Hybrid APNT: Terrestrial Radionavigation to Support Future Aviation Needs

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BIOGRAPHY

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1. INTRODUCTION

The Federal Aviation Administration (FAA) Alternative Positioning Navigation & Timing (APNT) program is developing and examining solutions to provide terrestrial based radio-navigation capability that can support Next Generation Air Transportation System (NextGen) even with the loss of GNSS. Two technologies being examined are improved distance measuring equipment (DME) and passive ranging from DME and automatic dependent surveillance broadcast (ADS-B) ground stations. This paper details the concept and operation of Hybrid APNT which combines these two options to form a solution that contains the best features of each option.

Hybrid APNT combines true and passive ranging transmissions, particularly from the same source, to allow for the integrated use of DME and ADS-B ground stations and improve key performance areas. The combination of these ranging sources from the same ground station enables synchronization of aircraft clock with the ground and allows for interchangeable use of true and passive ranges. The combination helps address two key performance issues: coverage and capacity.

OUTLINE

This paper presents and details the concept of Hybrid APNT, one of three APNT solutions being assessed by the FAA. The background section covers the components of hybrid APNT and the potential modification to today's existing systems that would enable hybrid APNT capabilities. An important component of the Hybrid APNT is passive ranging or pseudolites (PL). Terrestrial pseudolites currently do not exist in the FAA navigational infrastructure. Selected means of implementing passive and true ranging on DME, ADS-B ground stations are outlined.

Hybrid APNT alternative is then presented along with its concept of operations. Hybrid APNT allows for many operational modes which are outlined.

Finally, the benefits of hybrid APNT in terms of coverage and capacity are analyzed. The analysis will show how the increased coverage with different hybrid APNT over traditional DME or pseudolites, even though the same stations and signals are used.

2. BACKGROUND

The APNT group was formed to determine and develop the promising solutions that provide FAA navigation, surveillance and other services in the event of a Global Positioning System (GPS) or GNSS degradation event [1]. The need for APNT is particularly important as envisioned use of GPS by aviation will increase in coming years. Under NextGen, GPS will be the primary means of navigation and surveillance. GPS will enable the operations that are needed to handle the increased air traffic levels anticipated in the 2025 time frame. Currently, GPS is often the only system capable of supporting many envisioned operations. Current legacy terrestrial based navigation systems either cannot provide the area navigation (RNAV) capabilities or the performance needed for sustained future operations.

TARGETED PERFORMANCE

The APNT solution should sustain aviation operations in the event of GPS unavailability. The solution will provide RNAV capability for en route operations throughout the conterminous United States (CONUS) as well as terminal area coverage in major airspace. For terminal operations, a minimum of RNAV down to 1.0 nautical mile (RNAV 1.0) is required. However, RNAV or Required Navigation Performance (RNP) operations down to 0.3 nautical miles (RNAV/RNP 0.3) may desirable. Another potential target is to provide position information for Automatic Dependent Surveillance - Broadcast (ADS-B) to support 3-mile and 5-mile aircraft separation. Currently, 3-mile separation rules require 92.6-meter position accuracy, which is a navigation accuracy category (NAC_p) of 8 [2].

APNT ALTERNATIVES

Three concepts are currently being evaluated for APNT: 1) positioning based on traffic information services broadcast (TIS-B) reports, 2) DME/DME, and 3) hybrid APNT. In the first concept an aircraft would get its position from ground transmitted TIS-B reports. TIS-B position reports supplies aircraft positions as determined by ground based surveillance - typically secondary surveillance radar (SSR). TIS-B is an existing component of FAA ADS-B operations. The second concept is to improve the existing DME system with some additional stations to cover current en route coverage gaps. Range measurements from multiple DMEs, gathered using scanning DME avionics, yields position and navigation information. The final concept is the topic of this paper.

DISTANCE MEASURING EQUIPMENT (DME)

DME is an internationally accepted and adopted two-way ranging system operating in the L-band of radio frequencies between 960-1215 MHz. DME and TACAN which adds an azimuth function for military users is widely deployed worldwide. As seen in Figure 1, within the United States, there are about 1100 DME or TACAN stations that are operated.

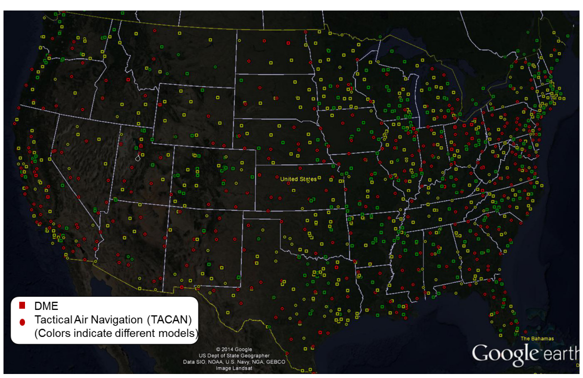

Figure 1. DMEs and TACANs Operating in the Conterminous United States

The system enables the aircraft to calculate its slant range to a DME ground station or transponder by transmitting an interrogation signal to the ground station and receiving a corresponding reply. Both interrogation and reply signals are pulse pairs transmitted on separate frequencies. From the interrogation and reply, the avionics then determines the round trip time and calculates the true range to the DME transponder, by knowing the interrogation time of transmission and the reception time of the corresponding reply. This operation is seen in Figure 2. More details on DME are provided in [3].

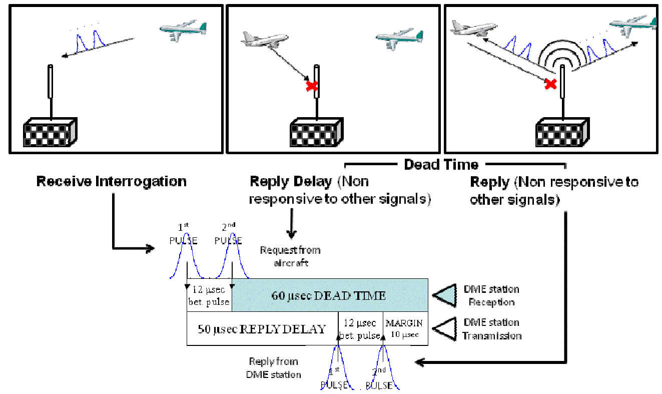

Figure 2. DME Transponder Operations (X channel)

DME for APNT

DME today can provide RNAV 1.0 capability for aircraft equipped with inertial aided scanning DME avionics - DME/DME/Inertial (DDI). Scanning DME or DME/DME (DD) scans, interrogates and processes multiple DME stations and frequencies to get near simultaneous true ranges from these stations. DDI provides RNAV capability for en route with inertials enabling coasting over DME coverage gaps. Improvements in DME accuracy and capacity are desirable to support NextGen terminal areas, especially for high density airspaces.

The APNT team has investigated several means of improving DME for APNT. For accuracy, the team determined that DME could meet RNAV 0.3 accuracy levels. Meeting this level could be met mostly by taking credit accuracy of today's DME as fielded equipment and avionics perform the better than specification. It would also require some small changes to existing transmitters to improve reply delay accuracy [4].

A DME passive ranging capability can provide capacity, coverage and other benefits. The capacity benefit comes from allowing users to passively range thereby reducing the need for true ranging and DME interrogation. The APNT team has developed a DME-based passive ranging signal that can be implemented in a backwards compatible and transparent manner. A proof of concept implementation of this DME pseudolite (PL) is presented in [5]. To enable the capability, the DME ground station would transmit some of its reply signals in a pseudo random sequence in time to provide range and communicate data. The transmission would be in addition to the nominal replies to aircraft interrogations.

The DME PL design is backward compatible because it uses the existing DME transmissions and today's ground stations can be induced to generate the signal. It is transparent in that legacy users would ignore these replies much as they would ignore replies to other aircraft. Furthermore, DME PL would also be able to communicate data needed for positioning, integrity and security [5]. As DME PL only requires a fixed and limited number of transmissions, it may be reasonable to implement on some current DMEs that are not available for DME/DME positioning. For example, DMEs associated with instrument landing system (ILS) installation need to be available for ILS users. As interrogation by navigation users not on the ILS approach may result in the DME not being available for ILS users, the use of ILS DMEs is restricted to ILS users. However, ILS DME should able to provide DME PL while still supporting ILS users.

AUTOMATIC DEPENDENT SURVEILLANCE BROADCAST (ADS-B) GROUND STATION

The FAA has nearly completed deployment of the approximately 660 ADS-B ground stations in the United States, including the Gulf of Mexico. This is shown in Figure 3. A primary purpose of the ADS-B ground stations is to support surveillance by gathering aircraft ADS-B transmissions.

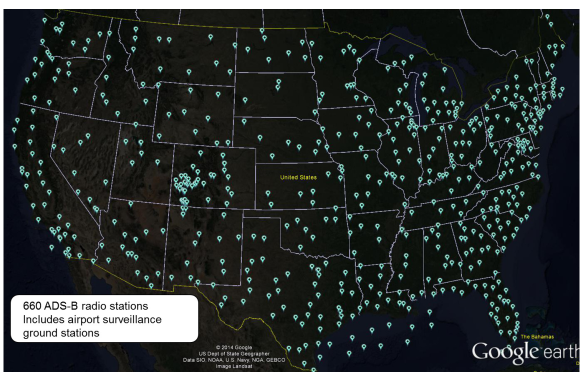

Figure 3. ADS-B Radio Stations Deployed in the Conterminous United States

ADS-B is supported by two protocols: Mode Select (Mode S) Extended Squitter (ES) on 1090 MHz and Universal Access Transceiver (UAT) on 978 MHz. The former is compatible with legacy transponder equipment and protocols. Hence it is attractive to air carriers which already carry Mode S transponders. The latter is a new protocol with more data capacity and services. This is attractive to user, typically general aviation, who do not have Mode S transponder

The stations also serve to provide surveillance and other situational awareness information to aircraft. This includes aircraft information from secondary surveillance radar (SSR) through traffic information service broadcast (TIS-B) and rebroadcast of ADS-B reports (automatic dependent surveillance rebroadcast or ADS-R) transmitted on one protocol to users of the other protocol. UAT also provides weather information termed flight information services broadcast (FIS-B).

ADS-B Ground Stations for APNT

ADS-B ground stations can provide useful APNT services in several ways. The most important feature is ranging – either passive or true ranges. Another useful feature is providing data for integrity and security. Some potential means to enable these capabilities are briefly covered next.

Passive ranging is supported on UAT by the ground segment message [6]. This is a basic capability with a roughly 1 Hertz (Hz) update rate. Higher update rates are possible and one method using existing signals is discussed in [6][7]. Other options are also being investigated but they require modifications to UAT transmissions and scheduling. A passive ranging signal is also possible on 1090 MHz Mode S ES and would offer better multipath rejection. Enabling Mode S ES passive ranging would likely require defining a new message and transmission to support the capability. One new message would be a ground station location or "ephemeris" message. It would also require that the ground station indicate time of transmission implicitly or explicitly.

As spectrum congestion of 1090 MHz is an important consideration, the APNT has also developed a design that requires no new 1090 MHz transmission. Instead, we would require the existing 1090 MHz ground transmissions to be scheduled so they are transmitted at fixed time slots. UAT would provide data and reference time of transmission while Mode S transmissions, of which Mode S ES is a subset, would provide additional updates and multipath mitigation. Hence, the design leverages ADS-B on both frequencies for a combined passive ranging signal. This concept is seen in Figure 4 where the existing Mode S ES transmissions would be transmission time would reference the transmission time of UAT ground segment for each station. The time slots are separated by steps of Δ (e.g. 6 milliseconds) with each 1090 MHz Mode S message transmitted an integer number of Δ after the UAT ground transmission. The UAT ground segment transmissions are synchronized to coordinated time universal (UTC) and use time division multiple access (TDMA) preventing interference by transmissions from other stations. Proper selection of Δ would also result in non-interference between the Mode S ES ground station transmissions.

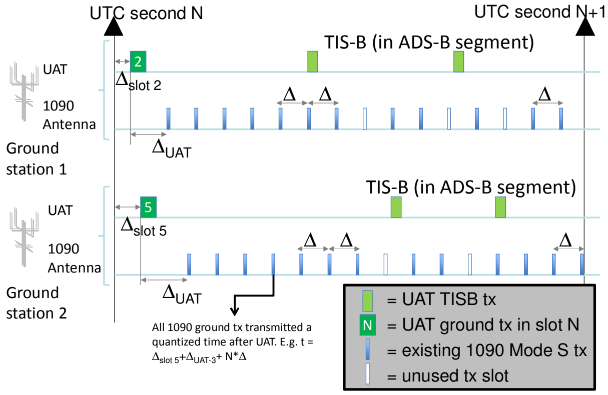

Figure 4. UAT + 1090 MHz Mode S ES Pseudo ranging Concept

ADS-B ground stations could provide true ranges with some operational and message changes. The APNT team is developing and examining a simple true range capability using existing ADS-B signals and operational capabilities. Commercial aircraft will carry 1090 MHz ADS-B and transmit position reports multiple times per second. These signals can be simultaneously used as interrogation transmissions resulting in no additional aircraft transmissions. Two reply links are possible from the ADS-B ground stations as shown in Figure 5. Use of Mode S ES requires new ground transmissions for reply and thus is limited by anticipated spectrum congestion and interference on 1090 MHz, particularly in high density airspace. The result is that true range using Mode S ES reply be constrained either in range or number of transmissions. Another reply link is UAT and in particular, using UAT ADS-R. This option may be possible with existing equipment and operations as currently ADS-R of Mode S ES ADS-B position reports are sent if there is an UAT equipped aircraft in the area. For either reply method to work, the reply delay – time difference between reception of the Mode S ES ADS-B and the transmission of the reply needs to be known and communicated in the reply. For the current UAT ADS-R "reply", Figure 6 shows that the time delay measured by our reference station between the two signals currently varies roughly from 50 to 200 milliseconds. Note that the measurement is not exactly the delay from receipt of the ADS-B and transmission of the ADS-R by the ground station but it is should be within tens of microseconds.

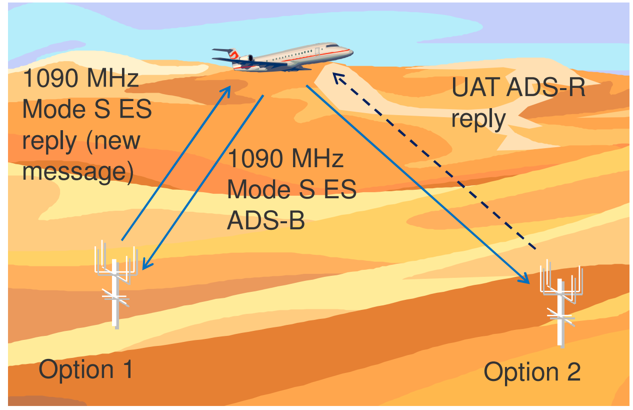

Figure 5. Potential Links for True Ranging from ADS-B Ground Stations

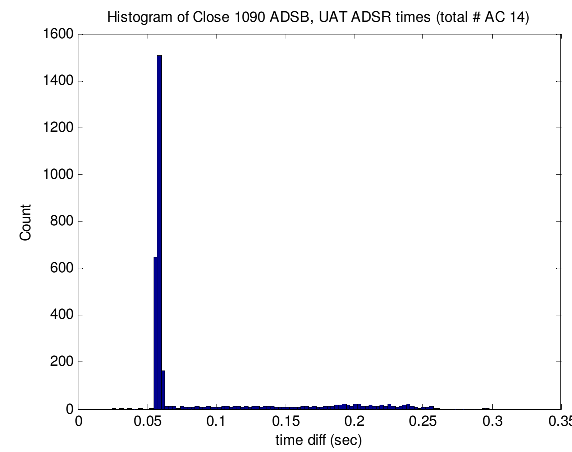

Figure 6. Time difference between receipt of aircraft Mode S ES ADS-B and corresponding UAT ADS-R from ground station

Combining DME & ADS-B for APNT

Both DME and ADS-B provide have existing capabilities that can serve APNT. Even more attractiveness is the potential of improving the capabilities and combining the offerings of these systems. The existing and potential capabilities relevant to APNT are listed in Table 1.

Source	Existing	Potential
DME/TACAN	True Ranges	Passive Ranges, improved accuracy, data capacity
ADS-B	Passive Ranges (UAT)	Passive Ranges (better multipath rejection) True Ranges Data capacity

Table 1. Precision of Selected DME/TACAN Reply Signals

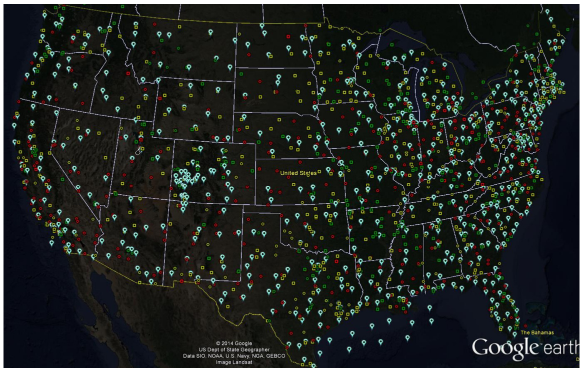

Figure 7. DMEs (squares), TACANs (circles), & ADS-B Radio Stations (pins) Deployed in the Conterminous United States

The combined use of DME and ADS-B is attractive as it may help significantly with key performance targets: coverage, capacity, accuracy and integrity. Coverage is especially challenging at low altitudes so a larger ground station network can be very beneficial. As DME and ADS-B ground stations are not collocated, together these two systems provide network of roughly 1700 geographically separated ground stations within the United States airspace. This is shown in Figure 7. Ideally, APNT could combine DME and ADS-B ranges to take advantage of both. This is the concept behind hybrid APNT and there are many possibilities for hybrid APNT to be implemented. Table 2 shows the existing systems which cannot be easily used together and possible hybrid APNT implementations based on improvements to DME, ADS-B or both.

Scenario	Passive Ranging	True Ranging	Required Upgrade or Change
Existing	ADS-B	DME/TACAN	
Hybrid APNT using ADS-B	ADS-B	DME/TACAN ADS-B	ADS-B true range
Hybrid APNT using DME	ADS-B DME/TACAN	DME/TACAN	DME PL
Hybrid APNT w. ADS-B & DME	ADS-B DME/TACAN	DME/TACAN ADS-B	ADS-B true range & DME PL

Table 2. Potential Operating Scenarios

3. HYBRID APNT CONCEPT & BENEFITS

The hybrid APNT concept combines the use of true and passive ranges to offer advantages, particularly for coverage and capacity, over pure true or passive ranges alone. With the hybrid APNT infrastructure, a user can position using passive ranges, true ranges or a combination of these ranges. The power of hybrid APNT concept comes from combine use of passive and true ranges from one station. This provides both a range measurement and synchronization of the avionics clock with the ground. This is shown in Figure 8. The result is that only one additional station providing any range (passive or true) is needed for horizontal positioning. Hence, with the envisioned infrastructure, the hybrid APNT use of both types of ranging results for benefits over use of true or passive ranging alone.

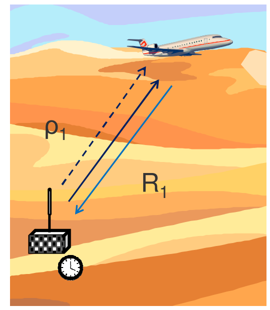

Figure 8. Passive & True Ranges from Same Ground Station to Synchronize APNT avionics with Ground

For the purpose of the paper, DME ground stations are presented as providing both true and passive ranges while ADS-B ground stations only provide passive ranges. However, concept is equally applicable with any of the last three scenarios shown in Table 2. The concept integrates naturally with the possibility of a more stable aircraft clock to maintain synchronization with the ground.

Concept of Operations

As multiple types and sources of ranging signals will be transmitted, the ground infrastructure and potential avionics can support several operational modes. Three specific modes for hybrid APNT: 1) True ranging (DME mode) 2) Passive ranging (PL mode) and 3) Hybrid or mixed ranging (hybrid mode). The section will discuss the features of each mode.

Since the DME infrastructure is a basis for hybrid APNT, aircraft can operate using DME only. As much of the existing commercial air fleet has installed DME/DME or DDI avionics, this allows them to operate effectively without new equipment. Furthermore, implementing hybrid APNT would be transparent to existing scanning DME equipped aircraft.

Hybrid APNT infrastructure also supports a solely one-way pseudolite mode. Pseudolite mode provides both high accuracy positioning and time synchronization with unlimited capacity. While pseudolite mode requires more stations - three PL stations are needed for horizontal positioning, it may be desirable for certain operations and users. At higher altitudes, there are generally enough PL stations in view without requiring true range operations and transmissions. This mode is also useful for power constrained aircraft (e.g., unmanned aerial systems or UAS) as passive ranging requires significantly less power than DME operations as no active transmissions are needed.

Hybrid APNT mode combines these two types of ranging to improve coverage and capacity. Like DME, Hybrid APNT avionics would only need two stations for horizontal positioning with good geometry. However, in hybrid APNT, the two stations do not need to be DME stations. In a basic hybrid APNT, the avionics would use the two way and one way measurements from one DME to synchronize the avionics clock with ground time. This allows the hybrid APNT avionics to calculate horizontal position with one more ranging measurement, including a passive ranging ADS-B station. This is the basic hybrid APNT implementation and is shown in Figure 9. While the implementation requires one DME station, this already represents a reduction of DME loading by half. With a high quality on board avionics clock, the hybrid APNT avionics could provide navigation with any two stations when using the clock to maintain time synchronization with the ground. With a calibrated clock synchronized to the ground station time, every ground station measurement becomes like a precise true range.

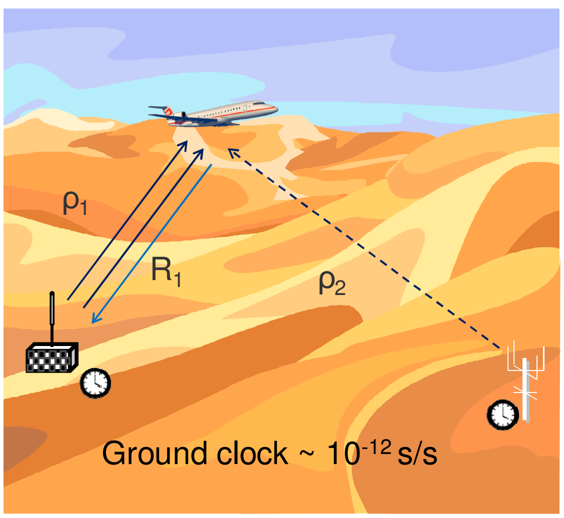

Figure 9. Basic Hybrid APNT Combination.

To support Hybrid APNT, avionics process both DME and ADS-B signals. With the basic Hybrid APNT implementation avionics only needs one channel for the interrogation/reply for true ranging while other channels can operate passively. Basic hybrid APNT avionics would only need a basic single channel DME (combined with a pseudolite receiver) rather than a scanning DME, reducing avionics complexity and interrogation load on DME. The notional structure of avionics supporting basic hybrid APNT is shown in Figure 10. It has one DME true range channel and multiple passive ranges for DME, Mode S ES, and UAT (*N, M, K* ranges respectively). Each DME passive range requires a separate frequency channel whereas UAT and Mode S ES only use one frequency for all station transmissions. Note that having both Mode S ES and UAT may not be necessary. An analysis of coverage and capacity are provided in the next sections.

Hybrid APNT avionics can use basic crystal oscillators (XO) such as those found on DME avionics. These typically have stability of 10^{-5} seconds per second (s/s) and are adequate to measure the DME round-trip time. More importantly, Hybrid APNT can take advantage of a slightly better clock, roughly 10^{-8} s/s. This can be achieved with a properly and recently calibrated temperature compensated crystal oscillator (TCXO). Such oscillators are typical of GPS avionics. If regular calibration is not available, an oven controlled crystal oscillator (OCXO) should achieve this level of performance even after a year of aging. Depending on accuracy targets, this clock would allow for several seconds of coasting.

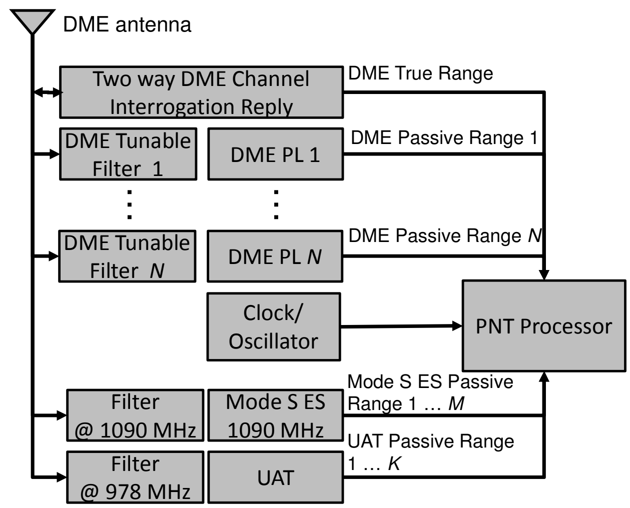

Figure 10. Notional Basic Hybrid APNT Avionics using DME 2 way range

Benefits

The combination of passive and true ranges described under the Hybrid APNT concept allows 1) ADS-B and DME stations can be used together and 2) passive range measurements to be treated like a true range with aircraft clock synchronization. One resulting advantage is improved coverage from being able use for signals and needing only two stations (with aircraft clock synchronization) for positioning. Since aircraft only need at most one true range signal for horizontal positioning, this reduces the interrogation on DME when using hybrid APNT instead of DME/DME. Another benefit is that it has lower loading requirements on DME stations.

4. PRELIMINARY COVERAGE ANALYSES

One benefit of hybrid APNT is improved coverage. It will have better coverage than pseudolites only. The basic hybrid APNT implementation also should generally have comparable or better coverage than true ranging from DME or ADS-B ground station. The benefit over latter occurs because hybrid APNT allows for the combined use of both DME and ADS-B ground stations.

A basic coverage tool was developed to examine the benefits of hybrid APNT. For the analysis, two regions are examined: 1) San Francisco (SF) Bay Area and 2) Salt Lake (SL) City Area. The coverage tool calculates the line of sight (LOS) at each examined altitude using a 4/3rd earth model for radio horizon. The coverage range is assumed to be about 100 nautical miles (nm). The horizontal dilution of precision (HDOP) and horizontal protection level (HPL) coverage is shown in this paper. The HDOP is used to illustrate the geometry dependence. As coverage typically driven by integrity, the coverage of targeted HPL is examined. The calculation of HPL depends on the bound models for the various components of range and position error. While these have been developed for the potential APNT signals, they are preliminary.

San Francisco represents a region with good DME coverage with only a few ADS-B ground stations. These ground stations are located at San Francisco airport (SFO), Woodside and San Jose. The Woodside ADS-B is close to an existing DME/TACAN station. There are several ADS-B ground stations at SFO to support airport surveillance. Figure 11 to Figure 13 show the HDOP for pseudolite, DME and basic Hybrid APNT at 500 feet above ground level (AGL), respectively. DME and ADS-B stations are labeled as red squares and black triangles, respectively. pseudolite coverage is the worst. DME and basic Hybrid APNT HDOP coverage is similar with DME better in some places and Hybrid better in others.

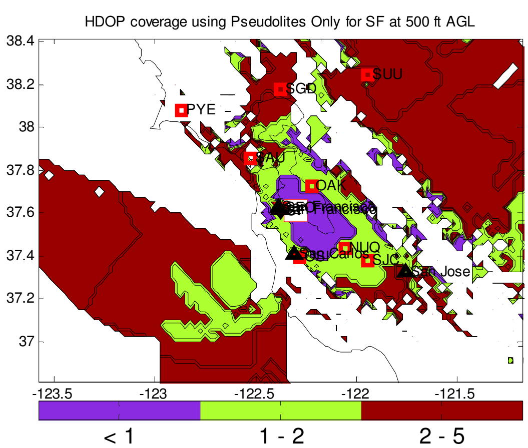

Figure 11. HDOP at 500 ft AGL with Passive Ranging from DME & ADS-B Ground Stations (SF Area)

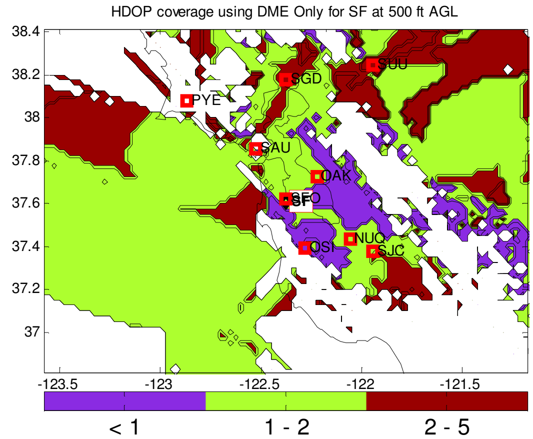

Figure 12. HDOP at 500 ft AGL with True Ranging from DME Ground Stations (SF Area)

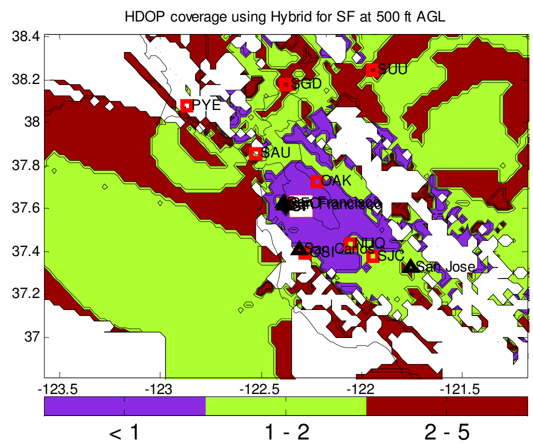

Figure 13. HDOP at 500 ft AGL with Basic Hybrid APNT, DME & ADS-B Ground Stations (SF Area)

Salt Lake represents a challenging area for APNT due to the surrounding mountainous terrain. SL is essentially surrounded by mountains, especially towards the east. Figure 14 shows the analysis region centered on Salt Lake City International Airport (SLC) along with the DME, TACAN and ADS-B stations around the analysis area. Figure 15 to Figure 17 show the HDOP for PL, DME and basic Hybrid APNT at 1500 feet AGL. There are a few ADS-B stations used (one to the west, northwest and southwest) that are used by outside the region displayed in the figure. Because of the additional ADS-B ground stations and their favorable geometry, hybrid shows significant improvement in coverage than DME.

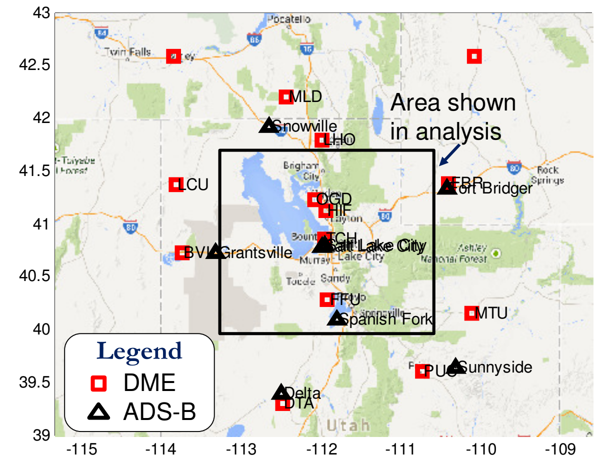

Figure 14. Salt Lake City Area and Potential APNT ground stations

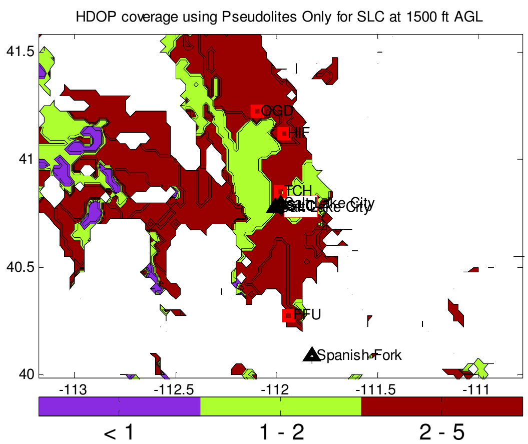

Figure 15. HDOP at 1500 ft AGL with Passive Ranging from DME & ADS-B Ground Stations (SLC Area)

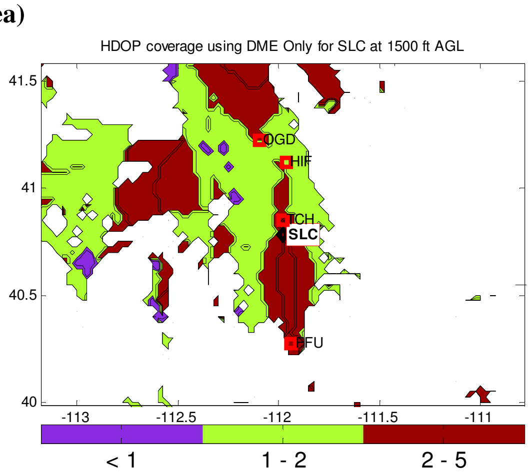

Figure 16. HDOP at 1500 ft AGL with True Range from DME & ADS-B Ground Stations (SLC Area)

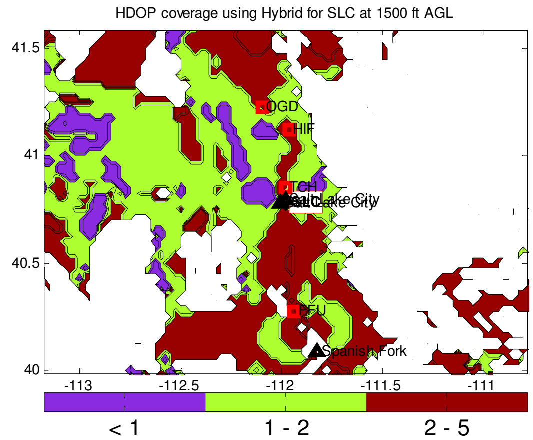

Figure 17. HDOP at 1500 ft AGL with Basic Hybrid APNT from DME & ADS-B Ground Stations (SLC Area)

Integrity Equation and Preliminary Error Bounds

Providing a safe protection level is one method to provide integrity. This method has been employed in systems such as space based augmentation system (SBAS) [8] such as the wide area augmentation system (WAAS). To calculate protection levels and determine coverage, we need an integrity equation as well as preliminary values for the various terms of the integrity equation. Equation 1 shows the preliminary integrity equation based on work conducted for WAAS and Loran [8][9]. The preliminary integrity equation depends on several factors. Error bounds are the basis of calculating HPL. The error bounds are divided into random and bias components, denoted in the equation by α and γ, respectively. Each α_i is the standard deviation (σ) of a Gaussain distribution that overbounds the i^{th} error component. In the integrity equation, the random component (which represents 1- σ value) is then inflated by a factor, κ_{PL}, of 5.33 to achieve a 10^{-7} bound (5.33 σ). The correlation between errors is used for weighting matrix (W) which is the inverse of the correlation matrix. The geometry matrix is used to calculate *K*.

$$HPL = \kappa_{HPL}\sqrt{K \bullet \alpha_i^2} + \sum_i \left| K \bullet \gamma_i \right| = \text{random} + \text{bias} \qquad (1)$$

Error bound budget for DME true ranges used for the analysis is shown in Table 3 as an example. The values are based off of [10]. Similar budgets were developed for DME, 1090 MHz and UAT passive ranges. The bounds are primarily driven by multipath. For a given level of multipath, UAT has about half the multipath error as DME. Hence, in the preliminary analysis, the values used for UAT total range error and its accompanying bound are about half that of DME. Of course, the values used do not represent a final value but rather our current best estimate.

The coverage tool allows us to rapidly re-evaluate if these values change.

Error Sources	Error Bound (1 sigma)	Type
Air/Avionics		
Aircraft clock interval error	3	Random
Aircraft Interrogation Signal	50	Random
Propagation to transponder		
Multipath	150	
Troposphere	2	
Interference		
A/C Cable Delay (bias)	5	Bias
Slant Range	6	Bias
DME Reply Signal		Random
Ground Reply Signal	20	Random
Ground Reply Delay	20	Random
Propagation to aircraft		
Multipath	100	
Troposphere	2	
Interference		
Survey Error (bias)	1	Bias

Table 3. Preliminary Error Bound Budget for DME

Protection Level Coverage

The HPL calculated using DME only for the Salt Lake City area at two altitudes (1500 and 5000 feet AGL) is shown in Figure 18 and Figure 19. Since the accuracy (2 σ) for RNP 0.3 is about 300 m, the targeted HPL for RNP 0.3 is approximately 800 m (5.33 σ for a 10^{-7} probability of exceeding). Given the error bounds used, most but not all areas with DOP below 5 can achieve RNP 0.3. In fact, the areas where DOP is in the 2 - 5 range have HPLs exceeding RNP 0.3 targets. At both altitudes, most of the North-South axis from Salt Lake City does not have adequate HPLs to support RNP 0.3. Note that much of the region east of Salt Lake City is still does not have coverage at 5000 ft AGL.

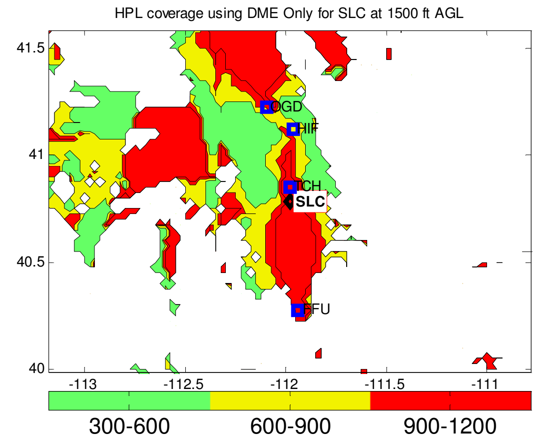

Figure 18. Preliminary HPL at 1500 ft AGL with True Ranging from DME Ground Stations (SL Area)

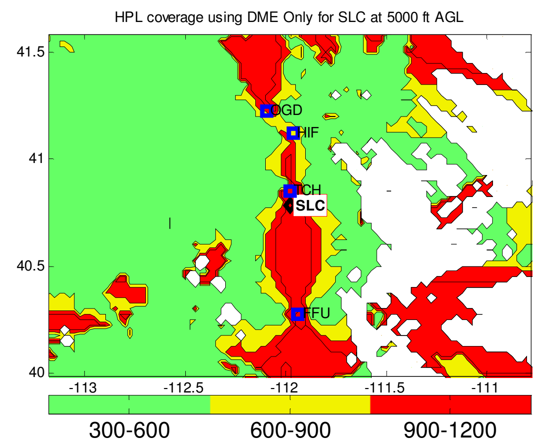

Figure 19. Preliminary HPL at 5000 ft AGL with True Ranging from DME Ground Stations (SL Area)

The Hybrid APNT HPL coverage for 1500 and 5000 feet AGL are shown in Figure 20 and Figure 21. Coverage area is noticeably better. Furthermore, the bounds are lower partially due to geometry and partially due to the assumed lower ranging errors for UAT. In fact, at 5000 ft AGL, there is few areas of without RNP 0.3 coverage, with some coverage to the east of Salt Lake City.

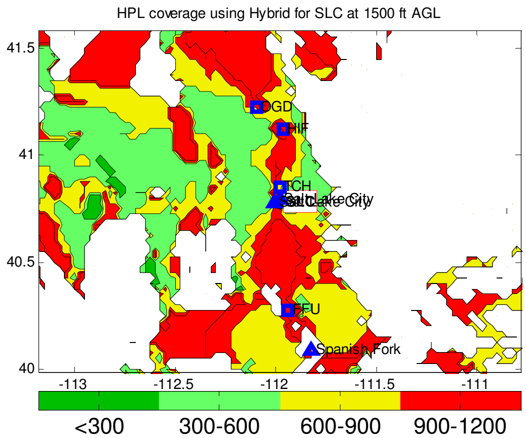

Figure 20. Preliminary HPL at 1500 ft AGL with Basic Hybrid APNT from DME & ADS-B Ground Stations (SL Area)

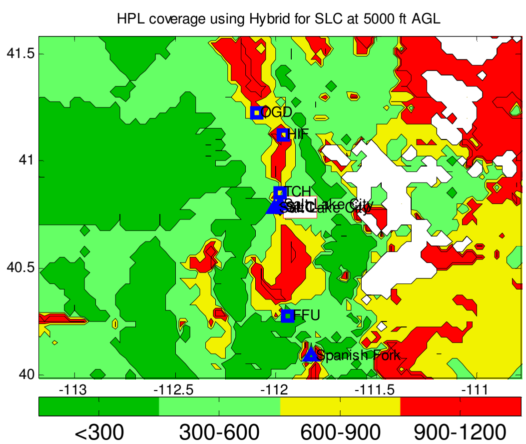

Figure 21. Preliminary HPL at 5000 ft AGL with Basic Hybrid APNT from DME & ADS-B Ground Stations (SL Area)

5. CAPACITY PERFORMANCE

Hybrid APNT capacity is limited as it needs to occasionally conduct two-way (interrogation/reply) interactions to obtain true ranges. In the scenario where we have DME true range, Hybrid APNT reduces the number of two-way interactions compared to traditional DME/DME. This is because the interaction only needs to occur for one station and with lower frequency (i.e. lower interrogation rates). The former reduces the number of interactions relative to DME/DME, which needs to interrogate at least two stations, by at least half. The latter depends on the quality of the avionics clock and is discussed next.

The analysis of coasting time where the aircraft relies on the avionics clock rather than interrogating a ground station for synchronization begins by determining the allowable clock error contribution. The clock error growth should not contribute too much to range error and with the APNT team using 50 nanoseconds (ns) (15 m) of error as the threshold for our initial analysis. Hence, the receiver can coast until the expected clock error reaches 50 ns.

Figure 22 shows the DME interrogation load of a hybrid APNT aircraft as a percentage of the load of a DME/DME equipped aircraft for various avionics clock quality. The figure combines the two factors (i.e., reduction of DME stations used and reduction of interactions by the clock). For example, normal DME/DME operates with 5-15 interrogations per second per DME. A 10^{-8} s/s clock would result in 50 ns of error after about 5 seconds of coasting. Hence, with the basic hybrid APNT implementation and a 10^{-8} s/s avionics clock, only one DME station needs to be interrogated (at 5-15 interrogations) every 5 seconds. The coasting reduces the number of interactions by a factor of five. The total result is that hybrid APNT aircraft with 10^{-8} s/s clock would interrogate 1/10th or 10% as much as a DME/DME aircraft. In other words, if all DME/DME aircraft were used hybrid APNT with a TCXO clock, a roughly ten-fold increase in capacity limit could be expected.

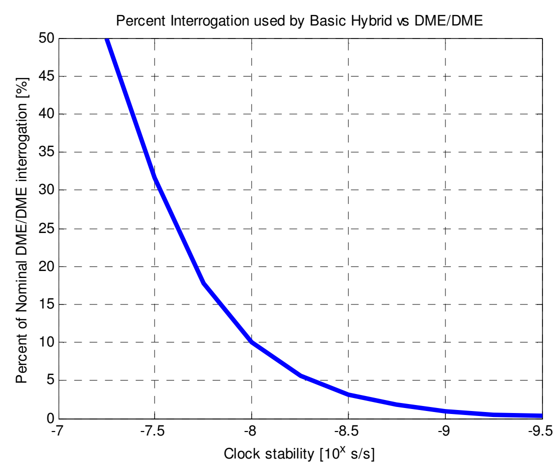

Figure 22. Basic Hybrid APNT DME Interrogations as a Percentage of DME/DME Avionics Using Two DME Stations

6. CONSIDERATIONS

Hybrid APNT development is ongoing. Hybrid APNT requires modifications to ground equipment, new avionics. Figure 23 shows a prototype real time software hybrid APNT receiver that is being developed [6]. Hybrid APNT also requires precise ranges from ground stations, especially those measurements used to calibrate the aircraft clock bias. We are researching how to improve the combined true and passive range to allow for very accurate clock bias calibration.

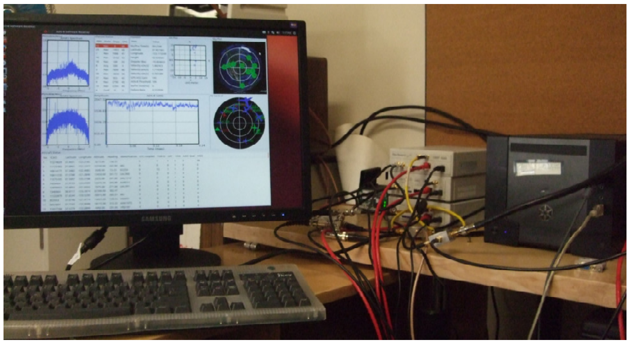

Figure 23. Prototype APNT Real-time Software Receiver for ADS-B Ranging

7. CONCLUSIONS

This paper introduces and describes the hybrid APNT concept. It illustrates how to implement passive and true ranging using existing FAA ADS-B radio stations to support hybrid APNT. This forms one of the building blocks of hybrid APNT.

The paper also examines two key benefits of hybrid APNT: coverage and capacity improvements over other APNT alternatives. Coverage improvements comes from being able to utilize more stations (DME and ADS-B) and from being able to treat passive ranges like true ranges with synchronization of the aircraft clock. The synchronization can be accomplished with one ground station if it provides both true and passive ranges. The coverage analyses indicate that hybrid APNT would have better HDOP and HPL than DME/DME or pseudolites, especially in the case of Salt Lake City. Capacity improvement derives requiring fewer two way interactions with DME stations for ranging, reducing the load on DME ground stations. This improvement derives partly from the avionics oscillator and the quality of the oscillator. If hybrid APNT avionics contained a TCXO, a ten-fold increase in DME system capacity would exist if all DME/DME users used hybrid APNT instead.

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DISCLAIMERS

The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the Federal Aviation Administration or Department of Transportation.

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