Techniques to Provide Resilient Alternative Positioning, Navigation, and Timing (APNT) Using Automatic Dependent Surveillance - Broadcast (ADS-B) Ground Stations

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BIOGRAPHY

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1. INTRODUCTION

The United States Federal Aviation Administration (FAA) Alternative Positioning, Navigation, and Timing (APNT) program is examining the use of existing FAA terrestrial infrastructure to provide navigation capable of continuing US National Airspace System (NAS) operations should Global Navigation Satellite System (GNSS) position, navigation, and timing (PNT) services be unavailable. The approximately 700 automatic dependent surveillance broadcast (ADS-B) ground stations in the United States, these ground stations represents a key existing infrastructure that can be leveraged to deliver APNT. However, ADS-B was not designed to provide high accuracy/high integrity navigation services – it was designed to provide surveillance to air traffic control (ATC) automation systems to support the safe separation of aircraft and advisory services to pilots. As a result, ADS-B transmissions do not inherently possess features, such as ranging or integrity, necessary to support APNT navigation requirements. This paper describes and analyzes some possible means for aircraft to use ADS-B ground station signals for precise positioning or ranging to support area navigation (RNAV) and potentially required navigation performance (RNP).

The paper first provides background on the United States (US) APNT and ADS-B programs. It examines how ADS-B signals can support APNT by either providing positioning directly or by providing ranging. The benefits and drawbacks to using position reports versus ranging from the ground is discussed. The body of this paper examines the two ADS-B protocols implemented in the US: Universal Access Transceiver (UAT) and Mode S Extended Squitter (ES) and how each could be modified to support pseudo and/or true ranging. Additionally, the paper explore ranging based on the combined use of signals from both protocols and how leveraging each protocol's unique features could help overcome some of the limitations of using a single protocol alone.

2. BACKGROUND

The FAA APNT group was formed to determine the performance required to sustain National Airspace (NAS) operations should GNSS services be degraded or unavailable and to develop effective solutions. APNT will need to provide resilient PNT services to support aviation navigation, surveillance, and other aviation applications [1]. The potential solutions developed by the APNT team all use terrestrial transmissions, as these are much higher power than satellite-based signals and are more difficult to deny or interfere with over a large area. As the FAA currently operates significant numbers of ground-based facilities throughout the NAS, the team recognized that APNT could leverage these assets to achieve the necessary capability while minimizing overall program cost. Two attractive assets are the Distance Measuring Equipment (DME) and Automatic Dependent Surveillance - Broadcast

(ADS-B) systems. DME is a two-way ranging system adopted in the 1950s. Its capabilities and how it could be developed to provide APNT services is discussed in several papers such as [2][3][4]. ADS-B ground stations can be used in combination with DME station using a concept called hybrid APNT [5][6]. Hybrid APNT is the most technically ambitious APNT alternative currently being considered by the FAA and combines the use of pseudo and true ranges. The combination is can be useful for determining the clock offset between the aircraft and ground system if the ranges come from a single ground station. The station thus eliminates one unknown (clock offset) and provides a range measurement. With such a station, one only needs one additional, pseudo range only station to get horizontal position. This is shown in Figure 3. The focus of this paper is on ADS-B signals and how we can design them to provide ranging to support APNT and the hybrid APNT concept.

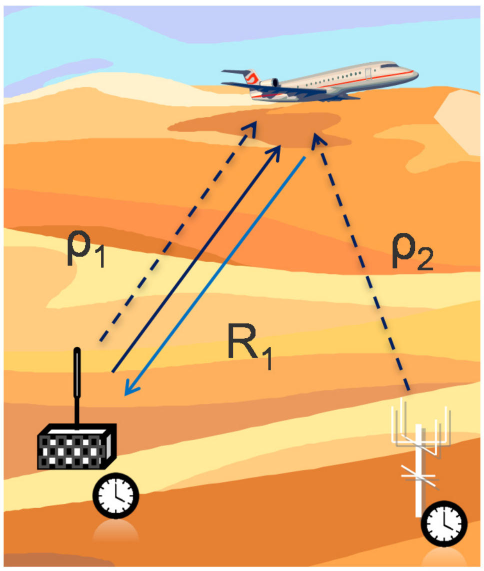

Figure 1. Hybrid APNT Concept using enhanced DME and ADS-B ground stations

Automatic Dependent Surveillance Broadcast (ADS-B)

ADS-B is a system used for aircraft surveillance whereby each ADS-B equipped aircraft continuously broadcasts its identification and position for use by the ATC system and other aircraft. In the United States, ADS-B is supported on two protocols: 1) Mode S Extended Squitter (ES) transmitting on 1090 megahertz (MHz) and 2) Universal Access Transceiver (UAT) transmitting on 978 MHz. Each protocol will be discussed in greater detail in later sections.

Each ADS-B equipped aircraft broadcasts its position, velocity, and intent information to support surveillance and situational awareness, but also supports several other related services, including ADS rebroadcast (ADS-R), traffic information services broadcast (TIS-B), and flight information services broadcast (FIS-B). ADS-B specifies GNSS as the source of the position information. ADS-R and TIS-B services are the means of transmitting aircraft position information from the ground. TIS-B information is derived from ground radar whereas ADS-R is derived from aircraft broadcasts. FIS-B is the broadcast of information, such as weather. For the purpose of this paper, “ADS-B signals” also include these other services.

ADS-B avionics are designed to support these services via two defined features: ADS-B Out and ADS-B In. ADS-B Out is an aircraft’s broadcast of ADS-B reports, which is mandated for aircraft operating in much of the NAS by 2020. ADS-B In is the reception of ADS-B and related services and is not included in the 2020 mandate.

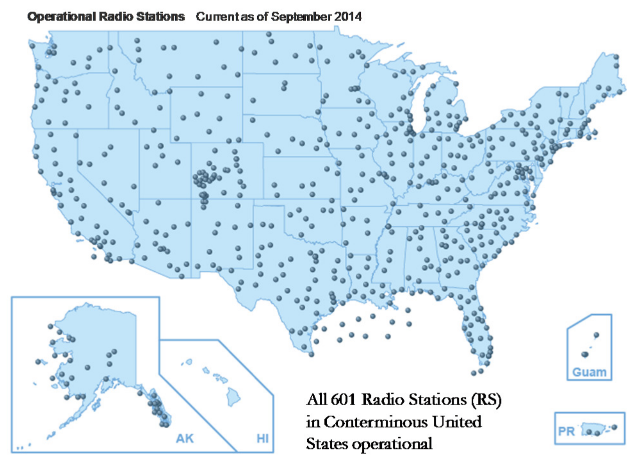

Figure 2. ADS-B Radio Station (RS) in the United States (as of Sept 2014) Image from FAA website

The US ADS-B system contains around 660 ground stations and several master stations. The US deployment is shown in Figure 2. ADS-B ground stations receive aircraft ADS-B and transmit the other ADS-B related services mentioned previously. An example of a ground or radio station (RS) is shown in Figure 3. A typical ADS-B ground station has an omnidirectional UAT antenna and four directional 1090 MHz antennas. The ADS-B master stations receive the data gathered by the ground stations and determine which messages each ADS-B station should send. The master stations may be very distant for the ground station. Similarly, radar and other ground surveillance input are gathered and sent to a TIS-B master station which produces the TIS-B message information. This station may be collocated with an ADS-B master station. The generated TIS-B report is then sent to the appropriate ADS-B ground stations for transmission. Figure 4 shows the notional architecture.

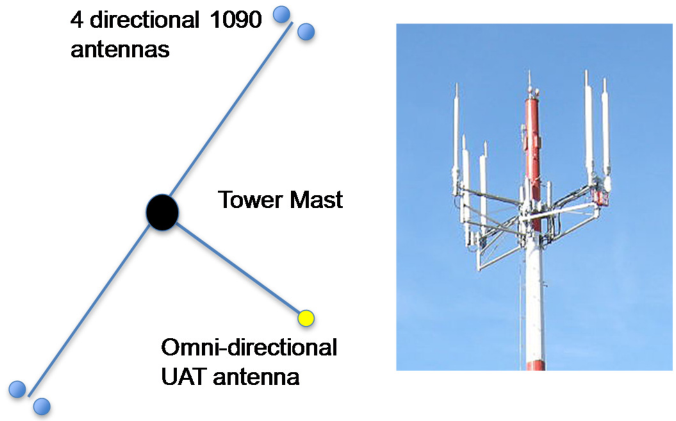

Figure 3. Top Down View of a Possible GBT Configuration. Information based on [7]. Image from ITT-Exelis via AINonline

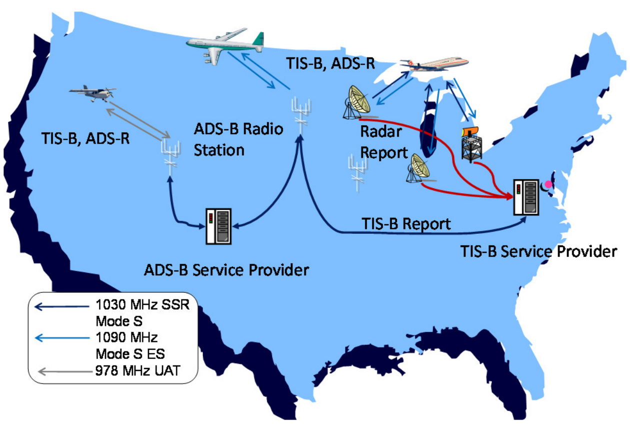

Figure 4. Notional ADS-B and TIS-B Ground System

Supporting APNT

The purpose of APNT is to develop a robust positioning navigation and timing (PNT) system that can support [8]:

- Safe recovery (landing) of aircraft flying in Instrument Meteorological Conditions (IMC) under Instrument Flight Rule (IFR) operations.
- Strategic modification of flight paths or trajectories to avoid areas of interference and manage demand within the interference area.
- Continued dispatch of air carrier operations to deny an economic target for an intentional jammer.
- Flight operations continue without a significant increase in workload for either the pilot or the Air Navigation Service Provider (ANSP) during an interference event.

As such, the APNT system solution needs to provide position and other information that can support the ability for aircraft to safely and securely navigate and maintain NAS capacity to preclude significant economic impact. As GNSS ranging measurements allow users to calculate accurate position frequently as well as precise time and position integrity, APNT ideally should also provide onboard integrity monitoring and precise time.

One way is for ground stations to provide ranges. Another possibility is to provide an aircraft its position directly, without the need for onboard calculations. This paper examines how ADS-B signals could provide either ranging data or position information transmissions, the pros and cons of each, and how they compare with other APNT alternative solutions. The current three candidate APNT solutions are: 1) Use of TIS-B as a positioning service, 2) DME/DME and 3) hybrid ranging based on DME and ADS-B signals. ADS-B signals are used for in the first and third alternative.

TIS-B as a Positioning Service

A possible means to provide aircraft positioning is for the aircraft to use its "ownship" position provided via TIS-B position reports. The system is attractive for several reasons: 1) an aircraft would only need to receive a transmission from one ground station to get its position; 2) existing ground infrastructure already provides this transmission; and 3) currently defined ADS-B avionics support TIS-B reception and decoding.

However, there are several challenges to using TIS-B position reports for navigation. First, TIS-B is currently an advisory service that does not meet the required navigation system performance to support area navigation. The generated position is calculated by an external service provider from potentially multiple information sources of differing quality. Coasting between position reports is generated by ATC automation system trackers certified for use by ATC displays – not for aircraft navigation or Flight Management System (FMS) input. Navigation services require a high level of integrity and trace-ability on the position output. Receipt of a position without the underlying data used to calculate it makes the determination of the integrity of the output position complex. Hence the ground system may require significant modification to support navigation integrity. Additionally, aircraft FMSs do not currently interface with existing ADS-B avionics that decode the TIS-B report. Hence new ADS-B avionics or changes to existing FMSs are needed for TIS-B based navigation. A third challenge is position error and latency. Surveillance accuracy based on radar varies with the type of radar, distance to target, and "feed-horn-to-screen" processing time. There are several sources of errors that come from the TIS-B process, including errors from the radar sensor, filtering and estimation, delay and latency, and messaging and quantization. Delay and latency are also variable and there are many delays in between the events of radar estimate to TIS-B report reception and decode. The multiple seconds of delay may make the report unsuitable as an FMS input. A final challenge is spoofing. ADS-B/TIS-B is unauthenticated and easy to replicate. Allowing an aircraft to use an unauthenticated position report would poise a cybersecurity risk that would be challenging to mitigate. While these challenges to TIS-B position report use for navigation could possibly be overcome, the mitigations will likely entail significant changes and costs to both the provider and users of the service.

However, despite these significant challenges for a TIS-B based solution, the potential for ADS-B/TIS-B transmissions to provide APNT services is still bright. ADS-B could provide ranging but in some cases, additional data need to be transmitted. Currently TIS-B is scheduled to be phased out following the 2020 ADS-B avionics mandate. The TIS-B transmissions could be replaced by transmissions that would support ground-based ranging.

Ranging Requirements

ADS-B ground stations are a potential ranging source. As they both receive and transmit signals, two forms of ranging are possible. ADS-B ground stations could be used to support pseudo ranges based on time synchronized transmissions or round trip true ranges from a transmissions sent in reply to a received aircraft transmission (i.e., similar to DME operation). In this section, we will review the basic elements needed for pseudo and true ranges. This serves as a starting point for determining the changes, modification or processing needed on each ADS-B signal to support these ranging capabilities.

Three key signal structure or message elements are needed to enable pseudo ranging for APNT. These are:

1) Identification of the time of transmission (TOT), synchronized to a common time base.

2) Identification of transmitting ground station and/or its precise location.

3) Integrity information.

To produce these pseudo ranging elements, the ADS-B ground station must be synchronized to a common time base and be able to transmit at the designated TOT. External integrity monitors may be necessary to check signal performance and provide alerts of out-of-tolerance conditions via message.

Similarly, true ranging also requires several signal structure, or message elements. For true range, a ground station would issues a reply to an aircraft's interrogation transmission. The ADS-B ground station reply would need to communicate:

1) Identification of the initiating aircraft transmission (the aircraft transmission that elicited the ADS-B ground reply)

2) Time between the transmission of the ground reply and the reception of the initiating aircraft transmission ("reply delay")

3) Identification of transmitting ground station and/or its precise location

4) Integrity information

To produce these true ranging elements, the ADS-B ground station would need to mark the time of arrival (TOA) of the initiating aircraft transmission. To calculate the reply delay, the ground station needs to know the TOT of the reply and the TOA of initiating aircraft transmission. This means that the ground station must be able to select the reply TOT *a priori*.

Evaluation

To evaluate the potential of ADS-B ground stations and signals for APNT, we collected and analyzed measurements from two ADS-B ground stations -- specifically the San Jose and Woodside ADS-B ground stations that can be received at Stanford University. We set up the data collection system on the roof of the Department of Aeronautics & Astronautics to gather intermediate frequency (IF) signal using the Universal Software Radio Peripheral (USRP). The USRP data collection set up is discussed in [9]. For time of arrival processing, we correlate to the 36 bit UAT synchronization header and the 4 pulse Mode S preamble, discussed in the later sections. This is basic processing and does not fully leverage much of the UAT or Mode S ES transmission. Improved TOA processing can be achieved and will be investigated in the future.

Figure 5. Woodside & San Jose ADS-B Ground Station and distance to Stanford measurement site

3. UNIVERSAL ACCESS TRANSCEIVER

Universal Access Transceiver (UAT) is a new signal developed for ADS-B that operates at 978 MHz [10]. UAT was developed to support aviation surveillance and provide important traffic and weather data to aviation users. UAT is attractive for APNT as it has an existing basic passive or pseudo ranging capability as well as several features that can be used to support other ranging functions (e.g., periodic messages to support a degree of synchronization to Coordinated Universal Time (UTC) as enunciated by a national source such as the US Naval Observatory (USNO)).

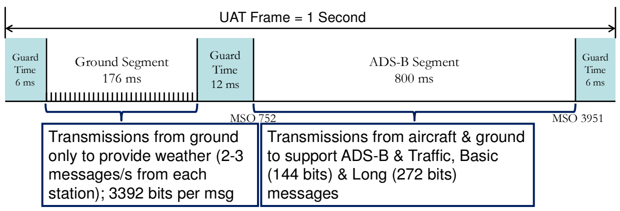

Figure 6. Potential of UAT Transmissions for Ranging in UAT Frame

The UAT frame is one second long starting on the UTC second as shown in Figure 6. It is divided into two segments: Ground and ADS-B. Transmissions are only allowed to start at specified MSO which are separated by 250 microseconds (μs). In the Ground segment, only transmissions from ground stations are allowed. There are 32 transmission opportunities or slots for ground transmissions. Not all MSOs are used with the slots separated by 22 MSO. Each ground station regularly transmits in 2 or 3 designated slots each second. The slots used are assigned so that proximate ground stations do not use the same slots. The ground segment messages are 4.2 milliseconds (ms) long and adjacent slots are separated by 5.5 ms. Hence, a message from one slot is unlikely to interfere with that transmitted in another, which minimizes intrasystem interference.

The UAT signal is modulated through continuous phase frequency shift keying (CPFSK) with the signal frequency varies by ±312.5 kHz. CPFSK keeps the transmitted energy mainly within a one MHz DME channel. An increase of 312.5 kHz (Δf) indicates a "1" bit while the same decrease indicates a "0" bit. Each UAT transmission uses a synchronization header consisting of thirty-six 0.96 μsec long bits. The synchronization bits used for the ADS-B segment are the inverse of those used in the ground segment.

UAT is also designed to support a comparatively high data capacity -- 3456 payload bits, including a 64 bit header, in the ground segment and 144 or 272 payload bits for a basic or long message in the ADS-B segment. Forward error correction is also used and not counted in the above payload bits. This is significantly higher than the Mode S ES transmission, which contains only 88 payload bits composed of a 56 bits message field and 32 bits for message and address information.

The UAT signal, as utilized according to the UAT Minimum Operational Performance Specifications (MOPS) [10], still has several limitations: 1) it only allows for a roughly 1 Hz range update rate; 2) it only allows transmission timing variations of up to 500 nanoseconds (ns) off UTC; and 3) it may have significant multipath errors relative to APNT accuracy and integrity targets.

Pseudo Ranging

UAT already has a built-in pseudo ranging capability in its ground segment, i.e., the accurate position of the source ground station and the time of transmission in the form of the slot ID (0 to 31) based on the information contained in the ground segment header. The slot ID can be converted to TOT (relative to the UTC second) by Equation 1. It also contains a coarse integrity flag for synchronization. As the message has significant data capacity, it may also be possible to use a few bits for additional integrity alerts related to ranging. Typically, there are two or three ground segment transmissions per second for each ground station, which are all transmitted within the first 182 ms of each second.

$$TOT = 6 + 5.5 \cdot (slot\ ID)\ ms \quad (1)$$

While the built-in UAT pseudo range capability is useful, it is desirable to overcome some of its limitations -- ideally with no impact or changes to existing users and systems.

Using the UAT ground segment results in approximately a 1 Hz range update rate as the time between two consecutive ranges may be 800 ms or more. If more frequent UAT ranging is demanded, ADS-B segment ground transmissions (TIS-B, ADS-R) must be developed to provide pseudo ranging. Currently ADS-B segment messages do not generally contain the necessary information for pseudo ranging - the most critical being TOT and source ground station identification. Other necessary information could be gathered from the ground segment transmissions. One way of supplying TOT and source station identification could be achieved by developing and transmitting new ADS-B segment pseudo ranging messages or extending existing messages. We developed a way to use existing messages and examined how the TOT and source identification can be determined from existing messages. Using existing message is beneficial for several reasons: 1) it provides more ranging messages; 2) it better uses valuable spectrum; and 3) no modifications would be required to existing infrastructure.

We examined if the TOT and source ground station identification can be made by leveraging the information from the ground segment transmissions. From ground segment transmissions, we know the stations visible and the approximate corresponding pseudo ranges. Over one

UAT frame, the pseudo range from ground and ADS-B segment messages, denoted by PR_{GND} and PR_{ADSB}, respectively, should be close (less than ~300 m, , the distance traveled by an aircraft at 600 knots in one second) even for a fast moving commercial aircraft. Recall that PR_{GND} is known but we cannot immediately calculate PR_{ADSB} because there is no TOT information. However, since TOT must occur at a specified MSO, we generate an estimate of PR_{ADSB} for each received ADS-B segment message and use PR_{GND} to determine if the estimate is correct.

To make the estimate, we refer to Equation 2 which shows that PR_{ADSB} equals the difference of time of arrival of the message at the aircraft (TOA_{AC}) from the transmission MSO (MSO_{true}) times 250 µs. For simplicity, the calculations shown neglect the initial 6 ms offset from UTC seen in Figure 6. While we do not know MSO_{true}, we know that it differs from any other MSO (MSO_{est}) by an integer number (N). We can try different values of N and get corresponding guesses ($PR_{ADSB,est}$) for the pseudo range as per Equation 5. If the transmission comes from one of the stations where we have a PR_{GND}, then there should be a $PR_{ADSB,est}$ that is approximately equal PR_{GND}. So if we can find N such that, for ground station M, we have PR_{GND} and $PR_{ADSB,est}$ reasonably match, then we have determined the TOT ($MSO_{est}+N$) and the transmitting station (M). This is shown in Equation 6.

$$PR_{ADSB} = TOA_{AC} - TOT_{GND} = TOA_{AC} - MSO_{true} \cdot 250\,\mu s \quad (2)$$

$$MSO_{true} = MSO_{est} + N \quad (3)$$

$$PR_{ADSB} = TOA_{AC} - (MSO_{est} + N) \cdot 250\,\mu s \quad (4)$$

$$PR_{ADSB,est} = TOA_{AC} - (MSO_{est} + N_{est}) \cdot 250\,\mu s \quad (5)$$

$$PR_{ADSB,station\ M} \cong PR_{GND,station\ M} \quad (6)$$

Another equivalent way to make the estimate is to calculate time of transmission assuming the signal is from one of the stations for which we have a ground segment pseudo range, PR_{GND}. This is seen in Equation 7. If we can identify a station M with $PR_{GND,M}$ that results in a TOT is close to a permitted transmission time or MSO (within ~ 300 m), then we have potentially identified the station and TOT. In rare instances, a user may have two or more different stations that satisfies the MSO criteria. How to handle this possibility is discussed later.

$$TOT_{est,station\ M} = TOA_{AC} + PR_{GND,station\ M} \quad (7)$$

We conducted analysis to verify the technique using static data from two local ADS-B ground stations. The resulting pseudo ranges from the ground segment (truth) and ADS-B segment match reasonably well. Figure 7 and Figure 8 show histograms of the ADS-B segment pseudo ranges derived using the described technique (bottom) along with the ground segment pseudo ranges (middle) and all pseudo ranges (top) for the San Jose and Woodside ADS-B stations. The pseudo ranges are close and implies that the MSOs should be correctly estimated. But they also exhibit some differences with the mean of ADS-B segment pseudo ranges exceeding that of the ground segment by about 15-20 m. The difference may be due to our simple processing as the ground and ADS-B segments use different headers. This difference is not the result of error estimating the MSO which would result an error of at least 75 km (250 µs). For both segments and stations, the standard deviations of the pseudo ranges are approximately 15 m.

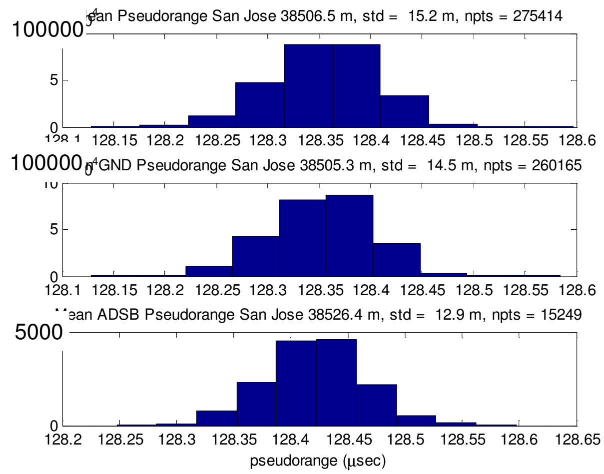

Figure 7. Histogram of Pseudoranges from San Jose ADS-B Station: All (top), Ground Segment (middle), ADS-B Segment (bottom)

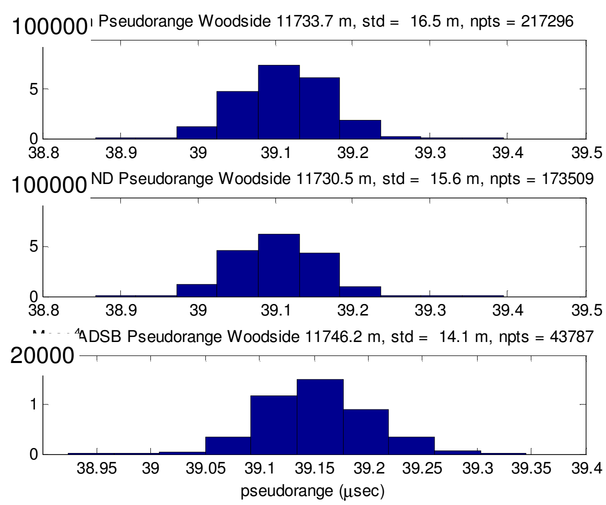

Figure 8. Histogram of Pseudoranges from Woodside ADS-B Station: All (top), Ground Segment (middle), ADS-B Segment (bottom)

However, ADS-B segment messages are only transmitted when there is a user in the airspace to use the information. As there are few UAT users, this may be infrequent. Figure 9 shows the number of ADS-B segment messages decoded from Woodside, CA station over a 24 hour period. While there can be 20 or more ADS-B segment transmissions from Woodside in a given second, often there are no transmissions as there are no UAT users in the region. If UAT based ranging with ADS-B segment signal is implemented, there should always be a couple of transmissions each second. On UAT, this should not be a problem as there is sufficient spectrum and no spectrum congestion issues.

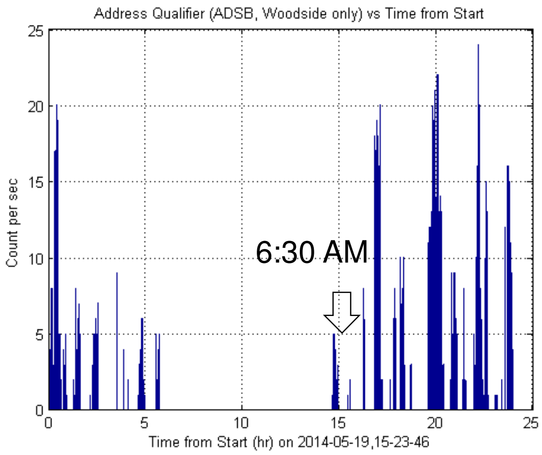

Figure 9. Count of ADS-B segment messages from Woodside over 24 hours

The described method using ADS-B segment ground transmissions for pseudo ranging is predicated on having ground station pseudo ranges being distinctly different, modulo 250 µs or 75 kilometers (km). This is generally true but not always. When the pseudo ranges are close, one may not be able to determine the transmitting station. One safe resolution when this occurs is to not use ADS-B segment pseudo ranges for stations whose ground segment pseudo ranges (those transmissions have station identification) are close, modulo 250 µs. A second solution to this ambiguity would be to implement an operational change – different ground stations transmit on a different subset of MSOs with the subset determined by some information related to the station, e.g., its station identification or location. A similar process is used for aircraft transmissions, where a pseudo random number based on the aircraft position determines transmit MSO [10]. A third solution is to add small amount of information to the message to resolve the ambiguity. This is discussed next.

Some ADS-B segment messages also contain the six least significant bits (LSB) of the transmit MSO, which could also be used to determine the TOT and the source of ADS-B segment ground transmission. Our measurements show that this is not a commonly transmitted message. However, it may be possible to use spare bits, such as byte 18, from existing ADS-R/TIS-B messages to provide some information about the MSO. Furthermore, if these bits are not adequate, then one can gain more data capacity to provide station and MSO information by using a long message instead of the more typical basic message.

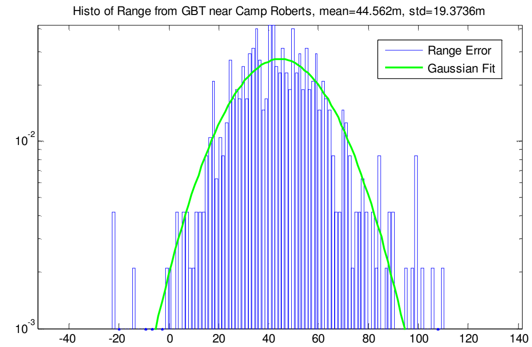

Figure 10. Normalized Histogram of UAT Pseudo range relative to GPS derived pseudo range estimate (truth reference)

Another challenge is that UAT only requires time synchronization to be within 500 ns, which in terms of ranging would add up to 150 m of error. This level of inaccuracy may be acceptable for en route and terminal domain navigation that require RNAV 2 and RNAV 1, navigation with accuracy of 2 and 1 nautical mile (nm), respectively. However, it would significantly impact APNT's ability support advanced arrival and departure procedures requiring 0.3 nm accuracy (RNAV 0.3). A potential solution for achieving the desired time synchronization that will not impact existing users is to have another monitor threshold and synchronization flag in the ground segment message. This flag would trigger if synchronization exceeds a tighter threshold - perhaps 50 ns. This may require changes to existing ADS-B ground stations.

Our measurements have shown that there can be a noticeable timing bias in the ground transmissions [11]. An example of the bias is shown in Figure 10 which shows the normalized histogram of our pseudo range errors versus a GPS derived solution. This bias does vary over time. The bias variation may be due to our processing and/or to the radio station clock not being very tightly steered due to the 500 ns timing limit. If the latter is the case, the error may be limited if UAT ground had a tighter threshold. We are currently investigating this issue.

A final, and perhaps the most significant challenge is UAT multipath performance. UAT has a relatively low bandwidth (< 1 MHz) and, as a result, its nominal envelope multipath performance can result in an instantaneous error of up to 60 m with a multipath signal that is weaker in power by 6 dB. This is shown in Figure 11. Carrier phase methods, such as carrier tracking to aid extended integration, are difficult as there are large time gaps (fractions of a second) between transmissions. Hence, reducing multipath error may require use of another signal as discussed later.

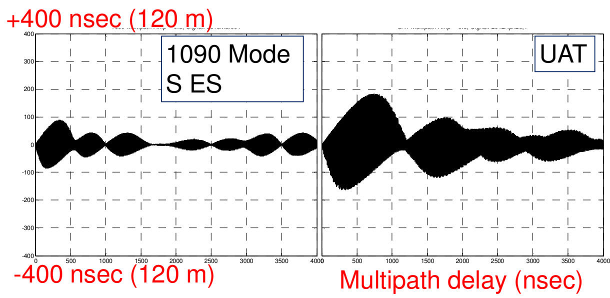

Figure 11. Multipath Envelope of Mode S ES and UAT for -6 dB power multipath

True Ranging

UAT can provide true ranges though some new transmissions will be needed. The number of additional transmissions may be limited as we can leverage existing UAT signals (i.e., ADS-B Out from the aircraft) to act as an initiating interrogation. New transmissions would be needed to function as a reply message as there is currently no transmissions from ground stations that performs that function. Hence, an ADS-B segment message, such as TIS-B or ADS-R, would need to be modified to act as a reply. Compared to a typical TIS-B/ADS-R, three additional pieces of information would need to be communicated in the reply. First is the reply delay, i.e., the time difference between reception of the initiating aircraft ADS-B Out and the transmission of the ADS-R reply. Second is an indication of which ADS-B transmission initiated the reply. A parity check using common, unique information, such as aircraft identification and position, could provide another way to check if a reply corresponds to a given interrogation. Either a new UAT message would be needed for the reply or the information could be tacked onto an existing UAT transmission. Third, there needs to be a means of identifying the transmitting station. Either an explicit identification or implicit one (such as that previously discussed for pseudo ranging.) An existing UAT transmission for the reply may require additional data capacity to provide these pieces of information. This may be achieved by using a UAT long message, instead of the basic message for ADS-R/TIS-B, which would increase data payload by 128 bits. As UAT is lightly used and organized, it should have the capacity to support replies to many aircraft without degrading the system. The effects of providing UAT reply broadcasts to all aircraft in a high density airspace has not been analyzed.

4. 1090 MHZ MODE S EXTENDED SQUITTER

ADS-B is also transmitted using Mode S Extended Squitter (Mode S ES) on 1090 MHz [12]. Mode S ES is an international standard for ADS-B and the preferred option for commercial air carriers. Its transmissions are modulated using on-off keying (OOK). An on-off keyed preamble indicates the mode of transmission (A, C, S, etc.). For Mode S, there is "on" signal, with duration of 0.5 microsecond (μsec), followed by "on" signals 1, 3.5 and 4.5 μsec after the first. Data then follows the preamble with a "0" and "1" bit represented by keyed "on" in the first or second half of each μsec, respectively. Figure 12 shows the preamble and some initial data bits from on-air data as well as an overlay of the ideal envelope. A Mode S ES transmission contains 112 bits of data, of which 24 bits is reserved for parity. This is discussed in our prior paper [9].

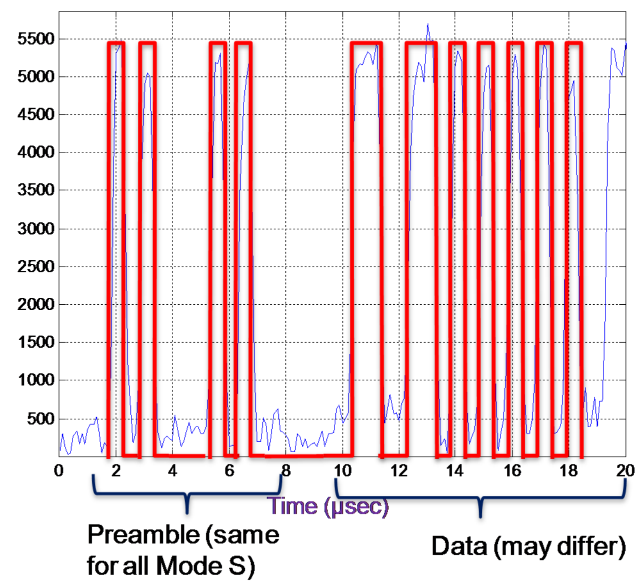

Figure 12. 1090 MHz Mode S/Mode S ES Preamble and Data

This signal could be beneficial for APNT as it has greater multipath resistance than UAT. This is shown in Figure 11. However, there are several limitations to using Mode S ES. First, it does not have a built pseudo ranging capability. Next, it has limited data capacity. Finally, the 1090 MHz spectrum is already congested. Overcoming these limitations presents a significant challenge. Solving the first two implies the need for new transmissions, which would further congest the spectrum and exacerbate the interference environment. Therefore, it would appear that the only prudent course of action would be to design ranging capabilities on Mode S ES that leverages as many existing transmissions as possible.

Pseudo Ranging

There are currently no ADS-B Mode S ES transmissions that provide the three key information needed for pseudo ranging - i.e., time of transmission, source ground station identification, and integrity information. To provide TOT, it would be desirable for Mode S ES ranging transmissions to be sent at specific, well defined opportunities like in UAT. This helps reduce the number of bits needed to communicate the TOT. This is important due to the low data capacity.

Figure 13 presents a simple proof of concept design to provide pseudo ranges while limiting the number of new transmissions. In this design, Mode S ES are only transmitted at specific, well defined times relative to the UTC second, which as with UAT, is used to define a frame. A new pseudo ranging message is transmitted per antenna per second. For a given antenna *i*, this message is transmitted $\Delta_{UTC,i}$ after the start of each UTC second. As discussed previously, there can be four 1090 MHz antenna and Δ_{UTC} may differ for each antenna to prevent interference at the same ground station. Existing messages are transmitted at scheduled times. These times are an integer number Δ after the transmission of new pseudo ranging message from the antenna. In other words, allowable TOT for antenna *i* is given by Equation 8 where *N* is an integer. These existing messages provide additional ranging measurements. By constraining its TOT, its source and pseudo range can be determined from its time of arrival in a manner similar to pseudo ranging using UAT ADS-B segment signals.

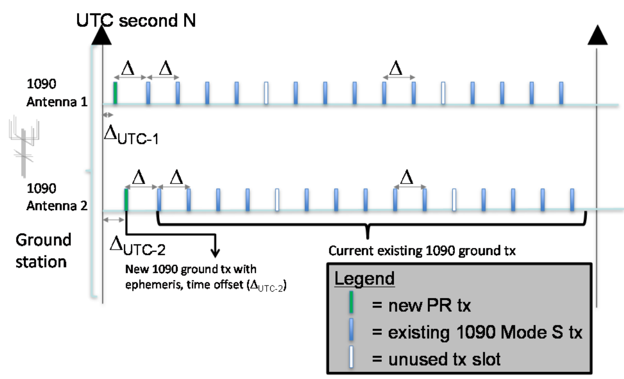

Figure 13. Transmission Concept to use 1090 MHz Mode S ES Messages to Support Pseudo Ranging

The concept does not require that every possible TOT indicated by Equation 8 contain a transmission, only that the transmission of any existing message occurs at a time consistent with Equation 8. Both Δ_{UTC} and Δ need to be communicated to the user but could be set *a priori*. These two parameters are used to help prevent interference between ground station transmissions and to implicitly identify the source of the transmission in a manner akin to using UAT ADS-B segment messages. We can also use *N* to provide more certitude about station. For example, each station may be limited to use only some integer values of *N* with the limit based on the station properties (e.g, location, identification, etc.).

$$TOT_i = \Delta_{UTC,i} + N * \Delta \quad (8)$$

The new pseudo range transmission at Δ_{UTC} will be a new message type that will provide ground station information – akin to GPS ephemeris. First, it is necessary to provide station identification and its location. We need to give each station a unique identification, e.g. the 24 bit International Civil Aviation Organization (ICAO) commonly used in ADS-B. As Mode S ES is data constrained, our design uses a 12 bit identifier that will support 4096 different stations. To provide station location, we could use a table look up to a preloaded database that has the locations for each the station. We choose to provide an ephemeris message with the station identification that gives more flexibility and allows for changes in station location. Figure 14 shows a proof-of-concept message design that provides station location with accuracy of within 1 meter using the 56 bit message payload structure used by ADS-B. This message would use either a new uplink format (UF) or a currently undefined UF message. The various acronyms used in Figure 14 are shown in Table 1. The third element, integrity information, could be provided using the undefined spare bits in these messages.

DF (18) [5]	CF [3]	StaID [12]	Type [4]	CPR F [1]	PL Tx F [3]	Ant F [2]	Spare [2]	Altitude [13]	CPR Lat [20]	CPR Lon [20]	Spare [3]

Figure 14. Ephemeris/Pseudo range message

We developed another new message that to provide greater accuracy and precise time, if desired. This message can share use of the transmission slot at $\Delta_{UTC,i}$ with the prior ephemeris message (e.g. alternate between the two messages). The message, shown in Figure 15, would provide precise time as well as provide information about the 1090 MHz antennas for more precise transmitter location. The message also defines the layout of the antenna set up so that each antenna can be accurately located relative to the station center location. This is desirable as an ADS-B ground station utilizes multiple antenna for 1090 MHz Mode S ES and having more precise transmission antenna location reduces bias error for integrity. The various acronyms used are presented in Table 1.

DF (18) [5]	CF [3]	StaID [12]	Type [4]	Spare [1]	PL Tx F [3]	Ant F [2]	Spare [2]	UTC Sec [25]	Year [8]	Ant Angle [8]	Ant Type [4]	Spare [11]

Figure 15. Precise Time/Antenna Location

Table 1. Description of New Message Contents

Name	Description	Bits/Range
Downlink Format (DF)	Standard Mode S ES ADS-B/TIS-B field	5 bits
Code Format (CF)	Standard Mode S ES ADS-B/TIS-B field	3 bits
Station ID (StaID)	Station Identification	12 bits
Type (Pseudolite message type)	Identifies the pseudolite message type (ephemeris, absolute time, others)	4
Compact Position Report Format (CPR F)	UAT can suffer from out of band interference as well as interference in the ADS-B segment	1 bit (Even/Odd)

Pseudolite Transmission Format (PL TX F)	Message transmission time offset from UTC second (Δ_{UTC})	3 bits (8 possibilities)
Antenna Format (Ant F)	Identifies which of the 4 antennas at the station is transmitting	2 bits (4 antennas)
Altitude		13 bits -1000 to ~24600 feet
CPR Lat/CPR Lon	Latitude and Longitude in CPR format	20 bits, < 1 m accuracy
UTC Sec	Seconds from start of the year	25 bits
Year	Year	8 bits (256 years from start year)
Antenna Angle (Ant Angle)	Use to describe layout of 1090 MHz antennas, direction (heading of antenna)	8 bits
Ant Type (Antenna Type)	Use to describe layout of 1090 MHz antennas	4 bits
Spare	Extra bits allows for modifications	

True Ranging

The modifications needed to support true ranging on Mode S ES are similar to those needed for UAT true ranging. As with UAT, the existing aircraft ADS-B transmission may serve as interrogations. The ground station would need to generate a reply transmission that includes a means of identifying the source ground station, the ADS-B interrogation that initiated the reply, and the reply delay. Even with the limited data capacity, we can create a new message that could contain the transmitting station identity, initiating aircraft transmission and reply delay. However, this solution does not scale with increasing air traffic since each additional aircraft requires a dedicated ground transmission which is not acceptable as 1090 MHz is already spectrum congested.

5. COMBINED UAT AND MODE S ES

The combined use of the two ADS-B protocols has some attractive features. First, the strongest points of each protocol can be leveraged to overcome weaknesses of the other. For example, as will be seen in the pseudo ranging designs, UAT with its higher data capacity would be used to provide data while existing Mode S ES could provide additional ranging measurements that are less affected by multipath. Another benefit is that they could be used as part of an interrogation-reply system to potentially provide true ranging without additional transmissions. The combination may provide a reasonable means of having both pseudo and true ranges from one ground station. This capability enables hybrid APNT.

A cost of using both Mode S ES and UAT signals is the need for avionics that support both protocols. While no such receiver exists, our discussions have suggested that there are dual protocol receivers being developed for ADS-B

Pseudo Ranging

While each protocol could provide pseudo ranging alone, combined use of the two can avoid further congesting the 1090 MHz spectrum while reducing multipath error when compared to using UAT alone. The APNT team developed a design does not requires any new 1090 MHz Mode S ES transmission.

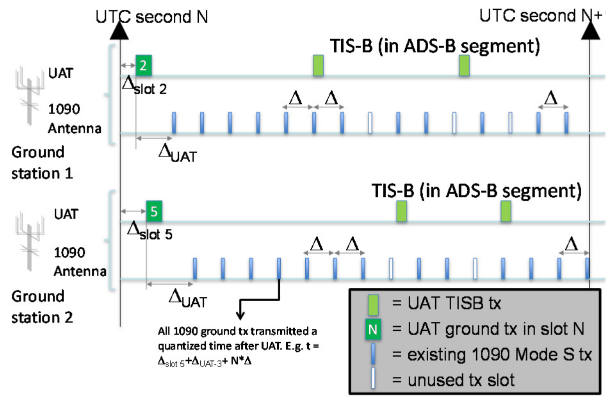

Figure 16. Transmission Concept to Use UAT and 1090 MHz Mode S ES to Support Pseudo Ranging

We developed a design concept that combines use of the two protocol avoid further congesting the 1090 MHz spectrum while reducing multipath error more than using UAT alone. The concept is shown in Figure 16. This concept would have UAT provide data and reference time of transmission while existing Mode S ES would provide additional updates and multipath mitigation. This design is essentially the 1090 MHz Mode S ES pseudo range design with the UAT ground segment transmission replacing the new Mode S ES pseudo range/ephemeris message described in that section.

As a result, the design requires no new UAT or Mode S ES MHz transmission. Instead, it requires the existing Mode S ES transmissions from a given ground station to be scheduled based on first UAT ground segment transmissions from that ground station, transmitted Δ_{UAT} after the UTC second. Like with the Mode S ES pseudo ranging design, the existing Mode S ES transmissions can only be transmitted at scheduled times. These times are integer number Δ after the transmission of first UAT ground segment message and given by Equation 9. Again not every TOTs given by Equation 9 need to contain a transmission.

$$TOT_i = \Delta_{UAT} + N * \Delta \quad (9)$$

Because UAT ground segment transmissions are synchronized to coordinated time universal (UTC) and use time division multiple access (TDMA), this limits interference by other UAT ground segment transmissions from other stations. Proper selection of Δ would also result in non-interference between the Mode S ES ground station transmissions. There are 32 UAT ground segment slots each separated by 5.5 ms, Δ could be chosen so that TOT from different stations differ by at least 172 μs = (5.5/32). This occurs if Δ = 5.328 ms. As a result, there are some limits on what Δ values are acceptable. Δ needs to be communicated to the user but could be set *a priori* while Δ_{UAT} is known from the UAT ground segment transmission.

ADS-B ground stations could provide multiple Mode S ES ranging measurements per second. This is seen when we measure the amount of ground only transmissions (TIS-B, ADS-R). Figure 17 shows the number of 109 MHz Mode S ES ADS-B ground station transmissions decoded per second over the course of four days. Up to 324 transmissions are decoded. These transmissions come from the two ADS-B ground stations visible. It also can contain transmissions from different antennas from the same station. The result is supported by Figure 18 which shows a zoomed in histogram of the number of TIS-B and ADS-R transmissions measured per second at Stanford. Spikes in the histogram occur at multiples of three suggesting that there are three sources of this information – two antennas from Woodside and one from San Jose.

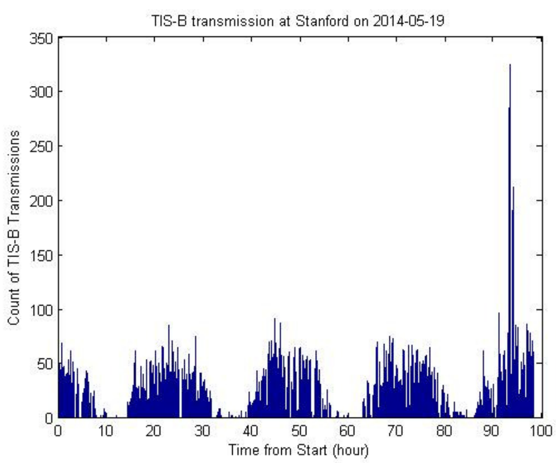

Figure 17. Number of 1090 MHz ground transmission per second at Stanford

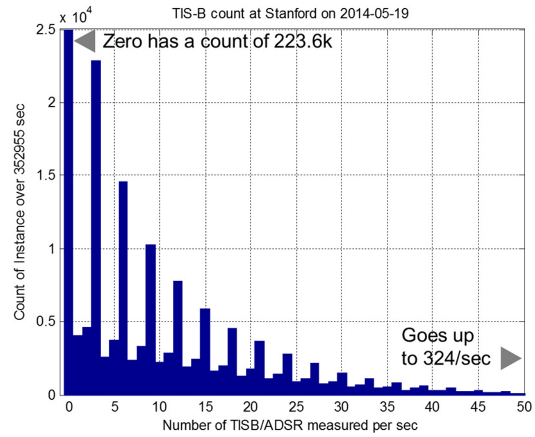

Figure 18. Zoomed histogram of number of 1090 MHz TIS-B/ADS-R transmissions received at Stanford data collection site per second

True Ranging

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 carry 1090 MHz Mode S ES ADS-B and transmit position reports multiple times per second. These signals could be simultaneously used as interrogation transmissions resulting in no additional aircraft transmissions. All ADS-B messages on Mode S ES would be rebroadcast by a ground station on UAT. Viewed in this sense, an ADS-B aircraft transmission and the ground ADS-R rebroadcast form an interrogation-reply pair that may provide a two way measurement to yield true range.

The concept may be possible with existing equipment and operations. Currently, UAT ADS-R of Mode S ES ADS-B position reports are sent if there is an UAT equipped aircraft in the area. As mentioned in the UAT true ranging section, compared to a typical ADS-R, the reply delay and transmitting ground station that needs to be communicated for the reply. The same solution discussed in that section can be employed. The attractiveness of this concept is that Mode S ES can operate without change. UAT would need additional data capacity in its ADS-R ground transmission. Again, if additional data capacity is needed, we can define a new UAT ADS-R using long message, instead of the basic message.

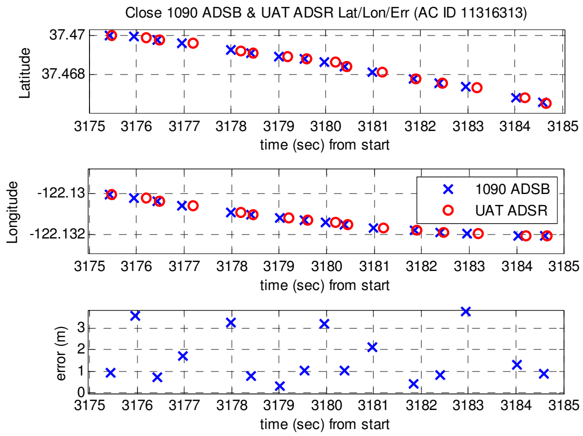

Figure 19. 1090 MHz ADS-B and Associated UAT ADS-R Reported Latitude/Longitude (Top, Middle) and Report Position Difference (Bottom)

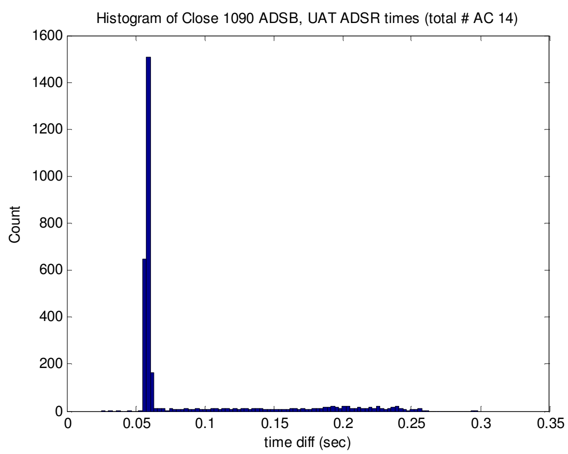

Figure 20. Time difference between receipt of aircraft Mode S ES ADS-B and corresponding UAT ADS-R from ground station

To examine the feasibility of the concept with existing ADS-B operations, we examine the currently transmitted UAT ADS-R. There may be a long delay between the Mode S ES ADS-B and UAT ADS-R transmissions as the ADS-B ground station may need to communicate with a faraway ADS-B master station between reception of the ADS-B and broadcast of the ADS-R. The top two plots on Figure 19 show the reported latitude and longitude from 1090 MHz ADS-B and the corresponding UAT ADS-R received at our data collection site over time. The corresponding ADS-R is typically received within 200 ms. The bottom plot on the figure shows the difference in the position reports. Figure 20 shows that the time delay measured by our reference station between the ADS-B out from an aircraft and the ADS-R "reply" currently varies roughly from 50 to 200 ms. 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.

6. CONCLUSIONS

ADS-B signals have significant potential for ranging and supporting APNT. This paper provides a comprehensive overview of how to use ADS-B signals for ranging and positioning. It shows how some ranging benefits can be achieved with little change to the existing system. It also outlines some designs that would provide ranging without requiring new transmissions.

Analysis of these capabilities using over-the-air signals show that it may be possible to obtain high update pseudo ranges from UAT without modifying the existing system. Accuracy could be improved by tightening timing tolerances. Using 1090 MHz ADS-B for ranging is more difficult due to spectrum congestion and would require operational changes and new messages. Combining both UAT and 1090 MHz ADS-B signal has potential for both pseudo and true ranging with small changes. Support of both capabilities allows it to provide a key enabler of hybrid APNT.

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