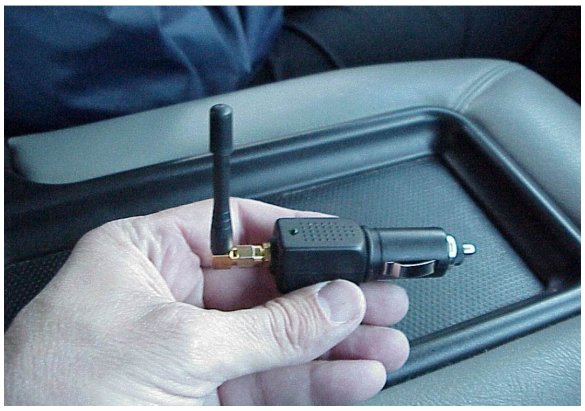

Figure 2: So-called "Personal Privacy Device" - PPD

of transmitting 0.5W of power on the GPS L1 frequency (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 Privacy Devices" - PPD

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

As a provider of safety and security radionavigation services that provide significant economic benefit, the FAA is keenly aware of this ever-emerging problem. That is the first step – to be aware that as a GNSS service user or supplier you are operating in harm's way. Figure 4 denotes an excellent example of this. Here, the FAA has installed a Local Area Augmentation System (LAAS) at 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 many thousands of trucks and automobiles pass by each day – a location dictated by siting criteria based on runway configuration. Being aware of the potential problems, the LAAS program is implementing system design aspects to mitigate the effects of interference sources and maintained safe and secure services[6]. It has been a valuable lesson – one that it is hoped will be taken up by PNT users and suppliers worldwide.

Figure 4: In Harm's Way -- FAA LAAS Installation at EWR

This is not an isolated incident. The FAA has detected PPD interference around the country, e.g., the Wide Area Augmentation System (WAAS) reference station in Leesburg, Virginia has detected regular sources of interference. The Federal Communications Commission (FCC) is working closely with FAA Spectrum Engineering personnel and has successfully identified a number of the interference sources – again, in-car PPDs. Although the owners of these devices have voluntarily turned them over to the FCC when made aware of their illegality, others continue to be observed periodically. While this has had no operational impact, it does show how widespread a problem PPD RFI is becoming [6].

THE IMPORTANCE OF PRECISE TIME & FREQUENCY

The US NAS, like the vast majority of parts of our country's critical infrastructure, has become highly dependent on precise time and frequency provided by the GNSS. The NAS uses time primarily for time stamping all forms of data, from surveillance position reports to controller-to-pilot communications, to Runway Visual Range measurements – primarily to ensure a complete legal record in the event of an incident that will support accident investigation in their recreation of events.

However, the NAS must also exchange large volumes of data and information to ensure the safely and the

efficiency of all users and operators. These data exchanges also require quality time and frequency services to ensure error-free transmission and reception, and in the future, improved levels of security. Most importantly, surveillance and navigation systems require the highest levels of time precision as the determination of position by measuring radio message transit time depends on precise time measurements and synchronization. As electromagnetic waves travel at approximately one foot per nanosecond (one billionth of a second), a clock difference of only 50 nanoseconds (ns) can negate the capability to correctly identify the position of an aircraft to within required tolerances.

The current NAS time and frequency needs are portrayed in Figure 5, below. Navigation for meeting required navigation performance (RNP) and RNAV as well as surveillance, in the form of multilateration, requires very precise time or synchronization (tens of nanosecond). However, the vast majority of aviation users do not require precise time; rather time to the millisecond level (10^{-3}) is more than sufficient for most purposes. Time stamping of data/events is probably the largest user of this information. For the FAA, this supports the need to accurately record and store for the required duration NAS operational information, which in part supports incident investigations.

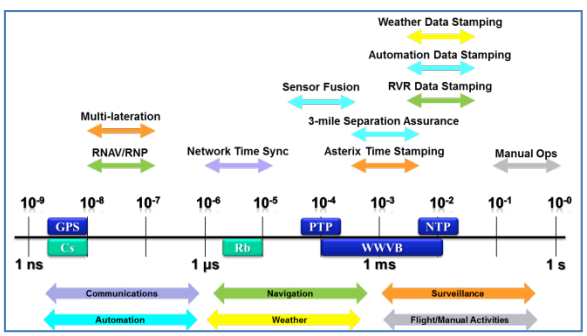

Figure 5: Current NAS Time Requirements

External to aviation, other user communities also have time stamping requirements and the need for precise time. It is interesting to note that the precision requirement for time stamping financial transactions has increased, as the result of these transactions becoming more and more computer-to-computer interchanges than person-to-person. While time stamping to the nearest second was previously acceptable, the metric is now milliseconds, and as our automation and communications networks improve with technology, one could expect the requirement to become even more precise. GNSS' efficient and effective delivery of precise time and frequency has been a prime enabler of this transition. But what happens when GNSS is not available? The same question applies to the establishment of the smart power grid. Currently, power networks use phase monitors to provide measurements important to the efficient and effective control of power generation and distribution. These phase monitors rely on GPS to synchronize their measurements and provide real time results. Loss of GPS timing capabilities could impair this function and result in inefficiencies and potentially power disruptions. Many cell towers still rely on GPS time services and past events in which GPS was lost has affected cellular communications. At least one cellular company preciously used Loran as an alternative timing source, but with discontinuation of that service in 2010, the reliance on GPS remains.

Next, we explore the two APNT alternatives that offer the potential to deliver precise time and frequency to aviation and other user communities. First, each alternative is described and its reliance on precise time synchronization is discussed. Then, the means by which each alternative can serve as a source of precise time and frequency is described – opportunities, but not without challenges. We begin with the multilateration alternative:

THE APNT MULTILATERATION ALTERNATIVE

The FAA's implementation of Automatic Dependent Surveillance – Broadcast (ADS-B) services throughout the NAS is proceeding and will support full user equipage required by 2020. The ADS-B system consists of 800+ Ground-Based Transmitters (GBT), which receive position information from aircraft broadcast either on the 978 MHz Universal Access Transmitter (UAT) frequency or the 1030 MHz Mode S extended squitter frequency and transmit aircraft position information for to aircraft to support situational awareness via both 978 MHz and 1090 MHz. The ADS-B program has also implemented multilateration capability at a number of locations in the NAS where traditional ground-based surveillance capability (i.e., radar) is not available. Multilateration works by receiving an aircraft's Mode S squitter transmission at multiple GBTs, determining the time of arrival (TOA) at each GBT, and calculating the aircraft's position. This requires GBTs clocks to be synchronized

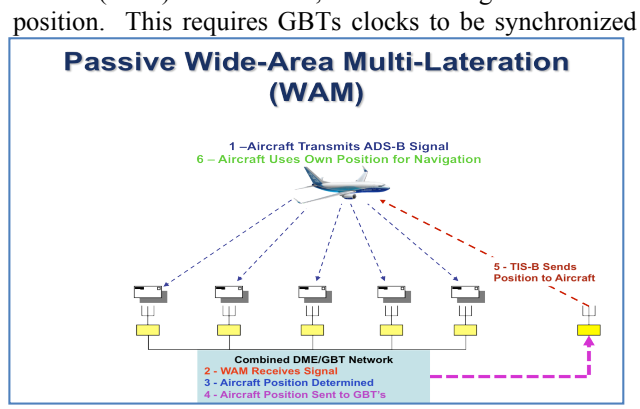

Figure 6: Multilateration Alternative

to a very precise level, as every nanosecond of clock bias inserts a foot of error in the calculation. The ADS-B

program indicates that they require time synchronization to be within 30 nanoseconds (approximately 10 meters).

Although in its current broadcast of aircraft positions for situational awareness "own ship" position is masked to prevent confusion, it is envisioned that the ADS-B multilateration determination of own ship position could be used to provide an aircraft with its own position and enable navigation in the event of a GNSS outage. The means of doing this is shown in Figure 6.

THE APNT PSEUDOLITE ALTERNATIVE

To describe the APNT Pseudolite Alternative, we start by describing the basic concept of pseudolites and passive ranging. A pseudolite is a terrestrial transmitter that sends a passive ranging or pseudo range signal in a manner similar to GNSS satellite ranging signals. Passive ranging uses the transmissions of synchronized signals from multiple, geographically dispersed ground transmitters. These signals are encoded with a means of determining pseudolite location and time of transmission, allowing users to calculate total travel time (and hence pseudo range) by measuring the time of arrival. Pseudolite location may be provided by the transmission directly or with unique pseudolite identifiers and a stored lookup table. As an 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 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 pseudolites, with reasonable geometry, are needed to simultaneously solve for horizontal position and the clock ambiguity between the user and the pseudolite system. The basic architecture is seen in Figure 7.

A benefit of APNT pseudolites to compliment GNSS is that the signals can be transmitted and are received at much higher power making them more impervious to RFI. 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 will be designed with data capability that can be used for strengthen or provide added ca GNSS.

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. The most straight-forward way is to synchronize the pseudolite stations to

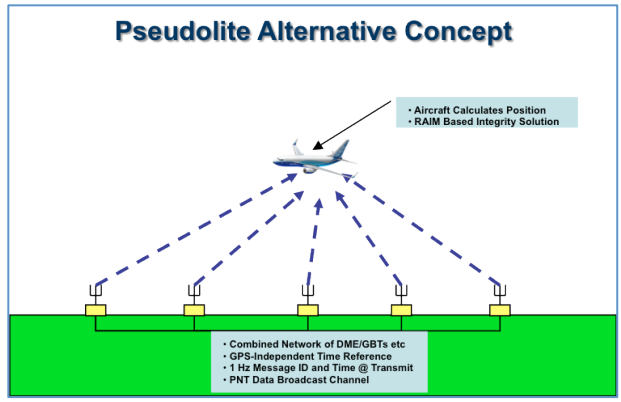

Figure 7: Pseudolite Alternative

Coordinated Time Universal (UTC). This 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 these high power pseudolite signals could be received by non-aviation users, 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

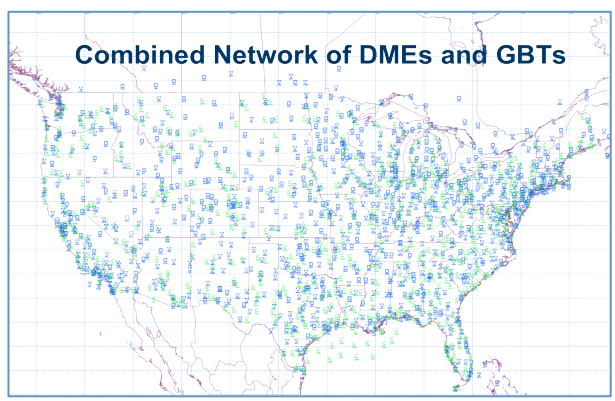

Figure 8: Potential Multilateration and Pseudolite Locations

pseudolites that could be co-located with existing DME and ADS-B Ground Based Transmitter (GBT) sites – over 1000 locations within the Conterminous US (CONUS).

POTENTIAL PSEUDOLITE SIGNALS

The FAA's APNT team have compiled and examined many Pseudolite Alternatives and implementation strategies. The primary signals currently under consideration are based on using:

- 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 first two signals utilize broadcasts that already exist in the NAS without any changes to their signal or message structure [2]. Transponder signals already exist but will need modification to provide a pseudo ranging capability. LDACS and UHARS are systems in development [3][4]. 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 time.

POTENTIAL MULTILATERATION AND PSEUDOLITE TIME SYNCHRONIZATION SOURCES

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. 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: Summary of Network based Protocols Requirements & Capabilities: Network Time Protocol (NTP), PTP, J.211 [7] summarizes the key characteristics for the major network timing protocols.

	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 [7]

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 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 multi-lateration (MLAT) system implemented in Steamboat Springs, Colorado, and in commercial pseudolite systems, such as Locata's Locatalites (the basis for UHARS) and ITT's 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 summarizes the accuracy levels of the methods discussed in this section.

Method	Accuracy (to UTC)
GPS Timing Receiver	40 ns**Error! Reference source not found.** (< 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 [7][8][9]

These solutions are not mutually exclusive; their elements may be combined to form a more cost effective solution by using existing and less costly infrastructure to provide the "final" mile. For example, a star network with a precisely synchronized central node that distributes to nearby elements could be used. One implementation would be to use satellite timing for the central node and transfer its time over existing line-of-sight or network connections.

Despite the reliance of the space-based systems on GPS/WAAS, the additional infrastructure required for terrestrial options clearly can become overwhelming. Further, our preliminary results with CRPA antennas for GNSS and interference cancellation, coupled with the fact that the WAAS signal is under the direct control of the FAA, makes this option an intriguing one to explore. Figure 8 depicts the means by which a pseudolite node could derive precise time from a number of alternative satellite assets – even in the presence of RFI. With a pseudolite solution at the aircraft, the avionic systems could be time synchronized with the ground and support more robust communications links. A user of this time service on the ground, knowing their position, would require only a single pseudolite reception to derive precise time.

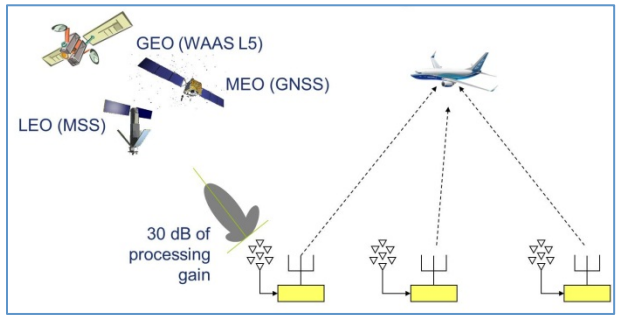

Figure 8: Ground-based Time Synchronization

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.

For non-aviation users, the solution is not quite as "good," but one might argue that it need not be. Because it would be much more difficult to receive line-of-sight transmissions from multiple GBTs and pseudolites at ground level, the ability to have an over-determined solution is greatly diminished; however, given that many ground-based time users remain stationary (e.g., cell towers, electrical grid phasemeters, etc.) or are relatively "slow movers," other means of ensuring integrity can be derived to meet their needs – typically much fewer 9's.

As Figure 8 shows, there will many, many places within the US where ground users will be able to receive signals from GBTs or pseudolites, or both. These signals will be high power and transmitting in protected spectrum. They will be derived from US Government sources – either directly or via contract, and their quality and integrity will be thus assured. They can potentially provide great benefit to many user communities as a source of robust, GNSS-independent time and frequency.

A challenge, however, remains for the multilateration solution is on "the 1090 side" of the GBTs, where bandwidth is much more of an issue. Used primarily by air carriers, the ability to transmit time information on 1090 is important, but remains problematic and needs further study and discussion.

NEXT STEPS

The FAA is continuing to pursuing "the best APNT solution(s) The FAA plans to continue APNT research and develop R&D Multilateration and Prototype alternatives for the different alternative solutions, along with cost and schedule estimates, while it completes the analysis of alternatives. The FAA is also investigating ways in which the DME-DME alternative can provide greater benefit to aviation users.

First and foremost, the APNT remains a research endeavor. The "best" answer is still, as they say, *to be determined*. What is most important, again, is that the potential problems and impacts 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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