Alternate Positioning, Navigation, and Timing (APNT) Pseudolite Alternatives

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"It should be noted that the views expressed herein reflect the personal views of the authors and do not reflect the views or positions of the Federal Aviation Administration or their respective organizations."

ABSTRACT

The Federal Aviation Administration (FAA) has initiated an APNT program to research various alternative strategies that will ensure that the PNT services necessary to safely, securely, and efficiently support the US National Airspace Systems' (NAS) transition to the Next Generation Air Transportation System (NextGen) will be ensured. This paper discusses the Pseudolite Alternative, one of a number of alternatives being examined to determine how best to maintain the safety, security, and efficiency of the NAS in the event of a loss of Global Navigation Satellite System PNT services. It examines different methodologies for implementing this alternative and discusses the pros and cons of each. Most importantly, it examines how the Pseudolite Solution can work in tandem with other APNT alternative to mitigate risk to all NAS users when they are no longer able to rely on GNSS area navigation.

INTRODUCTION: Overview of the APNT Pseudolite alternative, its benefits and challenges, and how it can contribute to the overall APNT solution.

The APNT Pseudolite alternative uses multiple, geographically dispersed, terrestrial transmitters to provide passive or pseudo ranging signals that an aircraft can use to accurately calculate its position. The primary benefit of this passive ranging alternative is that it provides unlimited capacity, which is important considering the anticipated large increase in traffic and traffic densities by 2025 that will utilize the Next Generation Air Transportation System (NextGen). The possibility of transmitting pseudolite signals from distance measuring equipment (DME) and ground based transceiver (GBT) sites mean that some of the transmitter sites needed to support the signal are in place and it may be possible to implement with little to no additional sites.

Passive ranging uses the transmissions of synchronized signals from multiple, geographically dispersed, ground transmitters. These signals are encoded with a means of determining station location and its time of transmission, allowing users to calculate total travel time (and hence range) by measuring the time of arrival. Station location may be provided by the transmission directly or with unique station identifiers and a stored lookup table. As the aircraft is generally not synchronized with the ground transmitters, its calculated total travel time is biased by the difference ground and user clocks and hence the range is a pseudo rather than a true range. This total travel time is the calculated from the *time difference* between transmit time indicated by ground clock and received time measured by user clock). As a result, if the user clock synchronization to the ground is not known, an extra measurement is needed to solve for this bias. With passive ranging, three stations are needed to solve for position rather than two with a true range system such as when multiple Distance Measuring Equipment (DME/DME) positioning is used. To mitigate this issue, this paper also describes means to synchronize the aircraft clock and the ground system clocks.

Utility to APNT

The FAA's APNT team is examining how pseudolite systems can help to meet program goals by serving as the primary APNT system or as a complementary part of a full APNT solution. The full APNT solution provides navigation to aircraft in three service volumes (seen in Figure 1):

- Zone 1: Class A airspace, Flight Level (FL) 180 (18000 ft) to FL 600 (60000 ft) over the conterminous United States (CONUS). High en route
- Zone 2: FL 180 to 5000 feet above ground level (AGL) over CONUS. This is low en route airspace
- Zone 3: Terminal area of specified major airports, currently top 135 busiest. This is a truncated conical area down to 500 feet AGL

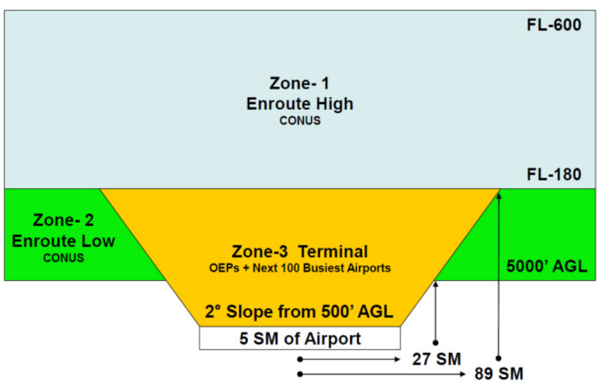

Figure 1. APNT Service Volume defined into 3 Zones. SM = statute mile. Operational Evolution Partnership (OEP) airports = top 35 busiest airports.

The goal for APNT pseudolite or any APNT solution is to support all three zones and their respective performance requirements. En route coverage (Zone 1 and 2) throughout CONUS will require a significant number of stations reasonably distributed. However, Zone 3 is likely the most challenging as its proximity to the ground reduces the number of stations visible due to line of sight blockage. This is especially problematic for a pure pseudo ranging or multilateration system which requires at least one more station for positioning compared to a true ranging system like DME/DME.

Even if a pseudolite system can serve only National Airspace (NAS) en route PNT, it may be a valuable and necessary component of the full solution. For example, if DME/DME becomes the primary APNT for the "high-end" equipped aircraft, the Pseudolite Alternative could provide a low cost, en route APNT solution for general aviation (GA) (more cost sensitive users), for whom scanning DME receivers may be prohibitively expensive. As described herein, a potential benefit of pseudoranging is simpler, less costly avionics, because the APNT signal could be passive and delivered on a single frequency.

While APNT must support navigation and surveillance through automatic dependent surveillance broadcast (ADS-B), the pseudolite alternative can provide additional benefits, e.g., security, improved GNSS service, and precise time. These features will improve the NAS's robustness and enhance the value of APNT to navigation, as well as to other users.

Pseudolite Alternatives

The FAA's APNT team have compiled and examined many Pseudolite Alternatives and implementation strategies. The primary ones 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 the Ultra-High Accuracy Reference System (UHARS)]
- Other FAA signals of opportunity

This paper focuses on the first two options, but also provides a brief discussion of the other ideas listed above.

Various pseudolite system architectures are also being examined to best utilize the existing ground infrastructure. The APNT team is considering the use of the 1100 existing DME/TACAN sites as a key component of the Pseudolite Alternative infrastructure. For en route coverage, this infrastructure, while possibly adequate when using DME/DME, is not sufficient for the basic pseudolite system which uses all passive ranging signals as this needs three stations for positioning.

Another architecture is to mix in occasional two-way measurements (such as traditional DME) to provide true range and time synchronization to the ground. This *hybrid ranging* architecture reduces the number of ground stations needed for horizontal positioning back to two, which improves coverage (comparable to DME/DME) while still maintaining high capacity. Having a true range and a passive range from a single ground stations allows for synchronization of the aircraft and ground station time. This effectively converts passive ranges to true ranges. With a good clock onboard the aircraft, adequate synchronization can be maintained so only two passive ranging signals can provide positioning. Thus two-way ranges are only needed occasionally – when aircraft clock synchronization is too far off.

OVERVIEW OF CANDIDATE TECHNOLOGY

UAT Passive Ranging

Overview of design

UAT is an attractive pseudolite option as the system already operates a signal designed for pseudoranging. The UAT minimum operational performance standards (MOPS) provides for support of pseudoranging with its ground segment message. The messages are sent at least twice per second from each station and are sent at specified start times, which allows for determination of time of transmission.

The UAT pseudoranging signals are the messages transmitted during the ground segment - the portion of each second solely dedicated to UAT ground stations - also known as ground-based transceivers (GBT). This segment contains 32 equally spaced message start opportunities (MSO) that define the slots where a ground transmission can be sent. Each slot is 5.5 ms in length, with the first slot starting 6 ms after the start of the Coordinate Universal Time (UTC) second (the start of the UAT frame) and occupying the next 176 ms. The ground message occupies only 4.3 ms of the slot and the extra time provides a buffer so that messages from different slots do not interfere. Figure 2 shows the UAT frame and the ground segment slots.

UAT pseudorange is determined by finding the time of transmission (TOT) of the ground segment message and calculating its time of arrival. Determination of TOT boils down to determining which ground segment slot the message used. This is seen in Equation 1, which shows how TOT (relative to the UTC second) is calculated from the slot number. Slot identification can be determined in three ways: 1) directly using the aircraft clock if it is roughly synchronized to UTC (within ~ 1 millisecond), 2) from earlier transmissions as messages from the same station shift one slot each second, and 3) decoding the message which contains the slot number. While it is not necessary to decode the message for ranging, decoding may be important as an integrity check.

$$TOT(msec) = 6 + 5.5 * (slot\ number - 1) \quad \text{(Eq. 1)}$$

Time of arrival is calculated using the synchronization sequence that marks the start of the transmission. The transmission contains a 36-bit synchronization sequence and 4416 raw bits in the payload, which yields 3392 bits after forward error correction (FEC). The UAT ground segment message is seen Figure 3. The data includes slot number, transmitter location, as well as transmitter location valid and UTC synchronization valid flags. Hence it contains all necessary information for positioning while representing a very small fraction of the total message content. Since the synchronization flag is pertinent to signal integrity and integrity cannot be determined otherwise, the full message must be decoded even though time of arrival (TOA) can be found without message decode. This limits the range of the pseudoranging signal as a higher received signal to noise ratio (SNR) is needed for message decode compared to determining TOA of the message.

The UAT ranging signal is transmitted by ground-based transceivers (GBT), the ground stations installed to support ADS-B on UAT and Mode S Extended Squitter. Approximately 700 GBTs will be installed by 2013 to support surveillance. The DME/TACAN sites could provide the additional stations needed to support coverage. This use may be facilitated as the UAT and DME can co-exist and perhaps even share equipment. For example, the GBT transmitting equipment utilizes a DME transmission antenna (dB systems) [17]. APNT coverage with signals from GBT and DME sites seems reasonable for supporting en route to 5000 feet above ground level (AGL). Since coverage for

Power Level Setting	Nominal Power	Minimum Power	Maximum Power
"Off"	0 Watts		(-80 dBm)
"Low"	10 Watts	7 watts (+38.5 dBm)	14 watts (+41.5 dBm)
"Medium"	25 Watts	16 watts (+42 dBm)	32 watts (+45 dBm)
"High"	75 Watts	50 watts (+47 dBm)	100 watts (+50 dBm)

Table 1. Power Levels for UAT GBT transmissions [1]

the major terminal areas considered requires additional stations, an option is to also transmit the UAT ranging signal using airport surface detection equipment (ASDE), Model X (ASDE-X). These systems already support ADS-B broadcast and studies are already being conducted to determine how these signals can be used more effectively in the terminal area. Coverage is assessed in more detail in a later section.

A benefit of UAT ground message is that it experiences little interference from intrasystem sources through its use of time division multiple access (TDMA) and intersystem sources by design. UAT is transmitted on 978 MHz (DME channel 1, a test channel in the US) and modulated using continuous phase frequency shift keying (CPFSK). An increase of 312.5 kHz (Δf) indicates a "1" bit while the same decrease indicates a "0" bit. Each bit is 0.96 μsec in length. Hence, UAT data capability and interference with existing signals are not major concerns.

UAT accuracy depends on its signal in space, transmitted power and its time synchronization. While the signal was designed primarily for data rather than ranging, we have found through both analytic and experimental results that it shows good ranging performance [3]. Note that UAT ground transmissions are about 10 times less powerful than DME, with output power typically 25 to 100 W as seen in Table 1. The time synchronization currently measured is roughly 100 ns. This level is well within specified tolerances of ±500 ns. This is the level required for the UTC synchronization flag to be set true. For APNT use, the desired tolerance would be closer to ±50 ns.

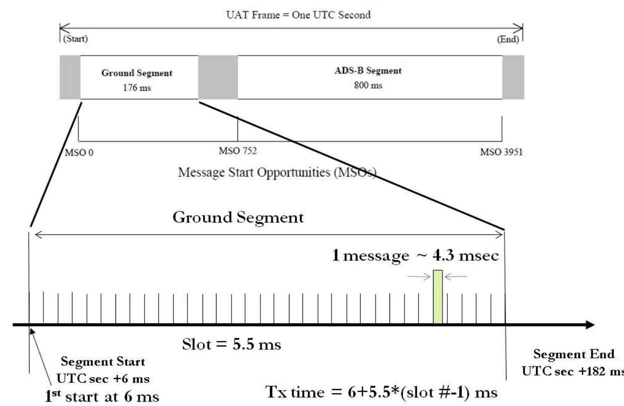

Figure 2. UAT Frame(grey areas = guard band) with expanded view of Ground Segment [2]

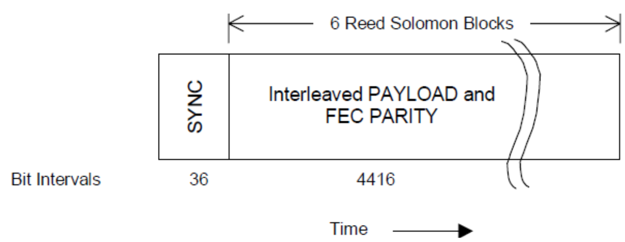

Figure 3. UAT Ground Segment Message (with Forward Error Correction (FEC)) [2]

Discussion of Benefits/Drawbacks

The primary technical challenge anticipated for UAT concerns coverage and multipath. Coverage at 5000 feet above AGL (Zone 2) with GBT is lacking in many areas due to the need for three stations. The coverage situation also degrades at lower altitudes. The lower structure airspace is important for GA en route navigation, we are examining the means of improving coverage, such as adding more ground stations (i.e., DME/TACAN) and hybrid ranging. Zone 3 coverage can also be challenging.

Additional ground stations would require means to mitigate the congestion caused by their added transmissions. Possible mitigation methods include managing the UAT TDMA allocation and perhaps adding a ranging dedicated signal.

Risk	Description	Action/Mitigation
Coverage in terminal areas	Not enough stations to provide 3 stations with good geometry throughout desired low altitude coverage area	Hybrid (mixed one way/two way Additional stations (need to manage spectrum, time slots)
Shadowing	Directions of signal unavailability due to blockage from other features in the installation	Coasting if direction is small
Multipath	Indirect signal from reflections causing increased range error	Improved signal processing
Interference		TDMA mitigates Develop means of using sync sequence only
Integrity	Is there integrity monitoring of signal in space relative to ranging? Timing accuracy (to 500 ns) is monitored	Need to assess what monitoring is done on transmitted signal. Determine what is needed for ranging integrity
Not international standard	UAT only adopted in the US (not Europe	Work on international standards Dedicate use to GA (non-international)
UAT restricted use above FL 180	UAT not to be used above FL 180 by rule, transmission lower power as a result	Change in rulemaking

Table 2. UAT Pseudolite Technical/Institutional Risk Area

Hybrid ranging is discussed later and requires a reasonably accurate clock onboard the aircraft. Another issue that needs to be examined is the possible shadowing of the UAT transmission at some GBT installations. Shadowing is the blockage of the UAT signal by other structures on the tower on which the UAT antenna is mounted and it can result in reduced coverage, because some directions will have attenuated or unavailable signals. Hence, the magnitude and effect of this shadowing on UAT pseudolite needs to be further explored.

Multipath is a challenge that affects accuracy and integrity. UAT was not designed primarily for ranging and measurements have suggested that multipath may hinder desired ranging performance. Additional analysis, measurement and processing design is needed to understand the effects of multipath and its significance for UAT passive ranging.

Integrity is an unknown. While the data and timing accuracy (to 500 ns) is monitored, it is not clear if the signal in space is monitored for its ranging accuracy. DME has local ground monitors and similar monitors may be desired for UAT signal integrity. These risks are summarized in Table 2.

The benefits of UAT are: 1) the already existing signal can be used with no modifications at approximately 700 ground stations, 2) UAT operates on a single frequency (allowing for lower cost avionics), and 3) the avionics being developed for GA use of ADS-B may form a significant base for delivery of APNT services to that community.

The drawbacks are that UAT is not used internationally and may not be desirable for commercial aircraft as they will be equipping with Mode S (1090 MHz) rather than UAT for ADS-B.

DME Passive Ranging (DMPR)

Overview of design

DME passive ranging (DMPR) utilizes existing, random DME squitter transmissions by initiating such transmissions at specified, pseudorandom times. The pseudorandom sequence is triggered by a ground interrogator (or other appliqué to the DME ground station) with a known delay relative to a common time base such as UTC. The DME broadcast encodes the time of transmission needed in pseudoranging. Data to provide ground transmitter location and security can also be encoded in a similar method.

Our initial design used 500 reply pulse pairs per second, with 150 for synchronization and 350 for data, to achieve the desired performance while not having a noticeable impact on DME capacity. This level is less than 20% of the capacity of many fielded DME transmitters, which can transmit up to 2700 ppps. It is even lower compared to newer systems which are capable of up to 5400 ppps [6]. The structure for the design is shown in Figure 4.

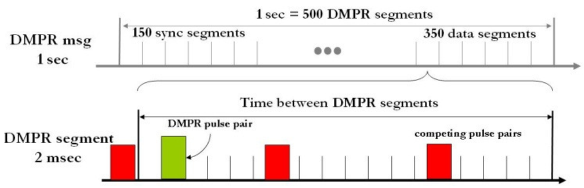

Figure 4. DMPR message & transmission structure

Ranging is supplied via a known synchronization sequence. The synchronization sequence provides alignment and identification of TOT with a sequence of pulse pairs sent at known times relative to the UTC second. This provides the pseudorange and also sets the time base allowing for data transmission. For the design, data transmission is accomplished by defining 350 two millisecond (ms) frames whose times are set relative the synchronization sequence. Data symbols are provided by sending a reply in one of several acceptable start times within the frame. The number of acceptable start times determines the number of bits per pulse pair or symbol.

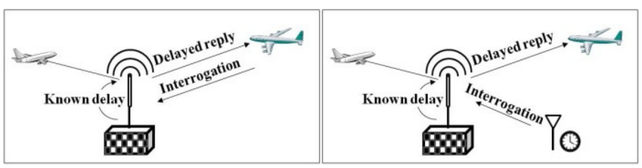

Figure 5. Comparison of nominal DME & DME passive ranging operations

Of course, some replies in the sequence may be interfered with or not sent. For the synchronization bits, reply losses are treated as data drops. For data bits, forward error correction (e.g. fountain codes) is used to mitigate symbol erasures and errors. Even with error correction overhead, it is anticipated that a post correction level of 800 bits per second (bps) is achievable in the worst case. The data transmission design and capabilities are discussed in [3][8][13].

Discussion of Benefits/Drawbacks

There are several technical challenges to DME pseudolite for APNT. One concern is how to ensure that the design can operate even with the DME Morse code or TACAN azimuth bursts. Another is to place DME pseudolite transmission from all sites on a common frequency to enable simpler, lower cost avionics. This may be even more challenging as we may need to add more DME transmitters, perhaps at GBT sites. Similarly, the DME signal has multipath concerns which are well known [7]. This can be mitigated by using a signal with faster rise time such as DME/Precision DME/P). The DME/P however is limited in transmitted power due to spectrum constraints. The impact and significance of multipath needs further study. A summary of these technical risks and potential actions/mitigations are presented in Table 3.

The benefits of DME passive ranging is that it uses compatible/complementary to DME/DME, and it does not modify the existing DME ground transmitters or signal (the goal is that it is just a small addition). Additionally, hybrid positioning is straightforward to implement using DME as the ground station can provide both its native ranging signal or a DME pseudoranging signal. The most significant drawback is that currently using multiple DMEs requires expensive scanning DME. A purely passive DMPR receiver may be lower cost.

Risk	Description	Action/Mitigation
Coverage in terminal areas	Not enough stations to provide 3 stations with good geometry throughout desired low altitude coverage area	Hybrid (mixed one way/two way Additional stations – DME from at sites (need to manage spectrum)
Operations with TACAN/Morse bursts	DME/TACAN transmit TACAN and Morse code pulse bursts that can interfere/supersede with DMPR	Assess interference levels Determine if bursts can be used to aid pseudolites Design signal to minimize effect of bursts
Multipath	Indirect signal from reflections causing increased range error	DME/P or other sharper rise time signal Improved signal processing
Interference	DMPR pulse pairs will be lost since the station must respond to other interrogation. Ranging and data components may be lost	Robust signal design (FEC, etc.) Assess effects If mitigation is necessary, determine means to prioritize
Complex avionics	Multiple frequency results in more complicated processing	Develop pseudo ranging signal on one frequency (spectrum issue)

Table 3. DME Pseudolite Technical/Institutional Risk Area

Other Pseudolite Technologies

Transponder signals on 1090 MHz (or even 1030 MHz) are transmissions to support secondary surveillance radars (SSR) and ADS-B (Mode S Extended Squitter). It is an attractive option for many of the same reasons as DME and UAT. Additionally, commercial aviation prefers the 1090 signal over UAT, because the signal exists, is being used at hundreds of FAA facilities such as ADS-B ground stations, ASDE and SSR, and they are already equipped. Furthermore, ASDE-X may provide a good source for 1090 MHz pseudolite transmissions resulting in more coverage near the airport terminal area [14]. This is an important benefit as terminal area coverage is a key concern. While it can be reasonably modified to support ranging, it would involve a change in the minimum operational performance standards (MOPS) as well as time synchronization. Another major technical concern is interference, as 1090 MHz is a congested channel and does not use any scheme (such as TDMA) to reduce interference.

Risk	Description	Action/Mitigation/Notes
Coverage in terminal areas	Not enough stations to provide 3 stations with good geometry throughout desired low altitude coverage area	Hybrid (mixed one way/two way Additional stations (need to manage signal congestion)
Multipath	Indirect signal from reflections causing increased range error	Discussions suggest that 1090 has better multipath performance than UAT, DME
Interference	1090 is a congested channel and significant can occur in high density airspace. Navigation is challenging as clear reception of signals from 3 stations is needed	Assess effects
New standards needed	No dedicate ranging signal set in 1090	

Table 4. Transponder Pseudolite Technical/Institutional Risk Area

Table 4 summarizes the technical and institutional risk areas for transponder based pseudolite based on transponder signals. While the list may not be as extensive, this reflects the lower maturity of technology understanding relative to DME and UAT rather than lower risk.

L-Band Digital Air-to-Ground Communications Systems (L-DACS) is a future communication system being developed by Eurocontrol that is designed to support the higher bandwidths needed in the future for air-to-ground communications. Two candidates are being developed. L-DACS1 uses a frequency division duplexing (FDD) scheme to interleave its signals in the white spaces between the DME channels across the entire DME band.

L-DACS2 uses TDMA/time division duplexing (TDD) in the national allotment channels 960-977 MHz just below the DME band (see Table 6).

Options	Access Scheme	Modulation Type	Origins
L-DACS1	FDD	OFDM	B-AMC, TIA 902 (P34)
L-DACS2	TDD	CPFK/GMSK Type	LDL, AMACS

Table 6. Comparison of L-DACS1 and L-DACS2 (OFDM = Orthogonal Frequency Division Multiplexing, GMSK = Gaussian Mean Shift Keying) [19]

Neither L-DACS candidates were designed with ranging in mind and some changes would probably be needed to support that functionality. The German Aerospace Center (DLR) is the lead architect of L-DACS1, and is currently examining adding ranging and assessing its performance as an APNT system. However, L-DACS1 could have a coverage limitation as L-DACS1 must be low power (~20 W) as to not interfere with normal DME operations. It

Risk	Description	Action/Mitigation/Notes
Coverage	Infrastructure for L-DACS not yet known but would face similar coverage issues if using GBT & DME	Hybrid (mixed one way/two way Additional stations (need to manage signal congestion)
Not on FAA timeline	No current plans known for implementing L-DACS in the NAS	
Signal performance	Ranging signal has not been defined, so accuracy/multipath performance is not known	Work to define signal so that it can meet APNT requirements within L-DACS specifications
Low received power	L-DACS1 operates in DME band & must be limited in power to not interfere L-DACS2 may have to be limited in power	Averaging signal can improve reception/accuracy

Table 5. L-DACS Pseudolite Technical/Institutional Risk Area

does have a continuous wave form that allows for more averaging, and thus mitigates some of the issues associated with power reduction. Table 5 summarizes the risks with L-DACS.

New spectrum signals offer improvements in accuracy, spectrum efficiency, and data capability. The APNT Team has already developed such a design, which was presented in [13] and is also examining the Ultra-High Accuracy Reference System (UHARS) being evaluated by the US Air Force, which is based on the Locata positioning system. These designs use TDMA to handle interference and near-far issues with spread spectrum widening the bandwidth for more accurate ranging while spreading energy to reduce interference from and to other signals.

synchronization without GPS through line of sight, cross-station measurements. UHARS operates in the 2.4 GHz industrial, scientific, and medical (ISM) band, requires 20 MHz of bandwidth per signal (it uses two signals), and provides 50/100 bps. An aviation system would likely use a single signal, which would be transmitted in protected spectrum between 960-1215 MHz. The difficult challenges related to introducing a new signal are getting stakeholder approval for the necessary spectrum allocation and fielding new equipment to support the signal. It may be possible to leverage existing sites and antennas (DME, UAT, etc.); however, this will most probably be neither simple nor straightforward.

Risk	Description	Action/Mitigation/Notes
Coverage in terminal areas	Not enough stations to provide 3 stations with good geometry throughout desired low altitude coverage area	Hybrid (mixed one way/two way Additional stations (need to manage signal congestion)
New spectrum allocation needed	New signal requiring ~ 5-10 MHz bandwidth will require allocation. Need to get concurrence from stakeholders (DoD, etc.)	Design for non-interference Work with stakeholders May be challenging as L band as already crowded with many vested interests
Interference	Many signal exists in the L band which can interfere with the signal	Assess effects Design signal robust to in band interference (DME, etc.)
New avionics/ ground equipment	New avionics and ground transmission equipment need to be designed and integrated with existing FAA sites	Adapt UHARS equipment Work with manufacturers to understand best design from their perspective

Table 7. New Spread Spectrum Pseudolite Technical/Institutional Risk Area

Pursuing a UHARS solution is desirable as user and transmitter equipment exists and is being manufactured by several companies, e.g., Leica and Hexagon/Novatel. In trials, it has shown the capability of being very accurate (< 2.5 m, horizontal with good geometry [27]) using code measurements and can maintain time

FAA signals of opportunity (SoO) in the VHF Spectrum is another important possibility, because these ground transmitters have high density. In particularly, broadcasts from automated weather-observing system (AWOS) and automated surface observing system (ASOS) may be a possible ranging and direction finding signals. Furthermore, many other FAA assets transmit on VHF including ILS

Risk	Description	Action/Mitigation/Notes
Coverage	Coverage, especially in Zone 3 is not known	Assess coverage Determine benefit and additional signals that can be used
Standards for use	No standards for using ASOS/AWOS signal for ranging	Determine additions needed to enable ranging
Signal performance	Ranging performance of signal has not been examined or tested	Assess signal design for ranging Measure transmitted signal
Integration	The signals from different systems need to be integrated for SoO pseudolite	
Integrity	The transmitter/transmission may not be subject to the same standards as navigation infrastructure	

Table 8. FAA SoO VHF Pseudolite Technical/Institutional Risk Area

localizers, VHF data broadcasts (VDB) and VHF Data Link (VDL) Mode 2. Having thousands of these stations – for example, there are 109 stations in California (see Figure 6) and 34 stations in Washington – bodes well for coverage.

We are just beginning to investigate this option and there are many technical uncertainties and unknowns including the utility of the signal for ranging (accuracy, etc.), actual coverage at altitudes, how to synchronize all the stations in a cost effective manner, how to develop low cost avionics as these signals occupies different frequencies and integrity of the system. Table 8 summarizes the identified risks.

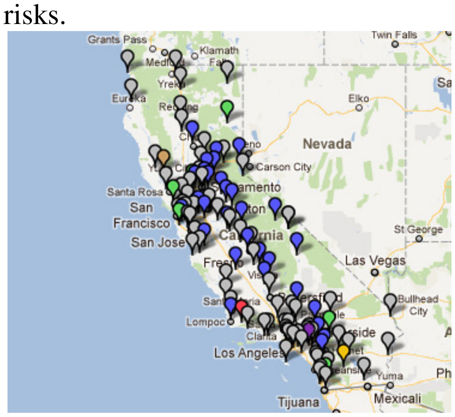

Figure 6. FAA VHF Assets in California (http://www.faa.gov/air_traffic/weather/asos/)

REQUIREMENTS & PERFORMANCE

Accuracy, Availability, Integrity, Continuity, Capacity, and Coverage

The key technical metrics to consider for any APNT system are accuracy, availability, integrity, continuity, capacity, and coverage, relative to the requirements to support NextGen operations.

The accuracy requirement derives from the APNT performance target of supporting Required Navigation Performance (RNP) 0.3 level navigation and surveillance for three-nautical mile separation. Table 9 shows the targeted signal ranging accuracy given the position accuracy requirements of the targeted operations, assumed worst case horizontal dilution of precision (HDOP) of 2.828, and a time synchronization accuracy of 50 ns. The positioning capability of any pseudolite system depends in part on its time synchronization. Given these assumptions, the signal accuracy required can be derived. Note that the derived signal accuracy target applies to any pseudolite system. Overall range accuracy required is derived from the position accuracy required by dividing by the worst case HDOP. For RNAV/RNP 0.3, the position accuracy is 0.3 nautical miles (nm) less the contribution of flight technical error (FTE). In the calculations below, it is assumed that FTE is 0.25 nm [30]. Range accuracy the root sum squared (rss) of time and signal accuracy and so signal accuracy required is the square root of the range accuracy required minus time accuracy as seen below:

Signal Accuracy Required = $(\text{Range accuracy required}^2 - \text{Time accuracy}^2)^{1/2}$

Signal Accuracy Required (RNP 0.3, FTE = .25 nm) = $[(307.62\text{ m}/2.8)^2 - (15\text{m})^2]^{1/2} = 107.5$ m

Pseudolite accuracy measurements/analysis

Analytic derivations and experimental tests are being conducted to estimate the signal accuracy of each pseudolite candidate. Currently, the APNT Team has analyzed and measured UAT and DME based passive ranging signals for over nine months in the

Operation	Position accuracy required	Range accuracy required, (HDOP 2.8)	Time accuracy (estimated)	Derived signal accuracy required
RNP 0.3	307.2 m	108.6 m	50 ns (15 m)	107.5 m
RNP 1.0	1793 m	634.0 m	50 ns (15 m)	633.8 m
Surveillance (3 mile separation)	92.6 m	32.7 m	50 ns (15 m)	29.1 m

Table 9. Accuracy Requirement (95%) for Pseudolite to support targeted operations, for FTE of 0.25 nm in RNP operations

Signal	Measured (distance from tx)	Estimated at 50 nm	Estimated at 100 nm
DME (11 pulses)	2 m (5.6 nm)	18.6 m	37.1 m
DME (100 pp)	N/A	6.2 m	7.2 m
UAT (36 bit sync only)	17.9 m (20.9 nm)	42.8 m	86.5 m

Table 10. Current Measured/Estimated Accuracy (95%) of Pseudolite Signals

San Francisco Bay Area. Table 10 shows the measurement results and uses the results to estimate performance at further ranges. These results are generally conservative as they employ simple signal processing and are also affected by residual transmitter timing errors [3]. However, the signal accuracy also needs to be inclusive of multipath, which has significant variations. Further study and analysis is ongoing.

Pseudolite Coverage

We have performed coverage analysis for passive ranging signals to determine the current coverage using existing ground infrastructures and means of improving coverage [9]. The coverage study was conducted in a generic manner so the results are applicable to any pseudolite system using the assumed ground infrastructure. The nominal ground infrastructure assumed included use of DME ground sites only DMEs (~1100 sites), and GBTs (~700 sites).

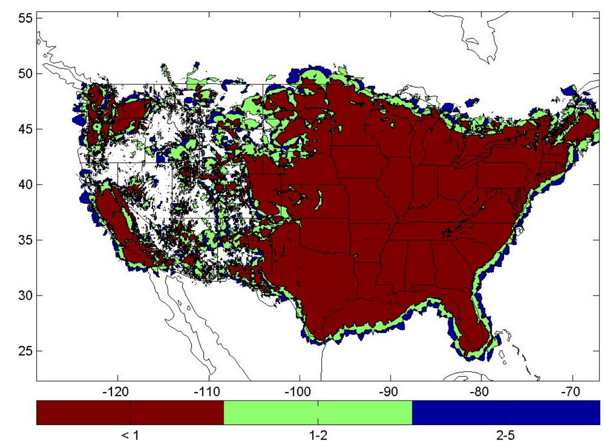

Figure 7. CONUS DOPs for Passive Range at 5000 ft AGL with DME & GBT [9]

For en route navigation, the coverage at various levels is examined. As the number of stations visible to an aircraft decreases with altitude, coverage at 5000 feet AGL is one key level examined. This provides the worst-case coverage for Zone 2 as it is the lowest altitude for that zone. Furthermore, Zone 1 will have better coverage as it is at a higher altitude and thus can receive more signals. Hence both Zone 1 and 2 will have reasonable coverage if coverage at 5000 ft AGL is reasonable. The result is useful particularly if passive ranging is to provide the GA alternative. Figure 7 shows the performance when using existing and planned DME and GBT stations. The mountain west is the only problem area at 5000 ft AGL though the coverage in that region is reasonable above FL 180 (Zone 1, not shown). For the analysis shown in the figures, signals from the DME and GBT sites are used up to zero distance from the facility. Appendix A of AC90-100A only requires that, for RNAV, DME be useable at distances of 3 nm or greater from the facility. If hybrid scheme is used whereby position can be calculated using two stations, the coverage improves and is shown in Figure 8.

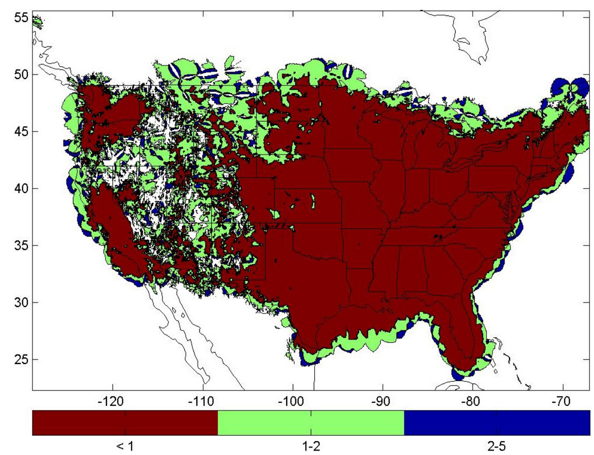

Figure 8. CONUS DOPs for True Range at 5000 ft AGL with DME & GBT [9]

Coverage in Zone 3 is the most challenging issue for APNT as the low altitude supported results in very few stations visible. Furthermore, the higher accuracy requirement (0.3 NM vs. 1 or 2 NM en route) means that FTE becomes a major factor. The coverage is studied on an airport-by-airport basis. Figure 9 shows the coverage for the San Francisco bay area. Rather than present the HDOP, it shows the RNP 0.3 coverage level assuming range accuracy of 108.6 m. This range accuracy comes from Table 10 and is the accuracy required to meet RNP 0.3 for HDOP of 2.8 or lower. Clearly the SF area is challenging due to terrain. For a similar analysis done for the Washington DC area (not shown), RNP 0.3 coverage is much better due to flatter terrain and more stations.

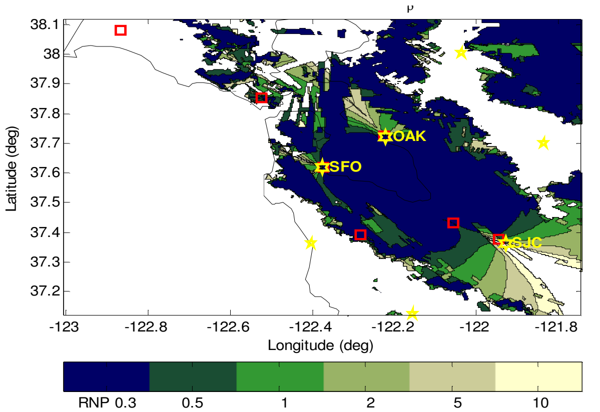

Figure 9. RNP coverage at 500 ft AGLwith Pseudolite using DME & GBT sites, assumed range accuracy is 108.6 m

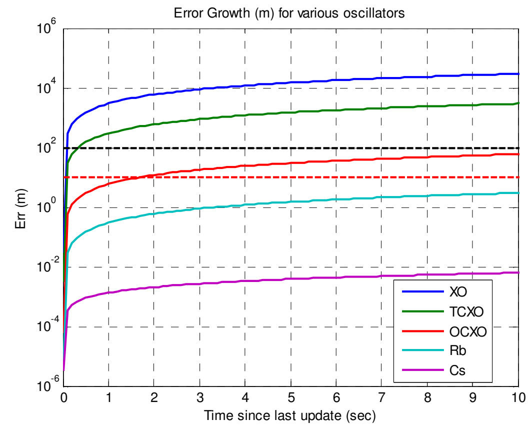

Figure 10. Clock Error Growth over time (various clocks) compared to approximate acceptable levels for surveillance (red dash) and RNP 0.3 (black dash)

Pseudolite Capacity

While the capacity of passive ranging signals is unlimited in terms of number of users that can be supported, the hybrid approach uses occasional two-way (interrogation/reply) interactions, which will limit user capacity. Hybrid reduces the number of two-way interactions compared to traditional DME/DME as the interaction only needs to occur for one station and may be less frequent (lower rate). The former reduces the number of interactions relative to DME/DME by at least half. Reduction from the latter (a lower interaction rate) only exists if the clock error growth is only a fraction of the overall accuracy requirement (we use approximately 10 m and 100 m for surveillance and RNP 0.3, respectively).

Even without this benefit, the hybrid ranging technique will support twice the capacity of traditional DME/DME. Note that from our DME capacity study, DME can support high density NextGen airspace if the avionics can handle lower interrogation to reply rates (reply efficiency) – 30% instead of the specified 70% [10]. Studies have indicated that many current receivers can operate at this reduced level [4].

Another consideration with hybrid ranging is integrity as the position solution when using two stations is highly dependent on coasting on the prior clock estimate. This means that there needs to be high confidence of the clock estimate and bounds on the growth of the clock error.

Ranging Method	Capacity	Min. Stations for 2-D positioning	Additional required equipment
Passive Pseudoranging	Unlimited	3	Passive ranging signal
Hybrid Ranging	Depends on frequency of 2 way interactions	2	Passive ranging signal New avionics Clock onboard aircraft

Table 11. Comparison of Passive Ranging & Hybrid Ranging for DME

Figure 10 shows the amount of coasting that different clocks can provide and still be below 10 and 100 m of error. The figure indicates that having a good oven controlled crystal oscillator (OCXO) or a rubidium quality clock (Rb) is needed at a minimum. As GPS chipsets use temperature compensated crystal oscillators (TCXO), this is a step up in cost.

So the benefit of hybrid positioning is that much fewer stations (~ 50%) can be used for positioning while having reasonable capacity. The drawbacks include the need for a high quality clock and confidence on clock estimates and error growth. A comparison table between pure passive and hybrid ranging is given in Table 11.

Pseudolite Continuity, Availability, Integrity

Continuity, availability, and integrity will be studied as the alternatives become clarified and reduced. As DME will be the basis for near term APNT, we have started cataloguing potential integrity concerns. Table 12 shows an example from our catalogue based on-air DME/TACAN signal. Specific monitoring will need to be developed. Each DME locally monitors it signal. That station may also be used to provide additional desired monitoring. Similar monitoring may be needed for other solutions (such as UAT).

Anomalies & Potential Faults	Problem	Mitigation (if necessary)
DME ranging anomalies	Rare, but occasional range jumps Diffraction seen in some measurements near mountains	Ground monitoring, avionics monitor, receiver autonomous integrity monitoring (RAIM)
TACAN pulse phase anomaly	Some TACAN burst pulse measured show slight frequency offset	Not issue for current avionics, new avionics using phase may have issue. Address in standards
Single DME pulse	Some single DME pulses are seen	Not issue for current avionics

Table 12. Anomalies and Faults List for DME based signals

DESIGN CONSIDERATIONS PSEUDOLITES FOR APNT

Stakeholder acceptability is as important as meeting strict performance requirements for APNT. For commercial aircraft operators, the APNT should not require a costly installation. Aside from avionics costs, a major component of cost is the installation time, especially since this is time that the aircraft would not be available for revenue use, and effort needed to run new wires and install new antennas, so reuse of existing installations is highly desirable. An additional consideration for commercial operators is international acceptability and adoption. Having one international system minimizes equipage for international commercial operators. For general aviation, the guiding principle from Original Equipment Manufacturer (OEM) equipment makers is that it should be low cost (~ $600). Having the signal reside in one frequency channel helps achieve this goal by not requiring expensive electronics to handle multiple frequencies near simultaneously. Both commercial and GA owners will need adequate transition time to upgrade all desired aircraft. Spectrum usage is another key consideration as a new signal must not interfere with existing signals and must be accepted by stakeholders of that spectrum. A final of interest is security of the signal. We have developed security algorithms that can overlay provided enough data (~250 bits per message) is available [29]. Table 13 summarizes these considerations.

Consideration	Most relevant stakeholder	Action/Mitigation
Low installation overhead	All aircraft operators, particularly commercial	Reuse of existing antenna & wiring installations
International adoption	FAA, Commercial	Signal existing in other nations
Low cost avionics	GA	Signals on 1 frequency
Transition time	All aircraft operators	Early development of alternatives & standards
Spectrum	FAA, DoD	Reuse of existing signals
Security of signal	FAA	Signal authentication data

Table 13. Stakeholder Considerations

SUMMARY & RECOMMENDATION

The current analysis indicates no one definitive solution. As seen in the Table 14 summary, all solutions have some desirable features but also many drawbacks and technical risks. The utility of the each pseudolite technology depends on the relative importance of the drawbacks. Furthermore, the alternatives are at different levels of technical maturity. UAT and DME signals for ranging have been studied in greater detail through analysis and measurements than, for example, L-DACS or 1090.

As a result, the technical concerns can be more precisely defined (multipath) instead of more general need for understanding signal performance.

Alternative	Technical Risks	Benefits	Drawbacks
UAT	Coverage in terminal areas Outage holes due to installation Multipath Integrity	Existing signal One frequency Equipage	Not international (but ok for GA) Not desirable for commercial aviation UAT use restricted above 18000 ft Lower power (vs DME)
DME	Coverage in terminal areas (DME from UAT sites) Design for transmitting all on 1 frequency Multipath TACAN/Morse code interference	Compatible/Complementary with DME/DME Hybrid with DME/DME better coverage Potentially international	Multiple frequency unless spectrum change
L-DACS	Not on FAA timeline Low power (must share band with DME)	Potentially international	Not yet on FAA roadmap Spectrum
1090 MHz	Coverage in terminal areas (1090 from DME sites) Interference Signal performance	Existing signal One frequency Equipage Potentially international	May not be desirable for general aviation Requires new MOPS & definition
New Spread Spectrum (UHARS, etc.)	New system requires spectrum allocation	High accuracy Economies of scale (user equipment developed for other applications)	Not international (but ok for GA) Low data rate (UHARS)
FAA VHF SoO	Signal performance Coverage performance Integration	Coverage (many ground stations) Existing resource Aircraft have existing VHF antenna	Not international Multiple frequency

Table 14. Benefits and Drawbacks Summary

A likely use of Pseudolite based APNT is to provide a low cost option to GA and other cost sensitive users and the most appealing way to achieve this is with UAT. This is a likely use as DME/DME is a leading candidate for commercial aircraft many of which already have such equipment installed. UAT is an existing signal which should be receivable by all UAT equipped users due to the ADS-B mandate in 2020. Its simplicity helps with equipment costs as well as additional benefits that come with receiving UAT (weather, traffic information) provide incentives to adoption. With transmission from DME sites, it should provide reasonable coverage to users above 5000 AGL and coverage below that level could be aid with on airport implementation in ASDE-X. Its drawbacks – not an internationally adopted signal and use limited to below 18000 feet by rule – are not major concerns to this low cost community. However, further stakeholder investigation needs to be conducted to understand if this solution really meets their needs and if it is something they will adopt.

For Pseudolites to provide a full solution to all users, both coverage and stakeholder issues need to be resolved. There is no clear technology that stands out as the best option. A significant technical challenge is coverage and implementing enough stations to cover requisite APNT zones. Gaining stakeholder acceptance is as critical as solving the major technical challenges. New, affordable avionics will be needed. Installation and out of service costs are reduced by use of signals (L-band, VHF) with existing antenna installations. However, even if there is an existing antenna, its use may not be easy. If a transceiving antenna (one that transmits and receives), such as DME, is used antenna transmission may lead to interference and unavailability issues.

NEXT STEPS

Several efforts will be conducted to more fully understand the technical merits and limitations of the alternatives and to develop the best Pseudolite option for APNT. Below is a summary of these efforts.

- Continue measurement campaign for pseudolite signals based on existing infrastructure (UAT, DME, 1090, FAA signals of opportunity). We will examine numerous different locations and different ranges

- Evaluate received data for signal accuracy (especially with multipath) and integrity
- Development of equipment for field tests of Pseudolites based on existing signals
- Coverage analysis of how many sites it would take to provide coverage to APNT service area using pseudolites (particularly for Zone 3)
- Coverage simulation for analysis for FAA signal of opportunity and first cut availability analysis
- Capacity study on 1090 pseudolite (aircraft 1090 transmission may interfere with ranging signal)
- Continue evaluation of L-DACS, UHARS

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