Flight Test of Universal Access Transceiver (UAT) Transmissions to Provide Alternative Positioning Navigation and Timing (APNT)

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BIOGRAPHY

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1. INTRODUCTION

The Federal Aviation Administration (FAA) Alternative Positioning, Navigation and Timing (APNT) program is developing technical solutions to provide robust terrestrial radio-navigation for Next Generation Air Transportation System (NextGen) airspace even if GPS is unavailable.

This is particularly important because many key NextGen operational improvements are currently only supported by GPS. Additionally APNT may be useful for unmanned aerial systems (UASs) as many of these systems currently use only GPS for navigation. The APNT solution will build on existing FAA systems to provide the desired navigation capabilities. The APNT team is evaluating the Automatic Dependent Surveillance Broadcast (ADS-B) system as its offers significant possibility for navigation.

OUTLINE

This paper examines the flight performance of the Universal Access Transceiver (UAT) ADS-B signals for navigation. The paper first covers background on the ADS-B and the potential benefits of using ADS-B for aviation navigation. The main body of the paper examines our March 2015 flight test and the analysis of the UAT navigation performance. Three key areas are covered: range performance, positioning, and the effects of interference on availability/coverage.

2. BACKGROUND

The APNT group was formed to develop the promising solutions that provide FAA navigation, surveillance and other services in the event of a GPS 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.

Specifically APNT would provide capabilities beyond today's aviation terrestrial navigation system – providing navigation to the terminal area and at lower altitudes. Today's distance measuring equipment (DME) system can support one nautical mile (nm) area navigation (RNAV) accuracy or RNAV 1.0 for en route throughout much of the conterminous United States (CONUS). APNT seeks to improve on today's performance by providing 0.3 nautical mile lateral guidance or better navigation with performance monitoring and alerting at altitudes of as low as 1,500 feet (ft) above ground level (AGL). This extends terrestrial navigation services to back up to GPS for critical terminal area and approach operations.

Automatic Dependent Surveillance - Broadcast (ADS-B)

The FAA has deployed approximately 660 ADS-B ground stations, known as radio stations (RS) in the United States, including the Gulf of Mexico. This is shown in Figure 1. The stations 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. ADS-B RS transmits information on two protocols: Mode Select (Mode S) Extended Squitter (ES) on 1090 MHz and Universal

Access Transceiver (UAT) on 978 MHz [2]. 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 users, typically general aviation, who typically do not have Mode S transponders.

Figure 1. ADS-B radio stations deployed in the conterminous United States

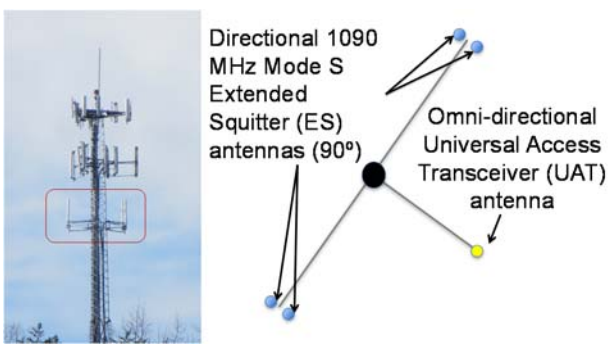


Figure 2. Leon, West Virginia ADS-B radio station on cellular tower (L) & notional antenna layout (R)

ADS-B RS are commonly installed on commercial cellular (as seen in Figure 2.) or on dedicated towers. UAT also provides weather information termed flight information services broadcast (FIS-B). An ADS-B RS typically uses one omnidirectional UAT antenna and four directional Mode S ES antenna. The Mode S ES have a 90 degree, 3 decibel (dB) beamwidth.

ADS-B for Navigation

While ADS-B was designed and deployed to support the Air Traffic Control surveillance functionality, the ADS-B infrastructure can provide coverage, accuracy, continuity and integrity benefits for navigation and APNT by helping mitigate key challenges. One challenge is to support navigation for airport terminal areas. When aircraft are closer to the ground, fewer terrestrial stations are available. ADS-B RS are, by design, not co-located with DME facilities. There are more than 600 ADS-B RS in CONUS. Our previous analysis has shown that these stations, when used with the approximately 1,100 DME stations can provide significant coverage improvements over DME alone for NextGen terminal area operations [3][4]. The combination of ADS-B RS and DME stations in CONUS is shown in Figure 3. These signals can be combined using the hybrid APNT concept [4][5] which combines pseudo ranges with true ranges.

Other challenges are the need for improved accuracy and improved resilience to multipath. ADS-B signals transmitted from the RS are also potentially more accurate than traditional DME signals. Ground [6] and flight test results presented later in this paper support this claim. Furthermore, 1090 MHz Mode S ES signals are sharper and have wider bandwidth than DME signals making them more multipath resilient [6]. Under the same multipath conditions, UAT experiences nine times the multipath error as wideband 1090 MHz Mode S ES. While UAT multipath performance in is not as good as with Mode S ES, it has half the error of traditional DME under the same multipath condition.

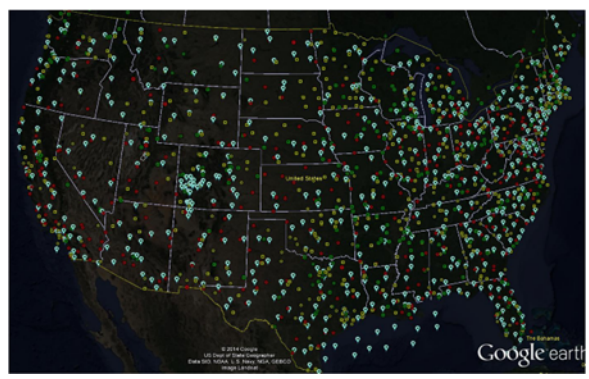


Figure 3. DMEs (squares), TACANs (circles), & ADS-B radio stations (pins) deployed in the conterminous United States

To use ADS-B for navigation, the navigation capability should be developed while minimizing changes and impact on ADS-B surveillance capabilities. Means of using ADS-B signals for navigation were examined in detail in [7][8].

UAT design allows it to be used for navigation with little to no change. The UAT transmission frame is one second long starting on the UTC second as shown in Figure 4. It is divided into two segments: Ground and ADS-B. Transmissions are only allowed to start at specified message start opportunities (MSO) relative to the start of the frame. In the Ground segment, only FIS-B transmissions from ADS-B RS are allowed. There are 32 transmission opportunities or slots for ground

transmissions. The regularly transmitted UAT FIS-B messages contain all the required information for pseudo range - station location and time of transmission (TOT).

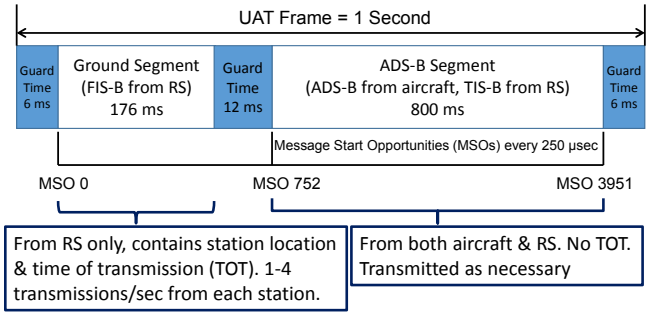


Figure 4. UAT frame & transmission structure

Each station transmits a fixed number of transmissions each second. One to four transmissions per second is sent in the surface, low, medium and high altitude tiers, respectively. This is shown in Figure 5. Each tier has designated sets of transmission slots used exclusively by that tier. Hence only stations in the same tier and using the same slot set may interfere with each other. In other words, stations serving different tiers will not interfere as they do not have slots in common. The stations are organized using a cellular layout with multiple low, fewer medium, and even fewer high altitude stations serving each region. This is notionally shown in Figure 6. The system is designed such that a user can always receive FIS-B needed for its airspace. For example, when the user goes up to an altitude where low altitude stations interfere, the user should have a medium altitude station available for data. The medium altitude station transmissions should not be interfered with by other stations and they will contain all the data from receivable low altitude stations. The design guarantees data availability but reduces available signals for ranging as it essentially designs in intra-system interference.

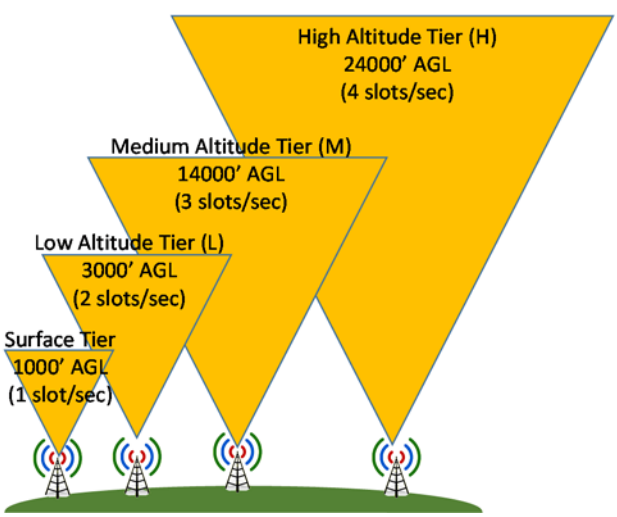


Figure 5. UAT ADS-B radio station tiers

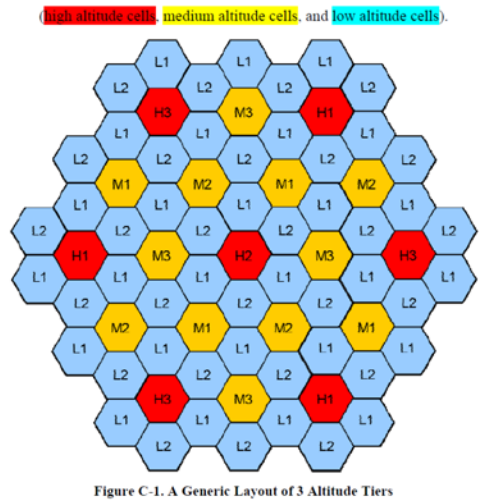


Figure 6. Notational layout of station tiers (L = low, M = medium, H = high, Number = slot set used) figure from [9]

Additionally, we have demonstrated that ground transmissions (TIS-B) from the ADS-B segment can also be used for pseudo ranging by leveraging information from the FIS-B messages [8]. Hence nearly all ground transmissions may be used for ranging without change to the message content. Some changes may be needed to support higher accuracy and integrity.

1090 MHz Mode S ES requires more significant changes to support ranging. This is because its ground transmissions generally do not contain TOT or transmitting station identity. Furthermore, its TOT is not fixed to specified time slots. Hence to use 1090 MHz Mode S ES, both TOT and station identity needs to be provided – either implicitly or explicitly. One solution is to create and transmit a new pseudo range message. However, transmitting many more messages would impact Mode S ES performance for surveillance. Since each ADS-B RS has multiple Mode S ES antennas that may have to transmit a new pseudo range message, this change could significantly increases the number of transmissions. Reference [8] details several ways for Mode S ES to provide pseudo ranging while limiting the number of additional or new transmissions.

3. FLIGHT TEST OVERVIEW

Stanford and Ohio University jointly conducted flight tests of APNT technologies in March 2015. This flight test demonstrated and evaluated key APNT technologies - enhanced DME and ADS-B for navigation. This paper examines the ADS-B subset of the tests. As seen in Figure 7, elements on both the aircraft and the ground were fielded to support ADS-B testing.

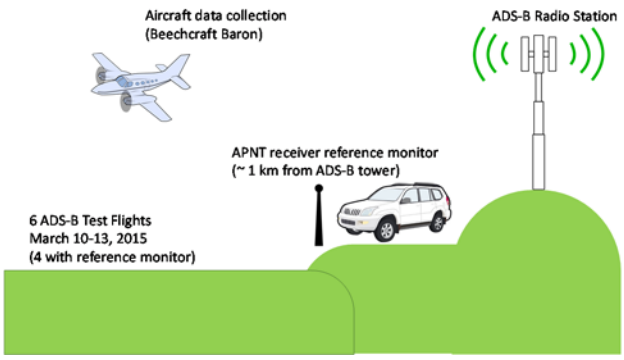


Figure 7. ADS-B elements of March 2015 flight test

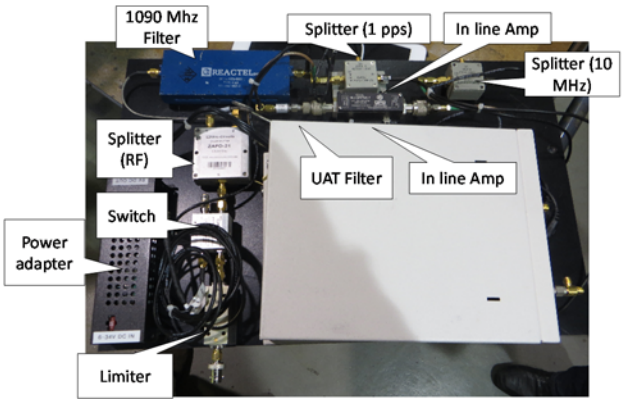


Figure 8. Airborne ADS-B collection rack shelf

The test aircraft used is a Beechcraft Baron fitted with a 19 inch avionics rack. This Ohio University aircraft test platform has been used on prior APNT testing [10]. Onboard the test aircraft was an ADS-B experiment rack shelf which contained data collection equipment for collecting UAT and 1090 raw signals samples from a DME/ADS-B antenna on the underbelly of the aircraft. The signals coming in the antenna goes through some signal protection components. One component is a limiter to suppress the effect of ownship transmissions. Another is a switch tied to the aircraft suppression bus which prevents our aircraft DME interrogations from entering into our data collection system. The signal is then split and sent to analog filters for UAT and 1090 MHz. Each signal has its own dedicated Universal Software Receiver Peripheral (USRP) using a daughter card to digitize the data, which is then sent to a data server where the raw RF is were stored for post processing by our software receiver. The USRPs are synchronized using the same 10 MHz clock input. This is shown in Figure 8. The Ohio University Robust inertial measurement unit (IMU) GPS Receiver (RIGR), which houses a Novatel OEM-V3 GPS, provides GPS observations and time tagging of the data and enables precise time of arrival (TOA) determination. We further refine the time tag and GPS position data collected using a post-processed precise GPS service such as Canadian Spatial Reference System (CSRS) Precise Point Positioning (PPP).

A ground monitoring station is used to collect reference data from selected ADS-B RSs. The monitoring was housed in a sports utility vehicle (SUV) which contain the data collection equipment racks. The ADS-B and data collection set up is nearly identical to that used by the aircraft system. Figure 9 show the equipment rack in the back of the SUV. Two different ADS-B RSs, Baltimore, Ohio and Leon, West Virginia, were measured on separate occasions.

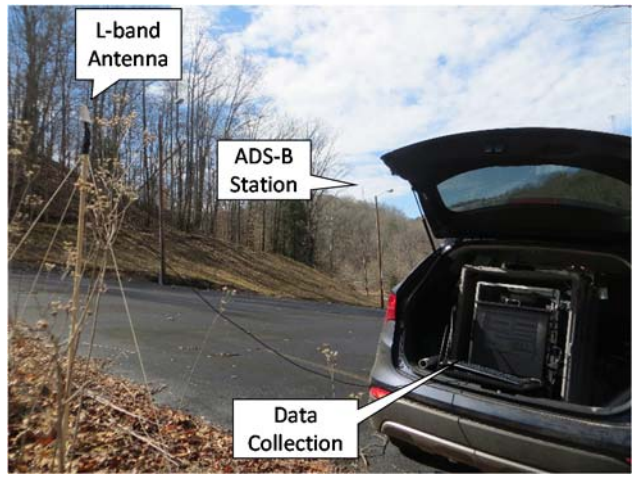


Figure 9. Ground reference station receiving the Leon, WV ADS-B radio station

Six test flights were performed from March 10-13, 2015. All six flights collected data suitable for assessing UAT performance. For four of the six flights, ground reference data were also collected. These tests are also be used for 1090 Mode S ES assessment, as the assessment requires reference measurement of TOT. This paper will focus on UAT range, position, and interference.

Figure 10 shows a map with the composite ground track of the flights along with the ADS-B radio stations observed. The flight tests were centered about Ohio University airport. Two flights were check-out flights, while others were flown to gather data in a wheel and spoke pattern about the airport at different ranges and altitudes. The inner spoke and wheel were flown at around 3,300 feet above mean sea level (MSL) and the outer spoke and wheel were flown at around 10,000 feet MSL. The cruise altitude of each flight is shown in Table 1 where AM and PM indicate morning and afternoon flights, respectively. The airport is roughly at 650 feet MSL.

The flights decoded UAT broadcasts from stations Ohio (OH), Kentucky (KY), West Virginia (WV), Virginia (VA), Michigan (MI), Pennsylvania (PA) and Tennessee (TN). These stations are shown in the figure with low,

medium and high altitude ADS-B UAT RS denoted by blue, yellow and red markers, respectively.

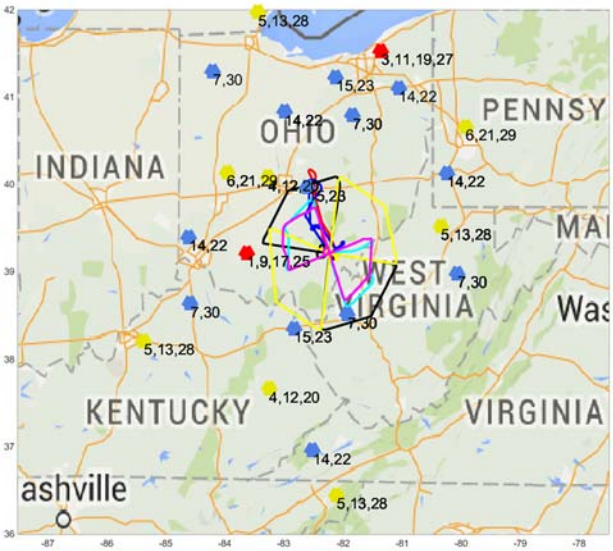


Figure 10. Test flight paths and ADS-B RS decoded (with slot numbers indicated)

Table 1. March 2015 flight altitudes (* indicates no ground reference measurements)

Date/Time	Cruise Altitude (MSL) ft
March 10 AM*	6000-7000
March 10 PM	4000-5000
March 11 PM	10500
March 12 AM	3300
March 12 PM	10300
March 13 AM*	3300

4. ANALYSIS OF UAT PERFORMANCE

The flight test data allows an examination of UAT performance not generally possible with ground testing. We assess range accuracy from multiple stations at a variety of ranges and altitudes. As multiple ranges are available, UAT position and position availability can be assessed. Finally, intra-system interference and its impact are assessed. This interference is only visible at altitudes where multiple stations can be received.

Range Decoding

The UAT signal is modulated through continuous phase frequency shift keying (CPFSK) with the signal frequency varied by ±312.5 kHz. CPFSK keeps the transmitted energy mainly within a one MHz DME channel. An increase of 312.5 kHz (Δf/2, following the nomenclature used in [11]) indicates a "1" bit while the same decrease indicates a "0" bit. Each UAT transmission uses a synchronization header consisting of 36 0.96 µsec long synchronization bits. The synchronization bits used for the ADS-B segment are the inverse of those used in the ground segment. The FIS-B message consists of a total of 4,452 bits with a payload of 3,456 bits after forward error correction (FEC).

TOA is estimated by forming a phase replica of the transmitted signal, correlating the replica with the incoming signal and finding the peak correlation. The 36 synchronization bits are typically used for the replica. However, given that we have a software receiver that can replay the data, we can also decode the full message and generate a replica of the full 4,452 bits. The FEC helps ensure that the replica bits are correct.

We compare the performance of using the two different replicas on the ground reference data. Two different ADS-B RS (Leon, WV and Baltimore, OH) were examined. Figure 11 shows the measured TOA when using full message and synchronization bits replicas. Using the full message resulted in less variation in TOA.

In conducting the analysis, we also found that the measured Δf/2 differed by from the nominal by about 4% with Δf/2 being about 299-300 kHz. Both stations exhibited this difference with slightly different Δf/2. We are taking additional measurements to examine this issue. The difference may degrade decoding but is likely not a significant data issue. It could have more significant effects on range error. As we do not know the deviation for each station, for our analysis, we still used the nominal Δf/2 for our replica signal.

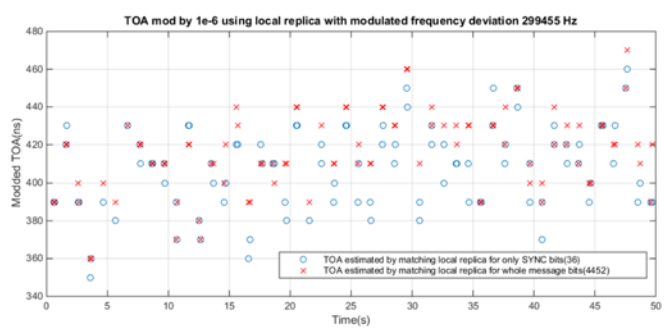


Figure 11. Measured TOA when using full message and 36 bit sync replicas

Accuracy

Range accuracy is calculated done by comparing the measured propagation time of the UAT FIS-B signal to the expected propagation time. Measured propagation time ($t_{prop,meas}$) is determined from the difference of measured TOA (TOA_{meas}) compared to the indicated TOT (TOT_{ind}) of the signal. The expected propagation time ($t_{prop,expected}$) is calculated using the range between the post-processed GPS position of the aircraft (xyz_{ac}) and the surveyed location of the ADS-B station (xyz_{adsb}). The expected propagation time also accounts for troposphere

delay (Δ_{tropo}) using the Millman model [12] and assuming 100% humidity. This expected time represents the truth value and the range error is the difference between measured and expected propagation times. The basic calculations are seen in Equations (1) and (2).

$$t_{prop,meas} = TOA_{meas} - TOT_{ind} \quad (1)$$

$$t_{prop,expect} = (\|xyz_{ac} - xyz_{adsb}\|_2)/c + \Delta_{tropo} \quad (2)$$

The resulting range error comes from errors introduced by processing, noise, multipath, equipment bias, GPS derived position, ADS-B station survey position and RS clock. Some of the equipment bias can be eliminated by removing the average bias from all stations. Figure 12 shows the range error after removing the average bias. Even with this removal, the range error will still contain some bias, albeit much smaller and mostly due to clock error on each ADS-B RS. In the figure, there are outlier error points that are several standard deviations from the mean. The cause of the outliers is an integrity issue and is being investigated.

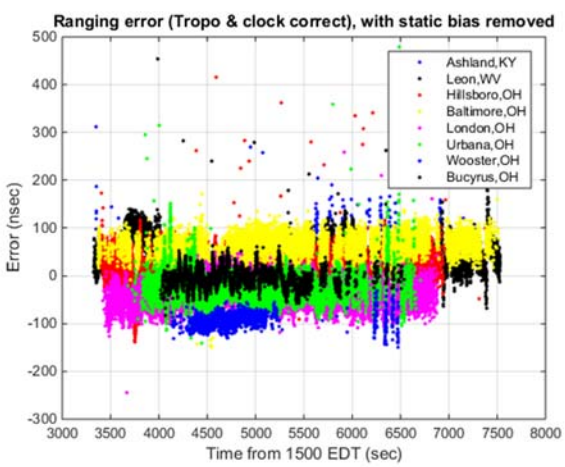


Figure 12. Range error from March 10, 2015 PM flight

From this data, the mean and accuracy (two standard deviations) of range error for each station on each flight is calculated. Figure 13 shows the location of the ADS-B RS seen in the analysis. Table 2 shows the mean, relative to the average bias over all stations, and the accuracies (two standard deviation or 2 σ) of the range error for the March 10 afternoon flight. This flight is at low altitude and the stations visible are generally within about 120 kilometer (km). The accuracy is around 20 m. Table 3 shows the accuracy for all six flights. As suggested by the greater number of stations measured, the March 11th and 12th afternoon flights were conducted at a higher altitude over a longer distance. The range errors in these flights are slightly larger than the other. Stations on these flights can be received at larger ranges. Additionally, there is more intra system interference on these flights. Overall range accuracy typically measured between 20-30 m. However, this does not consider the bias errors which will exist partly because of ground station clock differences.

Table 2. UAT range error on March 10 PM flight

Station	Mean (m)	Accuracy (m; 2 σ)
Ashland, KY	38.5	21.0
Leon, OH	10.4	24.9
Hillsboro, OH	3.2	19.6
Baltimore, OH	-3.2	26.1
London, OH	-19.7	16.9
Urbana, OH	-0.9	22.5
Wooster, OH	-28.9	15.4
Bucyrus, OH	1.5	16.2
Baltimore, OH (Ref)	-	12.6

Table 3. UAT range accuracy (m, 2σ), March 2015 flight tests

Station	3/10 AM	3/10 PM	3/11 PM	3/12 AM	3/12 PM	3/13 AM
Elizabethton, TN			26.7		24.0	
Wise, VA			23.2		16.7	
Jackson, KY			30.3		22.3	
Louisville, KY			18.0		18.5	
Ashland, KY		21.0	28.1	20.9	44.1	19.6
Leon, WV	17.6	24.9	26.4	27.5	18.6	25.4
Falmouth, KY					24.9	
Philippi, WV			22.6		15.6	
Hillsboro, OH	17.6	19.6	38.2	22.0	37.6	23.7
Hamilton, OH			32.5	18.8	31.3	22.0
Shinnston, WV	21.0		32.4	17.9	28.6	17.6
Baltimore, OH	27.5	26.1	29.7	23.2	19.0	23.6
London, OH	16.1	16.9	29.5	20.9	28.5	20.7
Washington, PA			20.0		20.0	19.8
Urbana, OH	17.7	22.5	29.3	32.8	30.6	19.2
Butler, PA			19.8		26.7	
Wooster, OH	18.4	15.4	23.2		15.4	
Bucyrus, OH	18.6	16.2	27.5	20.4	20.8	18.7
Cleveland, OH			26.8		22.5	

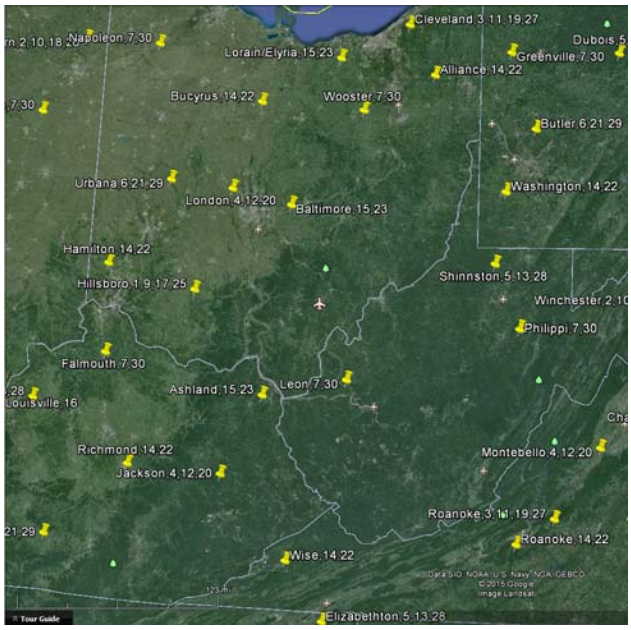


Figure 13. ADS-B radio stations in vicinity of flight test

Interference

The flight test also allowed us to examine the effects of intra-system interference due to transmission slot allocation. This interference was seen in the air and Figure 14 shows an example of the interference between the signals from two UAT stations in the time domain.

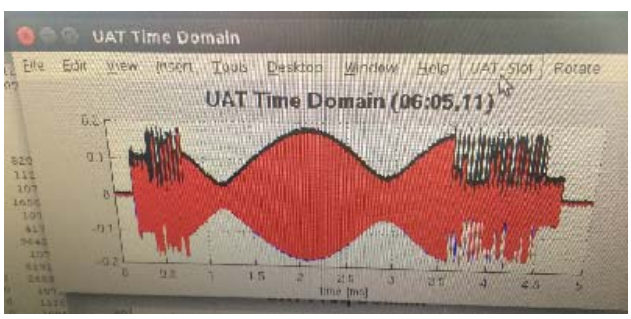


Figure 14. Interference between two UAT FIS-B (Time Domain)

In the flight test, signals are received from many stations, most of which are low altitude tier stations. Figure 15 shows the flight paths, the stations received and their assigned slots numbers. Stations having the same slot numbers can interfere with each other. The blue, yellow and red indicate low, medium and high altitude tier stations respectively. For low altitude stations, there are several stations that use the same set of slots, roughly four in the flight area shown. There are far fewer medium altitude stations using common slots. The figure shows stations using the same slots in the same shade of blue or yellow. For the high altitude stations, no common slot numbers were in the vicinity.

Figure 15. Test flight paths and ADS-B RS decoded (with slot numbers indicated); ADS-B RS sharing the same slots are circled with the same shade of color

Interference Effects on Coverage

The key questions to address are 1) "how much does the interference affect coverage?" and 2) "what is the operational effect of the reduced coverage?" The extent of the interference is examined by looking at the range at where message losses become significant. Figure 16 shows the average number of messages decoded as a function of distance for the March 10th afternoon flight. The figure shows the average for all low and medium altitude tier stations decoded and the top line indicates how many seconds of data are available for the average. Recall that for low and medium altitude stations, receiving all messages means having 2 and 3 messages per second, respectively. On the low altitude plot, there are three instances where the messages decoded drop off from full reception value. The drop off around 40-60 kilometer (km) is traced to aircraft maneuvers. At 80 km, one station starts exhibiting interference. The interference occurs at a range of 120 km for other stations. This is seen in the increase back to nominal at 100-110 km and the decrease thereafter. For the medium altitude stations, a sharp drop off is seen around 150 km out. This is likely due to line of sight limitation. At 4000 ft MSL, there should be little or no interference on the medium altitude stations.

Figure 17 shows a similar plot for the March 11 afternoon flight. This flight occurs at about 10,500 feet where greater interference occurs for the low and medium altitude stations. For low altitude stations, the average messages per second drops from its ideal value around 80 km. For medium stations, the coverage is good up to 140 km which is a little worse than seen in Figure 16. This is

expected, as there should be more medium altitude station interference since the aircraft is at a higher altitude.

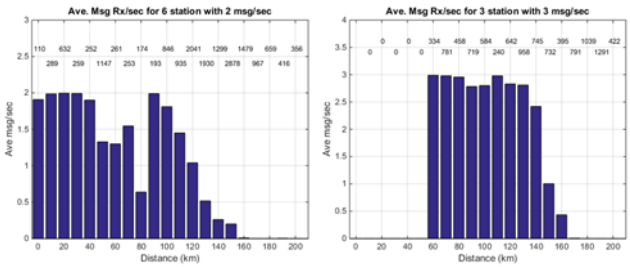
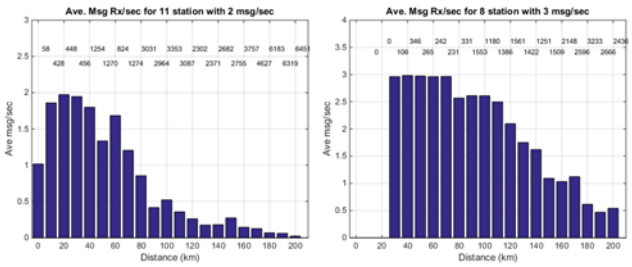


Figure 16. Average number of messages decoded per second versus distance for low (left, 100% = 2 msg/sec) and medium (right, 100% = 3 msg/sec) altitude tier stations (March 10, 2015 PM); Top number indicates seconds of data are available for the average



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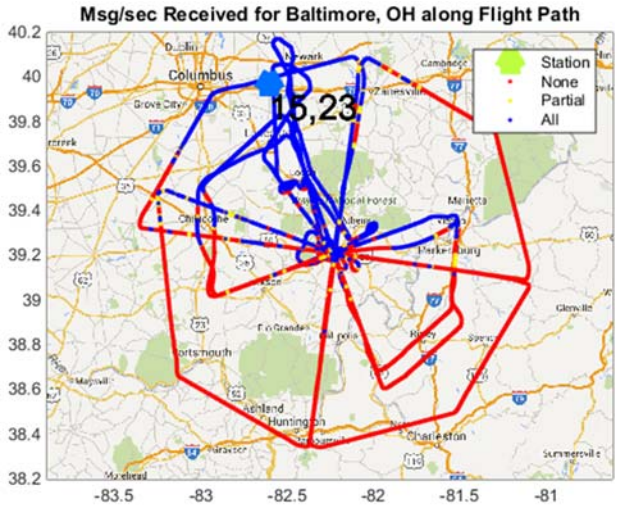

Figure 18. Reception of Baltimore

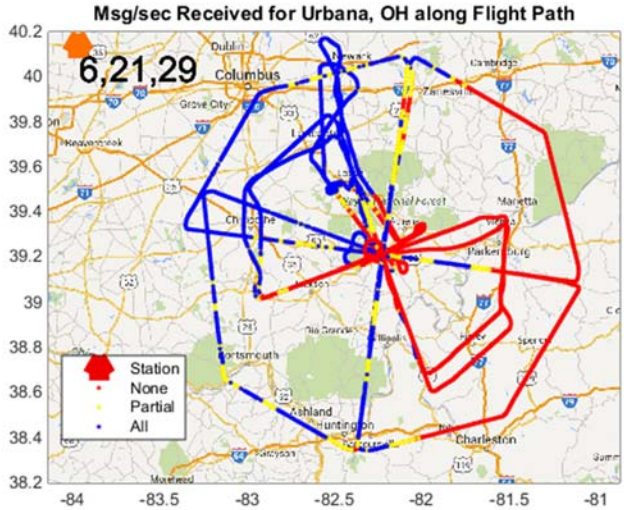

Figure 19. Reception of Urbana, OH station

The coverage difference can be seen in Figure 18 and Figure 19 which shows the reception of a low (Baltimore, OH) and medium (Urbana, OH) altitude, respectively. The plots show where the aircraft and received all, some (partial) or none of the signals from that station. The coverage area of the medium altitude station is significantly larger than that of the low altitude station.

A key reason for using ADS-B is to have more ranging signals at low altitude. The radio horizon limits the reception of signals at range and hence may limit the impact of the most distant interference source(s) on coverage at low altitude. Using a 4/3 earth radius smooth earth propagation model, we calculate the minimum altitude for which a signal is receivable at various distances from the source. The calculation provides the relationship between distance from the source of an interfering signal and the minimum altitude at which interference is experienced. An example of the result is shown in Figure 20 which assumes the interference source is on a 50 m tower. As an example, the circled point on the figure shows that an aircraft should only potentially experience interference from a tower 100 km away at an altitude of at least 640 m (2130 feet) altitude or higher.

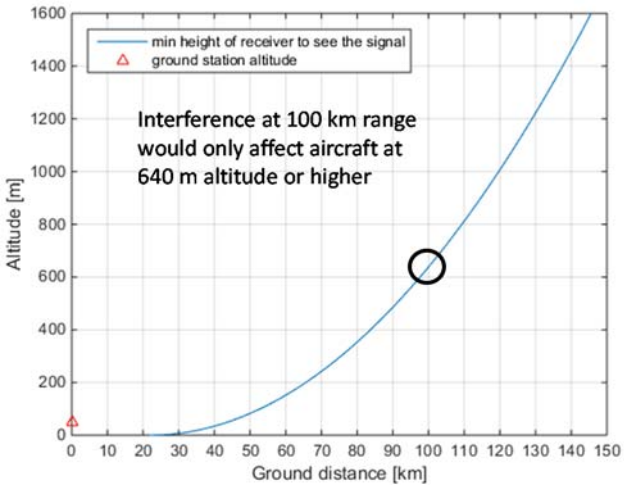

Figure 20. Minimum altitude at which an L-band signal is in radio line of sight from a 50 m tower vs. distance from the tower (4/3rd earth radius model)

Positioning

The flight altitudes and relatively flat terrain of Ohio means that signals from multiple ADS-B radio stations can be received even at reasonably low altitudes. This is sufficient for positioning even at altitudes of 3000 feet MSL or lower. Figure 21 and Figure 22 show the number of stations where we measure pseudo range for the flights on March 11 PM (~3300 ft MSL) and March 13 (~10500 ft MSL), respectively. Comparing the figures, the number of pseudo ranges/stations are measured increases at higher altitudes.

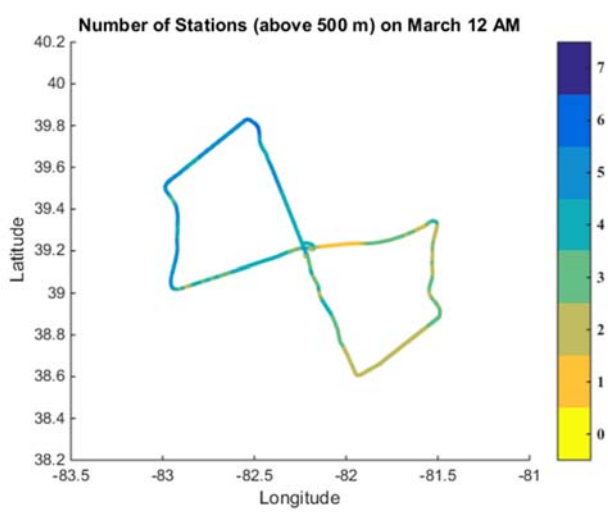

Figure 21. Pseudo ranges measured on March 12 2015 AM flight at 3300 ft MSL

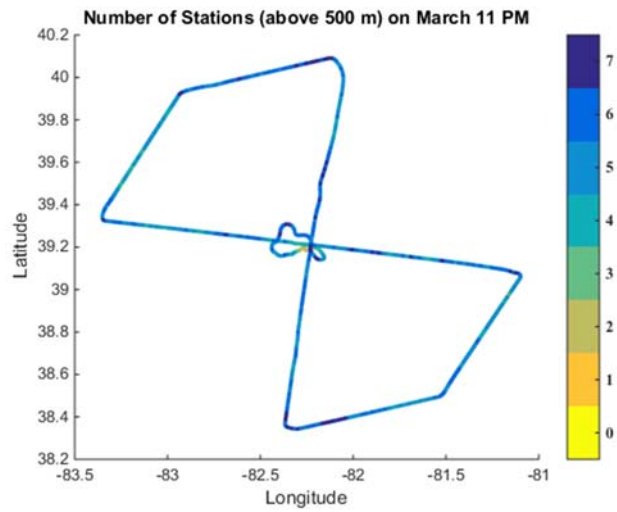

Figure 22. Number of Stations/Pseudo ranges measured on March 11 2015 PM flight (cruise at 10500 ft MSL)

An initial assessment of positioning was conducted using two position solution methods: 1) Bancroft method and 2) an iterative solution [13]. Bancroft method is a closed form positioning solution whereas the iterative solution requires an initial guess for position. The iterative solution is sensitive to the initial guess and a poor guess can cause the method not to converge to a solution. In the analysis shown in this paper, we examined two methods: 1) a hybrid of the two methods where the closed form solution to get an initial position estimate for an iterative solution [13][14] and 2) the iterative method with an initial guess used was the true location offset by about 7000 meters horizontally.

APNT signals only need to provide a horizontal positon solution as a barometric altimeter will provide the altitude information. Bancroft methods and the iterative solution method were adapted to take an externally provided altitude and solve for the horizontal position and time with only three measurements. Our adapting Bancroft's method required an estimate of the clock bias.

Figure 23 and Figure 24 show the positions from GPS, UAT with hybrid solution from March 12 AM (3300 ft MSL) and March 11 PM (10500 ft MSL). At 3000 feet MSL, there are some parts of the flight where a position could not be calculated as there were fewer than three signals. For flights at 10,000 feet generally had no problem with having adequate number of signals for positioning. The increase in available signals from increasing altitude more than offsets the losses due to increased interference.

Figure 23. Position results using GPS, UAT (Iterative based on close initial guess) March 12 AM flight (Minimum altitude of 300 m AGL)

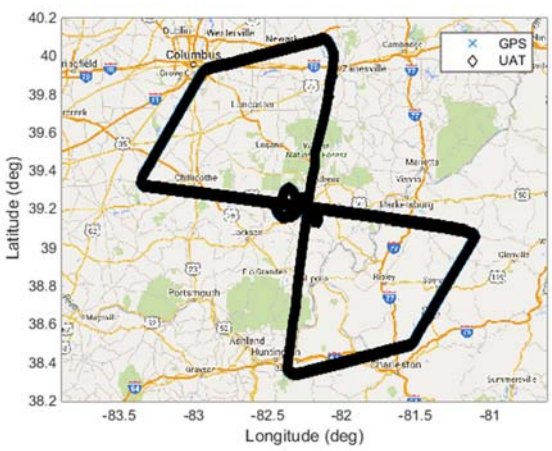

Figure 24. Position results using GPS, UAT (Iterative based on close initial guess) March 11 PM flight (Minimum altitude of 300 m AGL)

Figure 25 shows the distribution of the error in horizontal position when solved using the iterative method with a close initial guess for flights in the previous paragraph. The solutions shown have to be converged solutions. Furthermore, the solution has to have dilution of precision (DOP) less than 10 and be within 10 km of the actual point is used. The former criteria rules out cases of poor geometry. The latter eliminates solutions that converge to a different minimum or that are influenced by an outlier pseudo range. These requirements seem reasonable, as the navigator should have a previous solution that is within a short distance of the current position. The resulting accuracy is less than 100 m. The position errors are generally similar when using the hybrid methodology. However, there are some instances where the Bancroft solution produced poor initial guesses. As a result, these outlier instances had large position errors resulting in poorer error statistics.

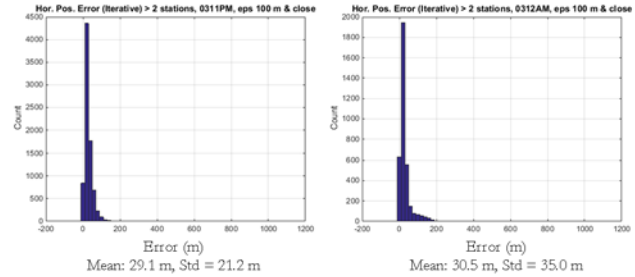

Figure 25. Histogram of position error from March 11 PM (left) and 12 AM (right) flight; Limit DOP < 10.

5. 1090 MHZ MODE S ES RANGING

The third effort in this flight test was the examination on 1090 MHz Mode S Extended Squitter for navigation. Similar to UAT, we want to examine the use of Mode S ES range and data at altitude. The challenge with Mode S ES is that the ground transmissions are not synchronized nor do they contain time of transmission. Hence to study this signal, we needed a ground reference station near the ADS-B ground station to measure the TOT. The processing of the 1090 MHz Mode S ES requires combining and correlating our ground station with our air data.

The measurement is complicated by use of four directional Mode S ES antenna at each ADS-B RS. As the neither the transmitting station nor the antenna is identified, the aircraft and ground may be receiving the same message from different antenna. Additionally, antennas may cause interference and errors. This factor may contribute to some of the errors seen in our results.

Correlation of Error with Azimuth

Ranging assessment is conducted by calculating time differences of arrival (TDOAs). First, messages from the aircraft and the ground reference station are matched using TOA and message content. For matched messages, the GPS tagged TOA from the ground ($TOA_{meas,gs}$) is subtracted from that of the aircraft ($TOA_{meas,ac}$) to get the measured TDOA ($TDOA_{meas}$). The expected or "truth" TDOA ($TDOA_{true}$) is calculated using the GPS position of the aircraft (xyz_{ac}), surveyed position of the reference station (xyz_{gs}) and the ADS-B RS position from the survey database (xyz_{adsb}). Again, the troposphere delay is factored into the truth result. The basic calculations are presented in Equations (3) and (4).

Figure 26 shows the resulting error as plotted as a function of the azimuth from the ADS-B station to the aircraft. The error is larger than expected from theory and previous static tests. The error also changed linearly in time and has correlation with azimuth. The correlation

with azimuth seems to suggest an issue with antenna and reception rather than the signal itself. More assessment is required.

$$TDOA_{meas} = TOA_{meas,ac} - TOA_{meas,gs} \quad (3)$$

$$TDOA_{expect} = \left[\frac{(\|xyz_{ac} - xyz_{adsb}\|_2)}{c} + \Delta_{tropo,ac}\right] - \left[\frac{\left(\|xyz_{gs} - xyz_{adsb}\|_2\right)}{c} + \Delta_{tropo,gs}\right] \quad (4)$$

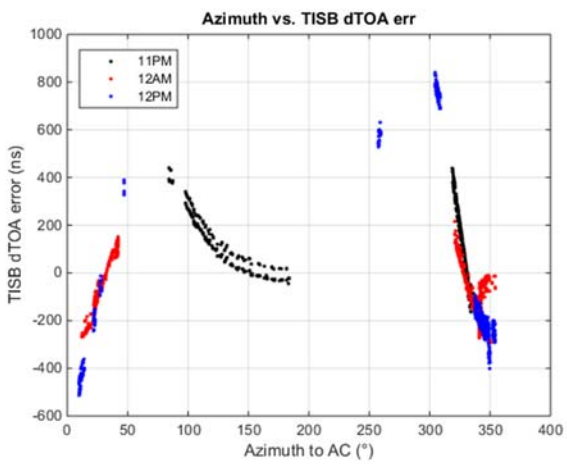

Figure 26. 1090 MHz Mode S ES TIS-B time difference of arrival error vs. azimuth from ADS-B RS to aircraft

6. CONCLUSIONS

This paper demonstrates the use of FAA ADS-B radio stations for ranging and positioning potentially suitable for navigation in a flight scenario. The flight test demonstrated actual performance in air and provided measurements of intra-system interference. Nominal accuracy of UAT in the air compares well to DME. UAT interference effects are seen. Analysis demonstrates the interference decreases coverage, especially for the low altitude tier station. The loss is ameliorated by the fact there is less interference at low altitudes where improved coverage is most needed. The first UAT only positioning that we know of was performed and achieved better than 100 m position accuracy. The positioning results showed that at 10,000 feet, there are plenty of other UAT signals to make up for signals lost to interference. However, interference should be an integrity consideration when treating a signal for navigation.

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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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