

# Evaluation & Comparison of Ranging Using Universal Access Transceiver (UAT) and 1090 MHz Mode S Extended Squitter (Mode S ES)

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**Abstract**—The FAA Alternative Position Navigation and Timing effort is developing technologies to provide navigation service capable of sustaining operations in the event of the loss of Global Navigation Satellite Systems (GNSS). APNT will utilize existing ground infrastructure to support this capability. One effort is to examine the use of the Automatic Dependent Surveillance Broadcast (ADS-B) ground infrastructure for ranging. This paper examines the use the two transmitted ADS-B signals: 1) 1090 MHz Mode S Extended Squitter (Mode S ES) and Universal Access Transceiver (UAT). It uses the transmitted, on-air signal to examine multipath, ranging and timing performance.

**Keywords**—APNT; UAT; Mode S ES

## I. INTRODUCTION

As the Global Positioning System (GPS) and other Global Navigation Satellite Systems (GNSS) are becoming increasingly integral to aviation operations, the US Federal Aviation Administration (FAA) and other Air Navigation Service Providers (ANSP) are looking to develop terrestrial alternative position navigation and time (APNT) systems to minimize the impact of a degradation of these satellite systems. The goal is to have an APNT system that can allow for the continuation of key Area Navigation (RNAV) and Required Navigation Performance (RNP) operations during periods when GNSS services are unavailable.

An attractive idea for APNT is the use of existing terrestrial infrastructure to provide passive or pseudo ranging signals. Passive ranging would allow for unlimited capacity to support high density airspace and allow for the combination of passive ranges from many different sources. One desirable source is the transmissions of Automatic Dependent Surveillance Broadcast (ADS-B) ground stations. ADS-B is being installed to support surveillance needs of today and future airspace. Though not designed for navigation, ADS-B and its related signals could be used to provide such a service as part of APNT. This use has several advantages. It has substantial infrastructure with nearly 600 ADS-B ground stations currently installed throughout the United States. Furthermore, APNT avionics can combine ADS-B passive ranging signals with other passive ranging sources such as distance measuring equipment (DME) based pseudolite

(PL) to extend coverage at nearly all regions targeted by APNT.

This paper examines the on-air performance of two ADS-B signals: 1090 MHz Mode S Extended Squitter (Mode S ES) and 978 MHz Universal Access Transceiver (UAT) using data collected in the San Francisco Bay Area. Mode S ES has the advantage of being wideband thus multipath resistant as well as an international standard. However, it operates on a congested frequency and is data limited. UAT has high data bandwidth and fewer interferers. However, it is relatively narrowband and not an international standard.

In this paper, we examine three key navigation performance areas for terrestrial signals: multipath, signal accuracy and interference. Multipath and signal accuracy are drivers for RNAV/RNP integrity and coverage. For the analysis, we developed data collection units that collect and accurately time stamps UAT and 1090 data. It allows for assessment of range accuracy through differential analysis. A comparison of UAT and 1090 performance in range is made using measurements from ADS-B ground stations which transmit both signals. The units also were used to find multipath data.

The final area of study is the effect of interference, especially on the congested 1090 MHz channel. This paper examines the effects of 1090 interference on TOA estimates and availability of the signal. It evaluates the implication of the measured interference and message loss rate. This signal availability is more critical for navigation than positioning. Navigation requires reception of signals from at least three ground stations and multiple times per second whereas surveillance requires only one signal every couple of seconds. Additionally other systems based on 1090 MHz signals such as multilateration depend on clear reception of the same signal at three sites.

The results show that each signal has advantages in different aspects. This suggests one means of providing an improved pseudolite service from ADS-B ground stations is possible through the combined use of both signal. This could provide a capability that has the best features of the two ADS-B signals.

## II. BACKGROUND

### A. APNT & ADS-B Signals

APNT is developing aviation navigation based on terrestrial ground stations to maintain the operational capacity and efficiency of the national airspace (NAS) even if GNSS is unavailable [1]. The terrestrial ground stations will be heavily based on existing FAA terrestrial infrastructure and transmissions. These operate in Aeronautical Radio Navigation Service (ARNS) bands and have international acceptance. The ADS-B infrastructure and its signals are being examined for their capabilities to support APNT. ADS-B ground stations, known as Ground Based Transceivers (GBT), have two forms of transmissions: 1) Mode S Extended Squitter (ES) on 1090 MHz<sup>1</sup> and 2) Universal Access Transceiver (UAT) on 978 MHz.

While the paper refers to automatic dependent surveillance broadcast (ADS-B) signals, these signals actually support several other related services including ADS rebroadcast (ADS-R) traffic information services broadcast (TIS-B) and flight information services broadcast (FIS-B). ADS-B is the broadcast of position, velocity and intent information to support surveillance and situational awareness. Currently ADS-B specifies GNSS as the source of the position information. ADS-R and TIS-B is the transmission of aircraft position information from the ground. TIS-B information is derived from ground radar whereas ADS-R is derived from aircraft broadcasts. For the purpose of this paper, TIS-B will be used to refer to both services. FIS-B is the broadcast of information such as weather.

### B. Prior Work

APNT is developing the use of ADS-B Mode S ES and UAT transmissions to support potential APNT solutions [2][3][4]. One solution is to use ADS-B signals to provide passive ranging. Another is the use of ADS-B aircraft transmissions for a ground based multilateration position solution which would then be transmitted to the aircraft.

To support this analysis, the APNT team previously examined the precision with which the Mode S ES and UAT signals could be measured. Multilateration using Mode S ES has been demonstrated in many places with a testbed multilateration site established in Colorado [12]. Additionally, [5] studied the use of Mode S ES signals for multilateration to determine an aircraft position on the ground.

One concern with the use of 1090 MHz ADS-B transmission, particularly on 1090 MHz is spectrum congestion. The Los Angeles (LA) Basin 2020 study conducted this problem when implementing Mode S ES for ADS-B [6][7][8]. The study analyzed the availability of 1090 MHz ADS-B signals in a future high-density airspace (i.e., LA Basin in 2020). It demonstrated that there could be significant interference and reception rates of 25% per transmission can be expected. This is sufficient for surveillance but APNT capacity

analysis shows that this is not sufficient for navigation, particularly if the signal is used to support multilateration [9].

This paper builds on the test bed developed in [5] to examine the performance characteristics and differences between the two ADS-B signals when used for passive ranging or multilateration. For APNT purposes, these two signals may be used in a complimentary fashion as they emanate from the same tower. The complimentary use can help mitigate the weaknesses and limitations of the individual systems.

### C. 1090 MHz Mode S Extended Squitter

The Mode S ES transmission is one of many transmissions operating on 1090 MHz. Transmissions at this frequency support surveillance via secondary surveillance radars (SSRs). They are primarily used by aircraft based transponders to respond to a ground radar interrogation thus providing the SSR with a round trip measurement and data, depending on mode. The transmissions are generally random. The data provided depends on the mode used (A, C, or S). Mode Select or Mode S allows for selective interrogation/response as well as more data. The existing Mode S signal used for SSR was modified to support ADS-B [8]. Mode S ES is an extended Mode S transmission in terms of data (and hence transmission time) that is spontaneously broadcast by the aircraft (i.e., sent without prompting from the ground).

Transmissions on 1090 MHz are modulated using on-off keying. Initially, there is an on-off keyed (OOK) preamble that indicates the mode. For Mode S, there is “on” signal, with duration of 0.5 microsecond ( $\mu$ sec), followed by “on” signals 1, 3.5 and 4.5  $\mu$ sec 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  $\mu$ sec, respectively. Figure 1 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 with 24 bits being for parity.

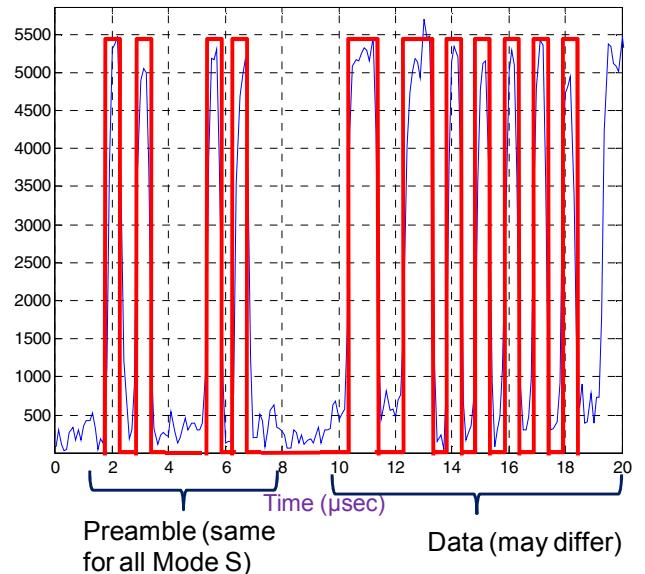


Figure 1. Mode S/Mode S ES Preamble and Data

<sup>1</sup> Mode S ES will be used in this paper to refer to the signal on 1090 MHz. There is also a Mode S on 1030 MHz.

#### D. Universal Access Transceiver

UAT is a new signal developed specifically for ADS-B and described in the UAT minimum operational performance standards (MOPS) [10]. It uses a DME channel that is unused in the United States and is organized using time division multiple access (TDMA). Specific message start opportunities (MSOs) are used by UAT transmissions. As a result of this and its design, there should be little intersystem interference sources. The organization of the UAT channel is seen in Figure 2. UAT transmissions are organized around a one second long frame that starts on the Coordinated Universal Time (UTC) second. Two segments are defined: ground and ADS-B.

The ground segment is dedicated to transmission from ground stations. It is organized in such a manner that ground station transmissions should not interfere with each other. There are 32 MSOs used in the ground segment. The time difference between each used MSO is 5.5 milliseconds (ms) which provides enough time for the message (~4.1 ms providing 3392 bits of data) and some buffer so as to not interfere with messages in adjacent used MSOs. These transmissions support pseudo ranging and provide FIS-B to the aircraft. The basic ground payload is seen in Figure 3 where the slot being the ordinal of the MSO used (e.g., slot 1 is the 1<sup>st</sup> MSO that can be used in the ground segment). UAT timing is maintained through the use of GPS at the GBT [11].

The ADS-B segment supports ADS-B and TIS-B. These are shorter transmissions and adjacent MSOs are 250  $\mu$ sec apart. These signals were not designed to support pseudo ranging. This effectively limits UAT ranging rates to be about 1 Hz unless ADS-B segment signals can provide pseudo ranging.

The UAT signal modulated using continuous phase frequency shift keying (CPFSK) where the signal frequency varies by  $\pm 312.5$  kHz. This keeps the transmitted energy mainly within the 1 MHz DME channel. An increase of 312.5 kHz ( $\Delta f$ ) 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  $\mu$ sec long bits. The synchronization bits used for the ADS-B segment are the inverse of those used in the ground segment.

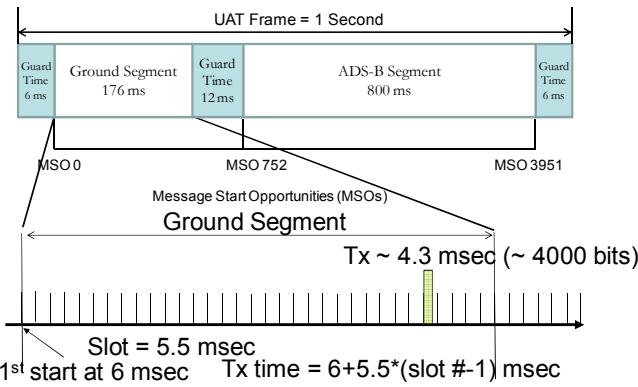


Figure 2. UAT Frame and Organization

**Table 2-4: Format of the Ground Uplink Message Payload**

Byte #	Bit 1	Bit 2	Bit 3	Bit 4	Bit 5	Bit 6	Bit 7	Bit 8
1	(MSB)							
2								GROUND STATION LATITUDE (WGS-84)
3								(LSB) (MSB)
4								
5								GROUND STATION LONGITUDE (WGS-84)
6								(LSB) P Valid
7	TIME COUPLED	Reserved	APPLICATION VALID	(MSB)	SLOT ID	(LSB)		
8	(MSB)	TIS-B SITE ID	(LSB)		Reserved			
9								Application Data
432								

Figure 3. Ground Uplink Message (UAT ground segment) from DO-282B [10]

#### E. Ground Based Transceiver (GBT)

ADS-B ground infrastructure will consist of approximately 660 GBTs in the conterminous United States (CONUS) to support surveillance. A typical GBT typically consists of one omni-directional UAT antenna and four directional 1090 MHz antenna. This is shown in Figure 5. These antennas are similar to those used for DME and are shown in Figure 6. 1090 MHz signals are transmitted in sectors rather than broadcast to all directions at once.

There are two GBTs currently operating in the San Francisco Bay Area and are shown in Figure 4. These are located in Woodside, California (CA) and San Jose, CA. The Woodside station is at high elevation (~ 700 m) and easily visible from the rooftops of several buildings at Stanford. The San Jose signal is also visible but as it is located at lower elevation (~250 m), there is more attenuation from buildings and other obstructions. Additionally, it is located further from Stanford University resulting in more attenuation.

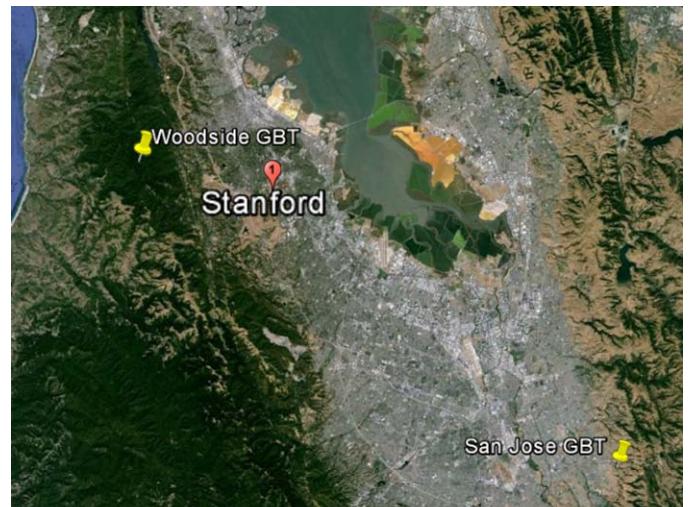


Figure 4. GBT near Stanford (Google Earth)

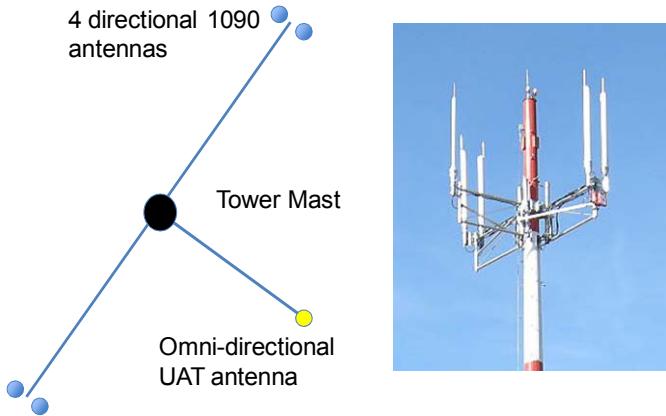


Figure 5. Top Down View of a Possible GBT Configuration. Information based on [12]. Image from ITT-Exelis via AINonline

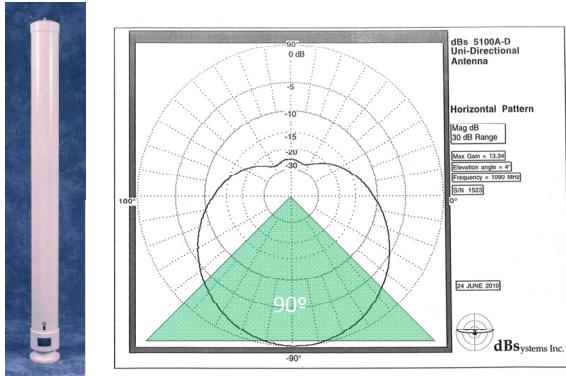


Figure 6. Directional 1090 MHz Antenna [images from dB systems, [www.dbsant.com](http://www.dbsant.com)]

#### F. Stanford Data Collection & APNT Software Receiver

Stanford is developing a Software Defined Radio (SDR) to support APNT and provide a prototype APNT receiver. The SDR is used to process data collected using USRPs. The hardware architecture of test equipment is depicted in Figure 7. The hardware contains one GPS antenna, one ADS-B antenna receiving 1090 MHz or UAT, one tunable filter, one Rubidium (Rb) Oven Controlled Crystal Oscillator (OCXO), three USRPs [12], one for each signal (GPS, UAT and 1090), and one host computer. The received GPS and 1090/UAT signals pass to USRPs, which are equipped with a DBSRX2 programmable mixing and down-conversion daughter boards. A 10 MHz external signal from a common Rubidium clock synchronizes the data collection from all USRPs. The USRPs are controlled by a host computer running the Ubuntu distribution of Linux. The USRP hardware driver (UHD) [13] software is used to configure USRP and daughter boards settings such as sampling rate and radio frequency (RF) center frequency. This flexible hardware set up supports a synchronized two-antenna signal collection system and real-time software receiver [14][15]. The RF signal from each antenna element is converted to a near zero Intermediate Frequency (IF) and digitized to 14-bit complex or in-phase and quadrature outputs (I & Q, respectively). The RF center frequency is set to 1575 MHz for GPS, 1090 MHz for 1090 and 978 MHz for UAT. The

sampling rate is set to 10 Megasamples per second (MSPS). The digitalized IF data is then processed in real-time and/or stored into hard drive in the host computer. Figure 8 shows a picture of the test equipment.

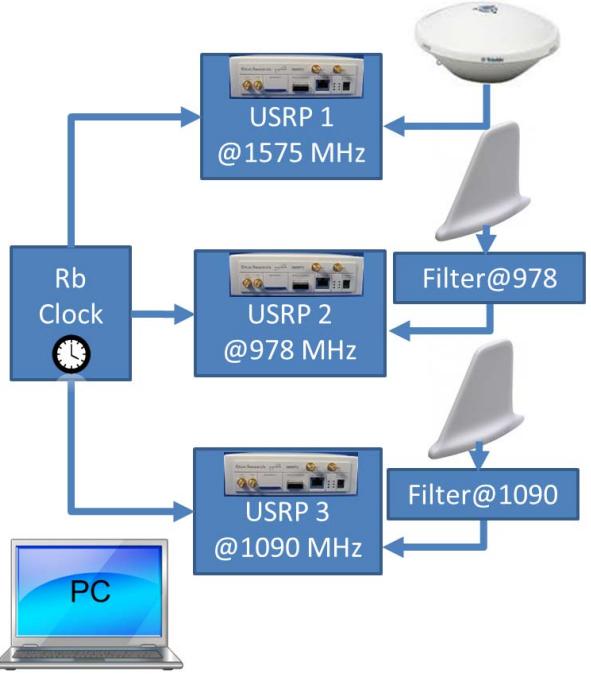


Figure 7. Block diagram of test equipment

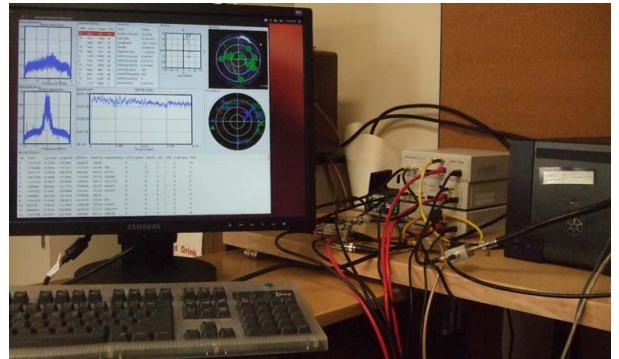


Figure 8. Data Collection Test Equipment Set up

The software architecture of receiver is shown in Figure 9. It starts by requesting data from two USRPs and then stores the data into separated 2-second-long queues. The USRPs are synchronized within 10 ns, so the data from all USRPs are assumed to be sampled at the same time. At every millisecond, data is processed in three working threads. The first thread performs the GPS processing for 12 channels. The thread executes functions including software correlator, signal acquisition/tracking and message decoding. The second/thread serve the UAT/1090 processing including signal demodulation and message decoding. At every 100 millisecond, another thread takes the measurement from all tracked GPS channels and then solves for the receiver position and timing. The result is used to correct the timing for compensating the clock drift. The timing is then used to determine the time of arrival (TOA) for UAT/1090.

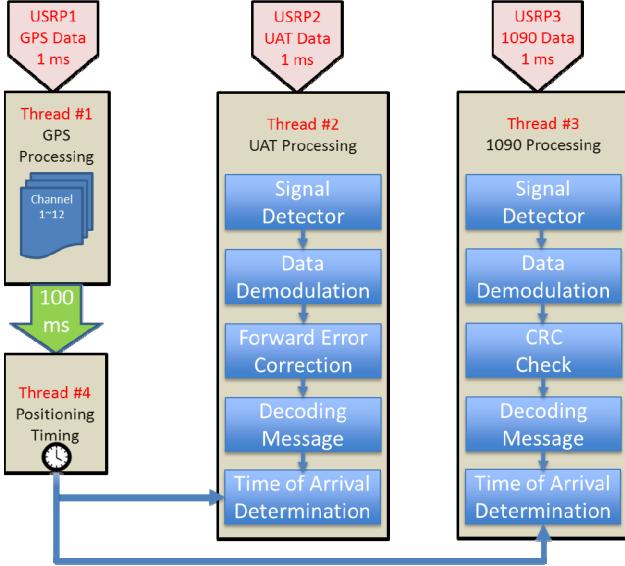


Figure 9. Software Architecture

### III. MULTIPATH

An important consideration in the use of terrestrial signals is multipath. The APNT team has identified this as being a key integrity issue. Mode S ES has a wide bandwidth as a result of its OOK modulation. On the other hand, UAT was constrained to maintain most of its energy within a 1 MHz band. Hence it is expected that Mode S ES would have better multipath performance than UAT. The multipath performance of the ADS-B signals was analyzed using on-air transmissions to quantify and qualify the difference.

#### A. Theoretical Analysis

The theoretical signal analysis used collected on-air data to examine the error induced by multipath. The analysis uses the on-air signal with a delayed and attenuated replica to simulate multipath. The result was processed by correlating to the preamble (Mode S) or synchronization sequence (UAT) to determine timing or range error induced by the multipath. The delay was varied to generate a multipath error curve.

Figure 10 shows the multipath error when using a Mode S ES signal collected at 40 MSPS. Multipath that is 3 decibel (dB) lower in signal strength than the direct signal (-3 dB multipath) is used for the figure. The result shows a maximum error of about 20 nanoseconds (ns) or 6 meters. With delays greater than 500 ns, the resulting error is even lower values – 10 ns or less.

However, 40 MSPS uses a fairly large bandwidth and the effect of using a smaller bandwidth was assessed. Figure 11 shows the multipath error when using a Mode S ES signal collected at 5 MSPS with -3 dB multipath. The resulting curve is a slightly different from the wideband results from Figure 10 in both character (more rounded) and in error values. The relative amplitudes and zero multipath locations are similar.

The low bandwidth case has a maximum error of about 90 nanoseconds (ns) or 27 meters.

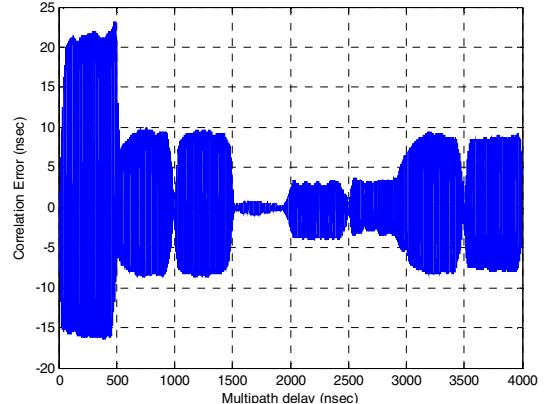


Figure 10. Multipath Induced Error on 1090 MHz Mode S Signal using on-air signal collected at 40 MSPS (-3 dB signal strength multipath)

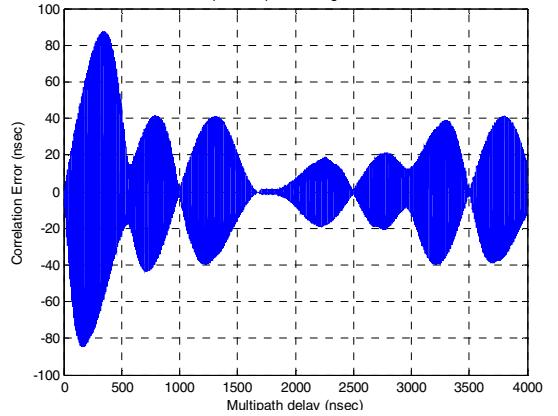


Figure 11. Multipath Induced Error on 1090 MHz Mode S Signal using on-air signal collected at 5 MSPS (-3 dB signal strength multipath)

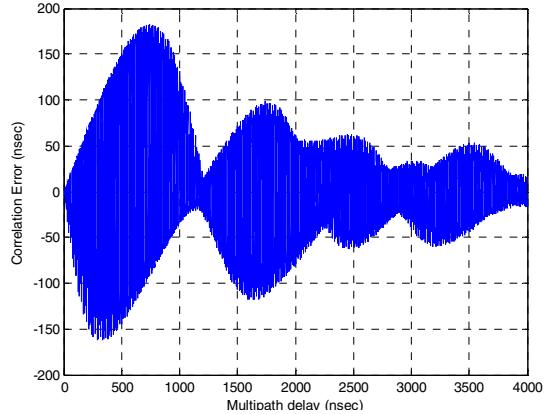


Figure 12. Multipath Induced Error on UAT Signal using on-air signal collected at 5 MSPS (-3 dB signal strength multipath)

The same analysis is conducted on UAT. Figure 12 shows the multipath error when using a UAT signal collected at 5 MSPS with -3 dB multipath. The greater susceptibility of UAT to multipath is seen. The maximum error level is around 180 ns (54 m) or about twice that of Mode S ES collected at the same bandwidth. This is 9 times larger than that of Mode S ES at 40

MSPS. Even worse is that there are fewer low or zero multipath regions with the error is larger over more delay values.

### B. 1090 MHz Mode S Multipath

We attempted to capture actual Mode S transmissions with multipath to see its effects. As aircraft frequently send Mode S collecting at a static site near air traffic offers many different signal paths and possible multipath reflections. Figure 13 shows data with Mode S multipath. Despite the multipath having relatively large amplitude compared to the direct signal, the multipath can be easily distinguished and its effect can be mostly extracted. This is a major benefit of the wide bandwidth Mode S signal. Processing determined the multipath signal is delayed by a little less than 1  $\mu$ sec or 300 m relative to the direct. Using that information, we can identify possible sources of the reflection. Figure 14 shows the data collection location and suspected multipath source.

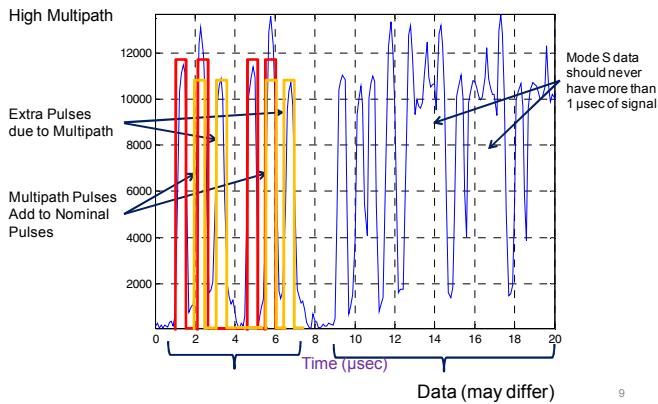


Figure 13. 1090 MHz Mode S Signal with Multipath



Figure 14. Potential Source of 1090 MHz Mode S Multipath (Site 2)

### C. Discussion

UAT multipath was not clearly visible in the data collection. One possibility is that there are multipath signals but we could not easily identify it. In other words, the UAT multipath signal is not easily distinguished from the direct

signal. Another possibility is that it is not observed. The UAT signals emanated primarily from two static sources – the two local ADS-B ground stations. Unfortunately, as few aircraft transmit UAT signals, the lack of different UAT geometric paths seen at our data collection locations is likely why we did not easily find UAT multipath signals. From the preliminary analysis, 1090 MHz Mode S ES is the preferred signal for multipath performance.

## IV. RANGE COMPARISON

### A. Data Collection

Several data collection efforts were made. Basic differential analysis used two closely spaced sites – on the rooftop of the Durand building at Stanford University. This is shown in Figure 15. These sites have relatively low multipath but there is some interference as the rooftop has many venting and other systems that may produce spurious noise. Mode S ES analysis was also conducted using more widely separated sites. This is necessary to determine the specific source (Woodside or San Jose) of the GBT Mode S ES transmissions since these transmissions (TIS-B) due not identify the transmitting station.



Figure 15. Data Collection Sites on Durand Building Roof for Differential Analysis for UAT and 1090

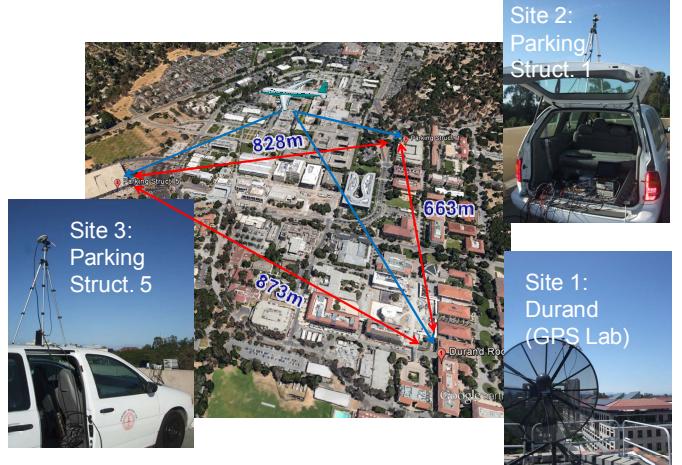


Figure 16. Data Collection Sites at Stanford for Differential Analysis for 1090 MHz Mode S

To support the analysis, the data collection locations were surveyed. Additionally, the GBT locations are determined from

the UAT broadcast information. This is used to calculate expected differential time of arrivals (DTOA).

### B. 1090 Mode S ES

Analyzing Mode S ES ground transmission requires the initial step of identifying the station source. While a signal can be identified through decoding as having come from the ground (TIS-B), the transmitted data does not identify the ground station source hence it is unclear which GBT transmitted a given signal. Two different methods were used to attempt identification: differential time of arrival (DTOA) and signal strength. In this paper, we use the term DTOA to refer to the difference in TOA of a given signal as measured by two data collection station. DTOA requires being able to measure a signal using two synchronized and well separated data collection stations. For well-placed, separated data collection sites, different ground stations will result in very different DTOA. DTOA should unambiguously if the data collection sites separated such that the DTOA for the two GBTs differ greatly. Signal strength identification, if possible, only would require one station. Differential collection was set up using data collection stations separated by over 800 m. Figure 17 shows the result with the top showing an average signal amplitude for the signal from each data collection station (RS1 and RS2). The bottom shows the corresponding DTOA. The results show that DTOA is needed as one could have both strong and weak signal strength associated with the same DTOA and hence the same station. This is likely due to the directional antennas used for Mode S with our data collection stations receiving signals from the main lobe of the antenna directed in our direction and the side lobe of another antenna. However, high signal strength is only associated with the closer Woodside GBT.

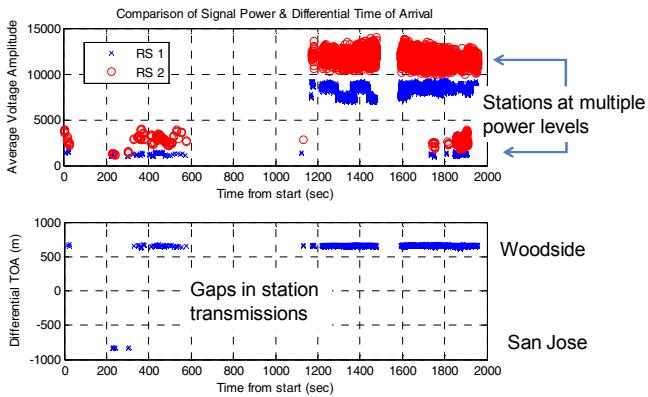


Figure 17. Comparison of Signal Power and Differential Time of Arrival for GBT Mode S ES transmissions

Having calculated the DTOA to determine the station transmitting the data, we can also compare the DTOA to the expected DTOA. Figure 18 shows the result for the low power (voltage amplitude above 5000 units based on the USRP output in Figure 17). The surveyed data collection station positions and published locations of the GBT were used to calculate the expected DTOA. The resulting distribution shows a mean bias from the expected DTOA of about 16.8 meters with a standard deviation of 5.7 meters. There are several sources of this error including quantization, differences in the broadcast GBT

location and actual antenna location, as well as data collection site errors (survey location, line delays and processing).

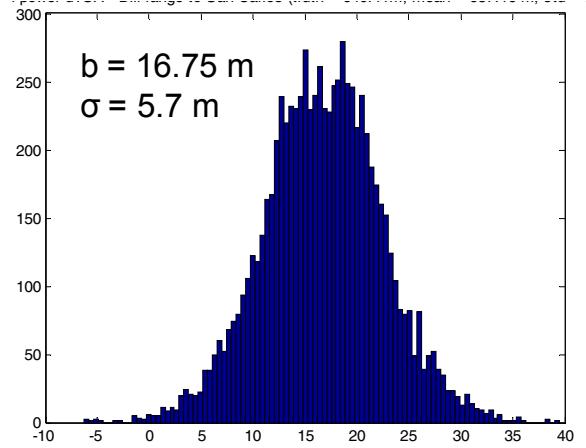


Figure 18. Histogram of Differential Time of Arrival (x axis is meters) of Mode S ES (TIS-B) from Woodside GBT (High Power, 800 m separate sites)

Figure 19 shows the result for the low power (voltage amplitude below 5000 in Figure 17). Compared to the high power case, the standard deviation is larger at 13.6 m as may be expected. Additionally, there is a 6 meter difference in error bias from the high power case. This may be because a different antenna is the source of the transmission. The GBT Mode S ES antennas can be separated by a few meters. The difference is something to be considered when using GBT Mode S ES transmissions for ranging.

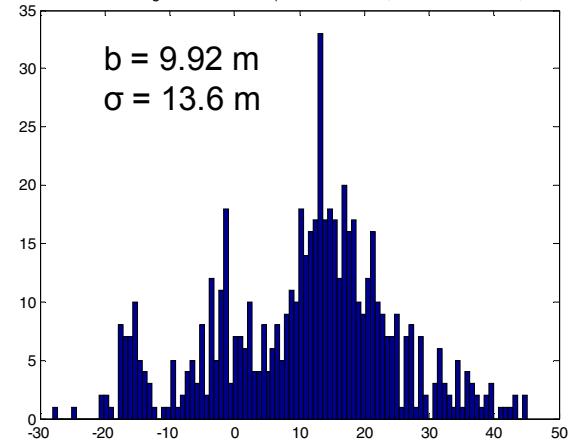


Figure 19. Histogram of Differential Time of Arrival (x axis is meters) of Mode S ES (TIS-B) from Woodside GBT (Low Power, 800 m separate sites)

We also wanted to conduct a direct comparison of UAT and 1090 Mode S ES (TIS-B) performance by examining measurements from the same GBTs at the same data collection sites. The closely spaced data collection sites shown in Figure 15 were used to analyze both signals. As mentioned before, the difficulty in using closely space sites is that it is difficult to determine which GBT provided a given Mode S ES signal. Figure 20 shows the TIS-B DTOA for this set up. The mean and standard deviation are 9.1 m and 7.2 m, respectively. The core distribution is from the Woodside GBT. While there are

many outliers, these are the result of a weaker signal from a side lobe of the Woodside GBT or from the San Jose GBT. If the analysis is limited to high signal strength signals, the “outliers” are eliminated with a reduction of bias to 6.64 m and standard deviation of 8.35 m. The results compare well with the UAT results.

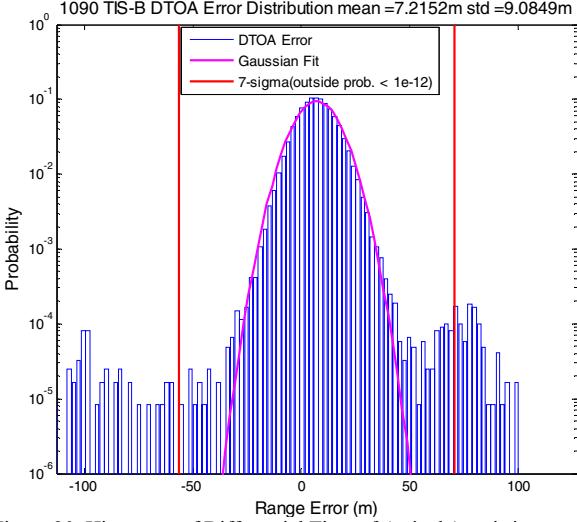


Figure 20. Histogram of Differential Time of Arrival (x axis is meters) of Mode S ES (TIS-B) from Woodside or San Jose GBT (Closely spaced sites)

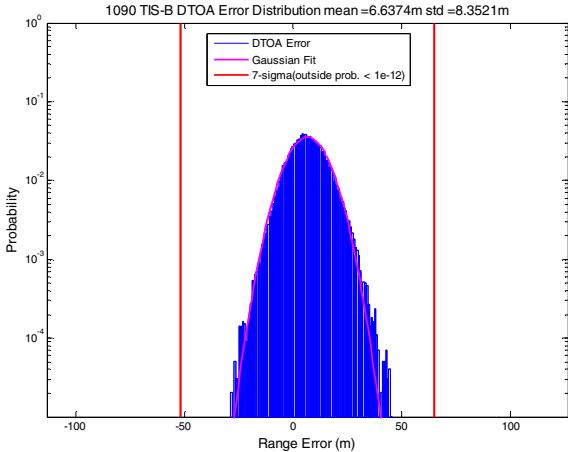


Figure 21. Histogram of DTOA (x axis is meters) of Mode S ES (TIS-B) from Woodside GBT (High Power, Closely spaced sites)

### C. UAT

A similar data collection and analysis is performed on the UAT signal. The ground message identifies the source station and the location of the station. The UAT signal was decoded to determine the GBT source of the signal. Signal strength and transmitted MSO can also be used to make the determination. Figure 22 and Figure 23 show the histogram of DTOA for UAT signal from the Woodside and San Jose GBT, respectively. The time series of the histogram data is shown in Figure 24. The expected DTOA for Woodside and San Jose are 21.6 ns (6.47 m) and 20.9 ns (6.28 m). Interestingly enough, Woodside has a larger bias (-6.81 m) and a larger standard deviation (9.69 m) than San Jose (mean of 4.14 m and standard

deviation of 8.04 m). Both distributions seem well fitted by a Gaussian with few outliers. Furthermore, note that the bias for the Woodside DTOA from UAT and TIS-B are very close, due likely to line delay and other errors in the data collection equipment.

From assessing the decoding, it was determined that the signals collected from data collection station 1 has less interference than data collection station 2. The interference is from local noise sources.

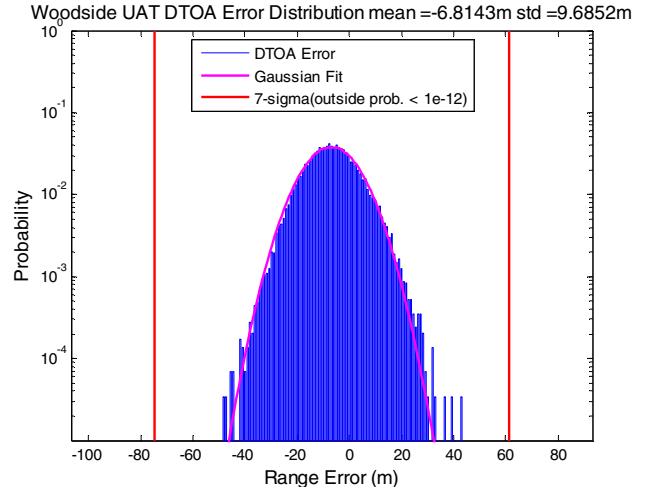


Figure 22. Histogram of Differential Time of Arrival (x axis is meters) of UAT from Woodside GBT (Closely spaced sites)

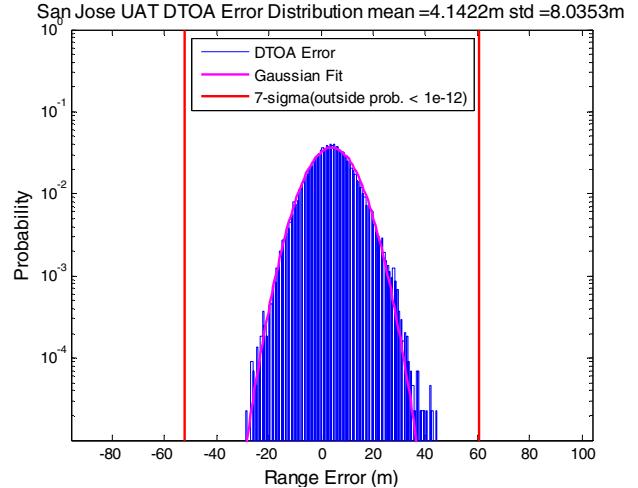


Figure 23. Histogram of Differential Time of Arrival (x axis is meters) of UAT from San Jose GBT (Closely spaced sites)

Since UAT transmissions are coordinated and synchronized to UTC, additional analysis can be conducted on the pseudo ranging capabilities of the ground transmissions. A pseudo range estimate can be made using the Equation 1 as an estimate for the time of transmission (TOT). The slot number is the ordinal of the MSO (the order of the opportunity – first, second, etc.) used by the ground segment for transmission. Having TOT and TOA, a pseudo range can be calculated for

each station. A single difference of the Woodside and San Jose pseudo ranges is used to eliminate the data collection clock error and results in a traditional time difference of arrival (TDOA). The TDOA calculated from the data at data collection site 1 is shown in Figure 25. The TDOA calculated differs from the truth by about -56.8 meters. The results show some variations with a standard deviation of 8.1 m. The variation should be indicative of how well the ground stations are synchronized as well as our measurement errors. This suggests that the ground stations are reasonably synchronized.

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

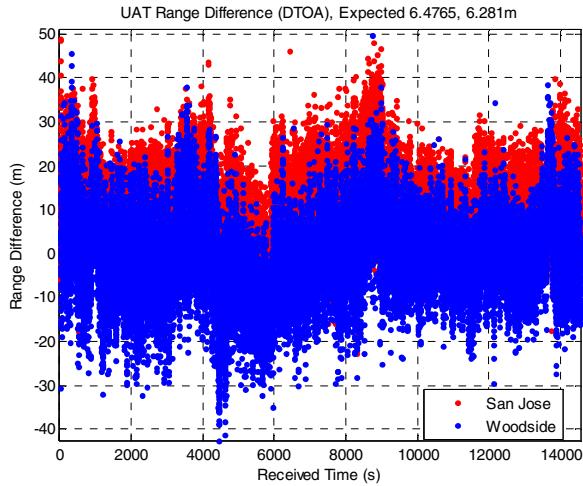


Figure 24. UAT DTOA Time Series

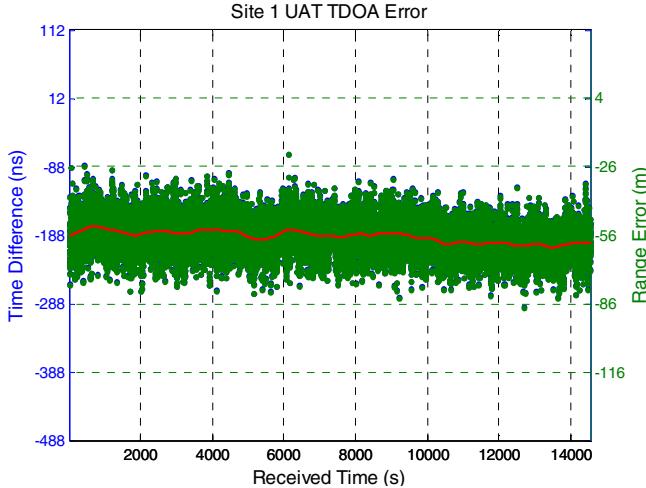


Figure 25. TDOA between Signal from Woodside and San Jose (Data Collection Station 1) [Red line is 1000 sample smoothing]

A double difference calculation can also be done to eliminate the effect of the data collection station clocks determine the precision of the UAT measurements. The calculation of the double difference is presented in Equation 2 whereby the DTOA from Woodside is subtracted DTOA from San Jose. The result is shown in Figure 26. It shows the error of the difference in DTOA from the expected value. The ideal result should be zero whereas the result has a mean around 36 ns or 11 m. The standard deviation of the result is low at 23 ns or 7 m. The result suggests that the UAT signal, without multipath, can be measured quite precisely.

ns or 11 m. The standard deviation of the result is low at 23 ns or 7 m. The result suggests that the UAT signal, without multipath, can be measured quite precisely.

$$Diff(DTOA) = DTOA_{SJ} - DTOA_{Woodside} \quad (\text{Eq. 2})$$

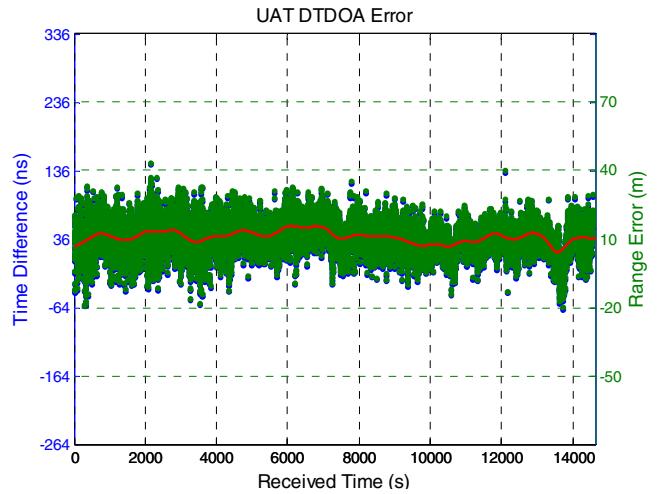


Figure 26. Mean double difference of UAT signals TOA [Red line is 1000 sample smoothing]

## V. INTERFERENCE

Interference on 1090 MHz is a major consideration. High interference and loss rates occur, especially with weaker signals. Additionally, while the evaluation has been done for surveillance but the requirements for navigation is much higher as reception of a signal is needed at three stations instead of one.

### Average Distance to 1090 Source vs. MLAT Loss of Positioning

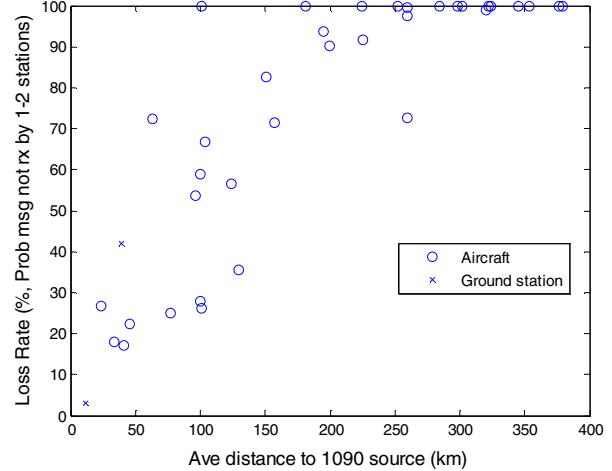


Figure 27. Probability of Not Receiving a Given Mode S Transmission at Stations 2 & 3 (Received at Station 1)

We assessed the probability of receiving a given transmission at three data collection stations located about 800

m apart. We selected the station with the lowest noise as the reference and only looked at signals that were received there. Figure 27 shows the probability that a given 1090 transmission is not received at all three data collection stations, given that it was received at the first data collection station. The probability is plotted as function of distance and is calculated using both aircraft and GBT transmissions. Each circle represents an aircraft and its average distance from the first data collection station is used for the plotting. The “x” represents the two GBTs whose distance to the data collection station is fixed.

This essentially represents an upper limit on the probability of not having a multilateration (MLAT) solution. The results show that the ability to receive a given signal falls quickly with distance. The result suggests that at ranges greater than 50 nm, multiple aircraft transmissions per second would be needed to assure a multilateration position solution.

## VI. SUMMARY & CONCLUSIONS

This paper provides an evaluation of UAT for ranging and positioning with on-air data. It provides a comparison of UAT and 1090 performance in multipath and ranging to determine the performance of the signals and how to best utilize the signals for APNT. The results of the paper indicate that both signals have good nominal accuracy comparable or better than pseudoranging using DME pseudolite (PL) [17]. Thus, combining ADS-B based pseudolite and DME PL can greatly improve the area of pseudolite service. 1090 MHz Mode S ES has better multipath performance than UAT. This is important as lower multipath error is useful for integrity which drives coverage. UAT has much lower interference, resulting in better signal availability.

These findings suggest perhaps another means of implementing pseudolites from ADS-B sources. As the signals are transmitted from the same tower, a pseudolite service based on a combination of the two signals can provide the best of features of both – good multipath performance and signal availability. Additionally, a carefully designed combination, as presented in [4], also allows for the use of both signals without increasing the amount of 1090 MHz transmissions. This is an important feature as the 1090 MHz spectrum is very congested.

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## DISCLAIMER

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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