Using Traffic Information Services Broadcast (TIS-B) Signals for Aviation Navigation

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1. INTRODUCTION

Airspaces around the world are introducing capabilities and infrastructure to handle higher traffic densities. Highly capable satellite based navigation is being adopted to help aircraft operate more efficiently in the future. Furthermore, Automatic Dependent Surveillance Broadcast (ADS-B), where aircraft and other users broadcast their precise position, velocity and intent, is being introduced to help manage these airspaces. This allows air traffic and other aircraft to have excellent awareness of the airspace users. Adoption of new systems and technologies will only intensify as future airspaces will have to handle more varied traffic such as unmanned aerial vehicles (UAV).

GNSS is critical to both future air navigation and ADS-B. Many of improvements in future airspace are primarily achieved with GNSS. This makes a robust, accurate terrestrial alternate essential should GNSS be unavailable. This paper examines using the Traffic Information Services Broadcast (TIS-B) service that is part of ADS-B implementation to provide terrestrial navigation. TIS-B would broadcast an aircraft position report generated using radar measurements. Conceptually, an aircraft may be able to use the reception of its own TIS-B report to provide knowledge of its position. This paper provides an overview of the concept and of the potential capabilities of the system.

2. BACKGROUND

ADS-B is the aircraft transmission of its position, velocity or intent. The transmissions are received by ADS-B radio stations (RS) and used air traffic to management the airspace. They can also be received by any aircraft with an ADS-B receiver to improve situational awareness. Several related services are also sent using the same channel. The radio stations station rebroadcast ADS-B transmissions. This is termed ADS-Rebroadcast (ADS-R) and is needed because, in the United States ADS-B can be transmitted two different protocols. The RS also transmit TIS-B which is the broadcast of air traffic information gathered by ground radar or other means available to the ground. This provides information on the position of aircraft that are not transmitting ADS-B.

TIS-B/ADS-B is supported multiple protocols. One protocol uses 1090 MHz and the existing Mode S ES format. 1090 MHz is used internationally for secondary surveillance radar and transponders. Mode S ES ADS-B has the benefit of being a worldwide standard with installed ground equipment. The second protocol used in the United States (US) is Universal Access Transceiver (UAT) on 978 MHz. This is a new protocol designed for ADS-B using a dedicated frequency. However, UAT is not used across the world.

1090 MHz Mode S ES

1090 MHz has traditionally been used by transponder systems serving secondary surveillance radars (SSR) and traffic collision avoidance systems (TCAS). This frequency was used to support several standards for the aircraft transponder transmissions such as Mode A, C, and S. Mode A and C are considered part of the air traffic control radar beacon system (ATCRBS) and provide aircraft identification and altitude, respectively. They support SSR operations. While Mode S is not considered an ATCRBS transmission, it also supports SSR. Mode S is also used for TCAS.

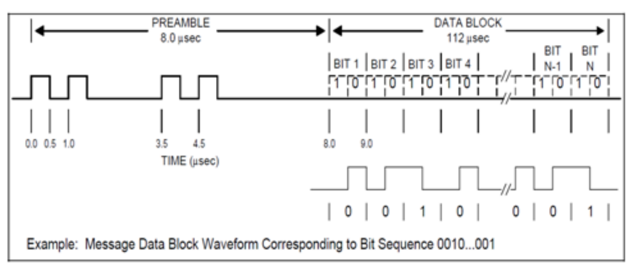

Figure 1. Mode S ES Waveform [1]

Mode S is modulated using on-off keying (OOK). Each bit is transmitted over 1 microsecond (μs) with the transmission on during either the first or second half of the period. If the transmission on during the first half than the data bit is "1" [1]. Basic Mode S has a 56 bit data payload. Mode S Extended Squitter (ES) is an extension of Mode S that provides 112 bits of capacity per message with 88 bits useable by payload and 24 bits for parity. The Mode S ES waveform is shown in Figure 1. Despite the increase bandwidth, two Mode S ES messages are needed to fully communicate position using the Compact Position Report (CPR) format. This assumes no knowledge of position. With coarse knowledge of one's position (roughly the continent where one is located), only one CPR message is needed [1].

The Mode S ES protocol was selected for use by ADS-B. Mode S ES signal is a desirable because it is internationally adopted and used. Because of this, commercial aviation generally will adopt Mode S ES as their means of implementing ADS-B.

Universal Access Transceiver

The UAT protocol was developed specifically for ADS-B and is being supported in the United States [2]. Unlike ADS-B on 1090 MHz, it is on a frequency solely dedicated to ADS-B (978 MHz) and was designed from the ground up to support ADS-B. It organizes the channel into 1 second long frames and specifies slots separated by250 millisecond (ms) where transmissions are allowed to start. The last 800 ms of the frame is termed the ADS-B Segment and is dedicated to ADS-B and TIS-B transmissions. This is the segment of interest for this paper. The Ground Segment occupies 176 ms at the beginning of the frame and is reserved for ground transmission of weather information. There are 24 ms in each frame that serve as buffers between the segments.

Two types of transmissions are sent in the ADS-B Segment. Either a basic or a long message can be sent. This is seen in Figure 2. The basic and long UAT transmissions contain a total of 276 and 420 bits, respectively. This allows a data payload of 144 and 272 bits for the basic and long messages, respectively. All UAT transmission use continuous phase frequency shift keying (CPFSK) with each bit occupying 0.96 µs.

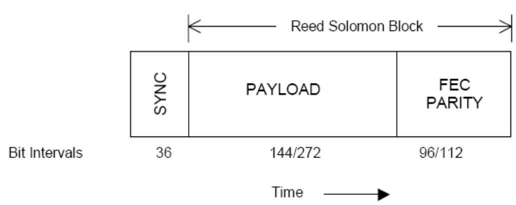

Figure 2. UAT ADS-B Segment Transmissions [2]

While any user can adopt UAT for ADS-B, the protocol has been primarily targeted at general aviation (GA) who generally are not equipped with Mode S transponders.

ADS-B Implementation

The ADS-B infrastructure is being field around the world. The build out of the ADS-B ground infrastructure and radio stations (RS) has been completed in the conterminous United States (CONUS). Figure 3 shows the 601 operational stations in CONUS. These ADS-B radio stations use either a dedicated tower or share an existing cellular tower. As such, they are not collocated with other ground assets such as distance measuring equipment (DME) or VHF omnidirectional ranging (VOR). The setup provides geometric diversity should ADS-B and DME be combined for ranging. Figure 4 shows the ADS-B radio station on a cellular tower in West Virginia, US and the general configuration of a US ADS-B RS. A RS typically has four directional Mode S ES antennas and one omnidirectional UAT antenna.

ADS-B has been implemented on many aircraft in the US and around the world. In the US, aircraft operating where Mode C transponders are currently required are mandated to carry ADS-B by 2020 [3]. This is essentially all controlled airspace, with the exception of some Class E airspace.

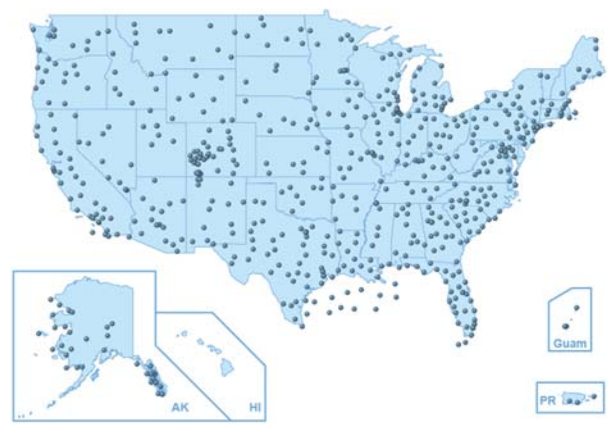

Figure 3. Installed ADS-B Radio Stations in CONUS

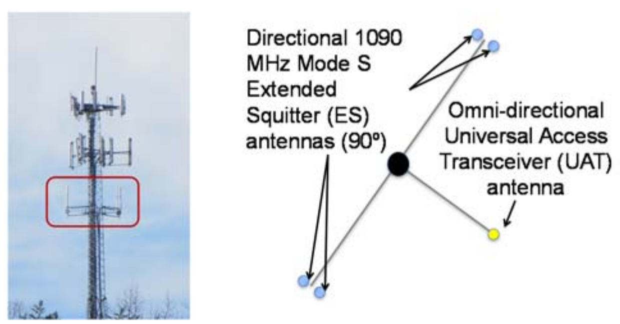

Figure 4. ADS-B on a Cellular Tower (Right) and Notational ADS-B Radio Station Set Up (Left)

Alternative Positioning Navigation & Timing (APNT)

APNT is a Federal Aviation Administration (FAA) program to provide robust navigation for aviation in case of GNSS degradation [4]. APNT will leverage existing ground navigation infrastructure as these provide a high power, interference resistant navigation of source. APNT will improve upon the capabilities of today's ground infrastructure to support future operations that are being enabled by GNSS.

APNT is important for ADS-B. ADS-B depends on aircraft having good knowledge of their position and velocity. Currently, the only approved source for ADS-B information is GNSS. However, should GNSS go away, an additional accurate positioning source is necessary to retain ADS-B and its benefits.

While APNT can benefit ADS-B, ADS-B can be beneficial for APNT. ADS-B offers several possibilities for aviation navigation. It can provide a pseudo ranging signal. This capability can be used stand-alone navigation or supplement other aviation signals such as distance measuring equipment (DME). The addition of ADS-B ranging to DME can greatly improve coverage at lower altitudes and help serve terminal areas. ADS-B transmitted from aircraft can be used to provide a ground calculated position solution through the use of multi-lateration. Finally, TIS-B can send aircraft positions derived from multi-lateration or radar tracking to aircraft for navigation. This paper focuses on this later alternative. The other alternatives are also been studied [5][6][7][8]. These have been evaluated for their potential to effectively contribute to a robust aviation navigation infrastructure.

TIS-B for Navigation

The concept of TIS-B for Navigation is to use existing surveillance operations, which generate aircraft position reports, based on radar measurements to provide navigation. This was suggested within the FAA as a means of providing position to aircraft using an existing service. TIS-B broadcasts position reports for aircraft from ADS-B RS. These positions are derived from radar measurements, typically SSR and extrapolated to the current time. SSR gather both range and azimuth from all aircraft as every aircraft is required to have a transponder. SSRs rotate every 5 or 12 seconds depending on the type resulting in regular measurements for each aircraft. The radar information is then passed onto the TIS-B service provider, which amalgamates the information to provide position. A tracker extrapolates the measured aircraft position to the time of applicability (ToA). The ToA is roughly the time that the FAA receives the position report at the Service Delivery Point (SDP). The report information is then disseminated to the ADS-B RS for broadcasts. TIS-B reports are only sent as necessary. Currently, TIS-B reports are sent only for aircraft not broadcasting their ADS-B position and only broadcast by ADS-B RS covering the airspace affected by that aircraft. Furthermore, the information is sent only if another aircraft can utilize that information. The TIS-B operational flow is shown in Figure 5.

Hence, no additional equipment is nominally needed to support a TIS-B for navigation service. The TIS-B system already generates aircraft position and broadcasts them. TIS-B operations may need to be modified so that the criteria for broadcast ensures that all aircraft not reporting position, even if they are equipped with ADS-B, have their positions transmitted. Additionally, there may need to be some assurance on performance – particularly integrity of the position report. While TIS-B for navigation may not serve all aircraft, it may be able to serve as an APNT for general aviation and other users that do not carry DME/DME or DME/DME/Inertial. Table 1 shows the performance target for a TIS-B. As RNAV is a specification on total system error (TSE), navigation system error is only allocated part of the error budget.

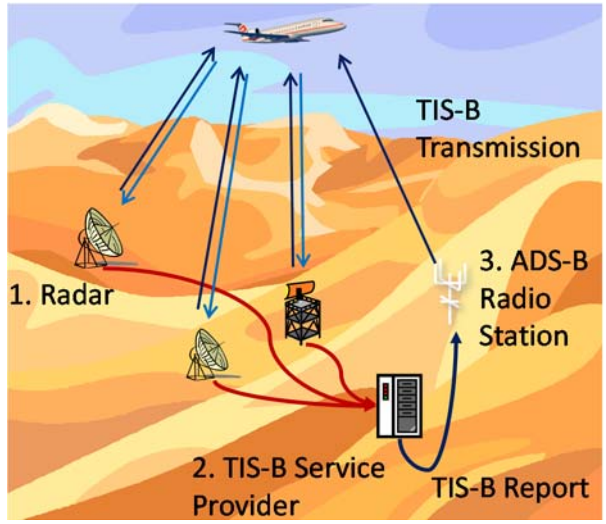

Figure 5. TIS-B Operational Flow

Table 1. Target Performance of TIS-B for Navigation

Performance	Target
Accuracy	RNAV 1.0 requires ~ 1600 m accuracy RNAV 0.3 requires < 556 m (307 m) accuracy
Availability	To be determined
Coverage	En route airspaces
Integrity	To be determined
Capacity	General aviation without DME/DME

Flight Test of TIS-B for Navigation

The APNT program desired an assessment of the real world capabilities of TIS-B for navigation. However, the budget and time available for the evaluation was limited. This presented an opportunity to see if commercial off the shelf and smartphone technologies could provide useful data for the analysis as these technologies can be utilize with low cost and with minimal installation. We had a flight of opportunity from a private Piper Saratoga II (shown in Figure 6). This was flown in the San Francisco bay area on December 1, 2014. The flight path is plotted on a sectional and shown in Figure 7. The Saratoga was flown carrying two GNSS data collection systems based on low cost commercial equipment. The first is a modified Samsung Galaxy Note 3 with external antenna and is shown in Figure 8. This system is capable of processing three constellation and Space Based Augmentation Systems (SBAS). It provides 1 Hertz (Hz) position with high sensitivity. The second is a u-blox 6 receiver used with Pixhawk flight computer with external battery and housing. This is shown in Figure 9. The u-blox receiver processes GPS/SBAS and provides 5 Hz position. These GNSS receivers were used to provide truth. A software defined radio (SDR), shown in Figure 10, located on the roof of the Stanford University Department of Aeronautics and Astronautics was used to gather the TIS-B transmitted from the two local ADS-B RS located in San Jose and Woodside, CA.

Figure 6. Piper Saratoga II

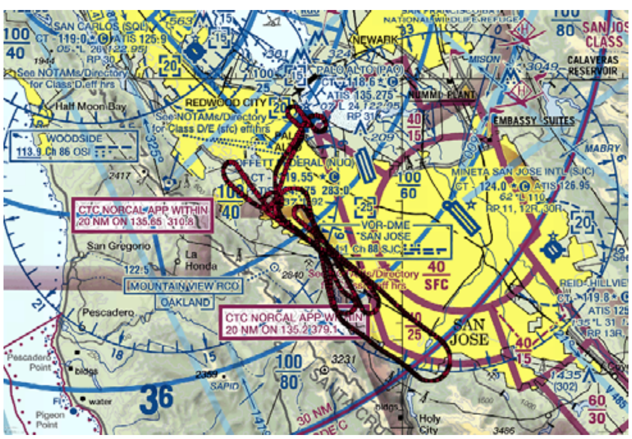

Figure 7. Flight path of Saratoga on December 2014

Figure 8. Modified Samsung Galaxy Note 3 with External GNSS antenna

Figure 9. u-blox 6 GPS receiver with Pixhawk (left)

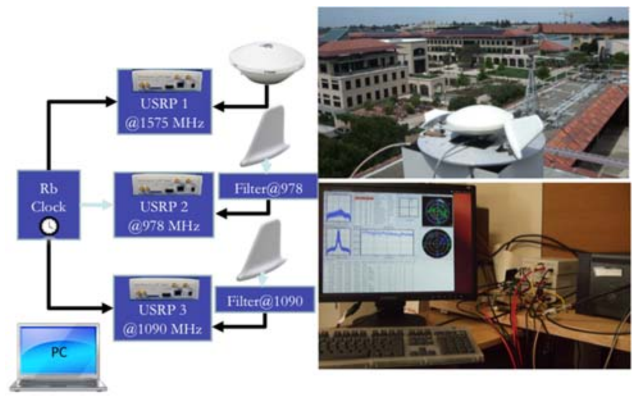

Figure 10. Ground ADS-B/TIS-B reference station set up at Stanford

We also received provided Surveillance Broadcast Services (SBS) data reports for the flight from the FAA Technical Center (FAATC). This data provides the system values and estimates for many parameters (position, velocity etc.) provided to the FAA at the TIS-B SDP. Some of the data are not included in the broadcast such as the time of applicability (ToA) and time of radar updates while other data such as position may differ from the broadcast. The paper will refer to these data sources as: 1) GNSS, 2) TIS-B and 3) FAA report positions, respectively.

3. ACCURACY

Accuracy is a key area of performance to be assessed. A basic target is for the system to support Area Navigation (RNAV) operations, in particular RNAV 1.0 or 2.0 nautical miles (nm) (RNAV 1.0 or 2.0). This level of performance supports en route and some terminal area operations in the future. Meeting RNAV 1.0 means achieving a total system error (TSE) with an accuracy of 1.0 nm. TSE depends on both flight technical error (FTE) and navigation system error (NSE). If the aircraft can achieve of 0.5 nm, then the NSE of TIS-B needs to have an accuracy of 0.866 nm

(1600 m) or better. For RNAV 0.3 nm, 307 m is a reasonable allocation assuming 0.25 nm for FTE.

Components of Accuracy

The overall accuracy performance of TIS-B based navigation depends on several major factors. For this paper, we separate the errors into three components. First is the error from the radar estimate of position. The second is the error induced from the tracker estimate of position at the time of applicability. The tracker extrapolates the position from past radar measurements to generate the position at a desired ToA. The tracker is believed to be linear (alpha-beta). This result is supported by data shown later in this paper. Finally, there is error due the additional latency or delay from ToA to the time the aircraft receives and uses the TIS-B position report. For the purpose of the allocation, we term this the broadcast latency error and define it as the additional error beyond the position error at ToA. In reality, all three errors are intertwined. For example, radar measurement errors affect the tracker position estimate and the tracker tries to account some of the errors due for system delays and latency up until ToA.

Radar Accuracy

An estimate of the accuracy of radar measurements and position estimates can be determined from the radar specifications [9][10] [12]. Table 2 shows the accuracy of three different radars: Air Route Surveillance Radar Model 4 (ARSR-4) and Airport Surveillance Radar (ASR) Model 9 and 11. From that we can estimate worst case position error. ASR-9 using Mode S has similar azimuth performance as an ASR-11 [11].

Table 2. FAA Radar Specified Performance

System	Range Error	Azimuth	Position Error (Calculated)	Update Period (sec)
ARSR-4 (En route) [9]	< 0.125 nm (232 m)	< .176° (307 m @ 100 km)	< 384 m	12
ASR-9 (Airport) [10]	< 0.03125 nm (58 m)	< 0.264° rms, < 0.16° rms, similar to ASR-11 [11]	< 464 m, 286 m, 151 m (Mode S)	5
ASR-11 (Airport) [12]	< 0.03125 nm (58 m)	< 0.08° rms (140 m @ 100 km)	< 151 m	5

Specifications tend to be conservative and actual radar accuracy is likely better. Our field data was examined to see the effects of radar measurements. The FAA SBS data showed that measurements from three local radars are used for the TIS-B positions. This is shown in Figure 11. The Mount Tamalpais ("Mt. Tam") radar is an ARSR-4 which is an en route radar that rotates every 12 seconds. Oakland and Moffett Field both operate an ASR-9 which rotate every 5 seconds resulting in a higher update rate.

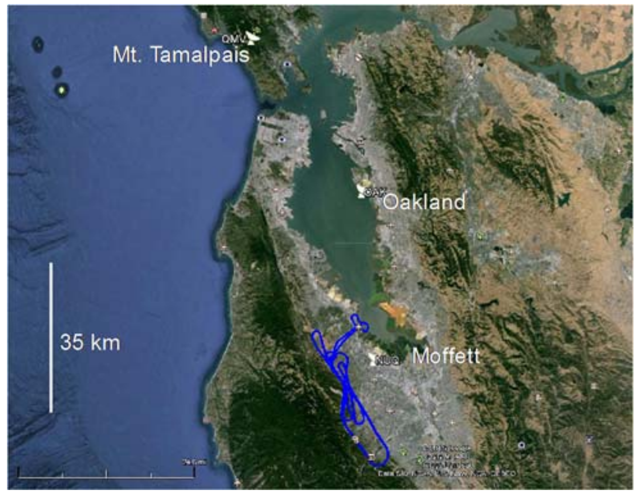

Figure 11. Radars used to generate TIS-B position report

Figure 12 shows the difference between the FAA SBS position following a radar update from a given station and the position measured by our GNSS receivers. This values apply at ToA and hence position error includes radar and tracker error. The left plot shows the result for Mt. Tam, roughly 70 kilometers (km) away and the right shows the result for Oakland about 35 km away. The performance from Mt. Tam has mean and standard deviation of 74.8 m and 41.7 m, respectively. For Oakland, these values are 64.3 m and 33.9 m, respectively. The result for Moffet field, which is much closer, is similar to that of Oakland. The two takeaways from the data is that the radar does make a difference and that, even with all the additional error, the worst case seen is not at the worst case level given by the specifications. For the ARSR-4, the worst case error from specifications would be 316 m at 70 km.

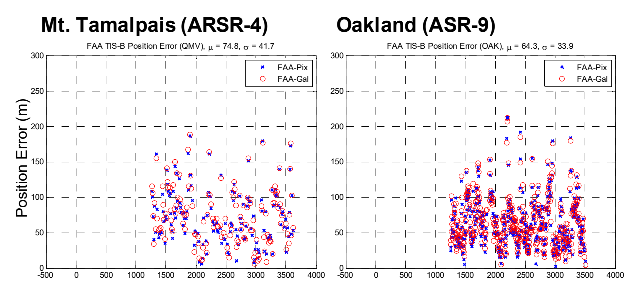

Figure 12. Position Error (FAA SBS vs. GNSS receivers) after update from Mt. Tam (Left) (μ=74.8 m, σ=41.7 m) & Oakland (Right) (μ=64.3 m, σ=33.9 m) radar

Tracker Performance

The second error of interest is the performance of the tracker. Unfortunately, the tracker is essentially a black box provided by the surveillance service provider. It is assumed to be a linear tracker using an alpha-beta filter that extrapolates based on velocity. We can examine a worst case level of performance. Figure 13 shows the error over time if we assume a path between a linear path and a constant three-degree per second turn that started just after the last radar update. It assumes an aircraft speed of 280 meters per second (m/s) or about 544 knots (kts). At 5 seconds, the tracker error alone is about 185 m. For the flight speeds of the Saratoga of 70 m/s, the error after 5 seconds would be scaled down to about 46 m. Later results in the overall accuracy section shows that the mean error during turns is greater than 50 m (90 m). Figure 14 shows the result for 70 m/s or 136 kts.

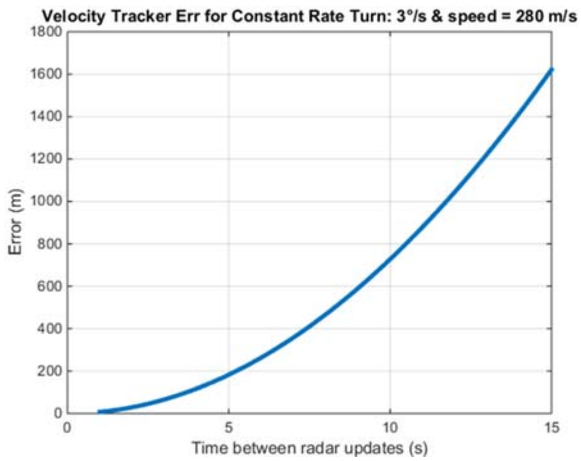

Figure 13. Velocity tracker error over a constant rate 3 degree per second turn at 280 m/s

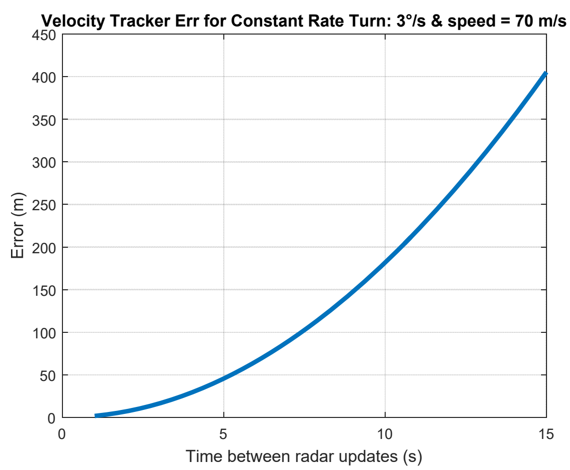

Figure 14. Velocity tracker error over a constant rate 3 degree per second turn at 100 m/s

Broadcast Latency

The TIS-B position used by the aircraft is delayed from the tracker estimate of position at ToA. It can take up to one second from ToA for the report to be delivered to FAA Service Delivery Point (SDP) which then provides it to the ADS-B RS. Furthermore, the ADS-B RS which schedules its transmission, propagation and avionics processing all introduce additional delays.

Figure 15 shows the latency from ToA to our reception of the message at our ground station at Stanford for Mode S ES based TIS-B. The typical delay between ToA and receipt of the Mode S ES TIS-B is typically between 0.5 to 0.8 s. Typically, as seen in the bottom of the figure, the message does change its position value, indicating additional extrapolation. The delay is similar for UAT as seen in Figure 16. Figure 17 shows the differences in the FAA SDP position and the TIS-B broadcast position versus the difference in ToA and reception time for Mode S ES TIS-B. The TIS-B position differs from the FAA SDP value and further extrapolates for the broadcast delay. The extrapolation is similar for both turn and straight flight. Figure 18 shows the plot for UAT TIS-B. Note that the extrapolation is not as clear for UAT TIS-B.

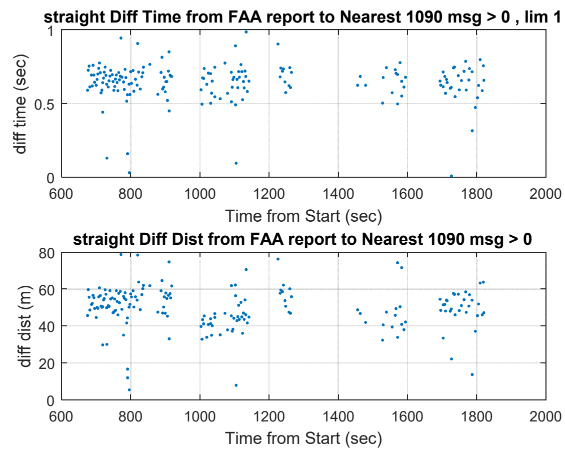

Figure 15. Time difference (top) & position difference (bottom) between FAA Mode S ES from SDP & on-air TIS-B.

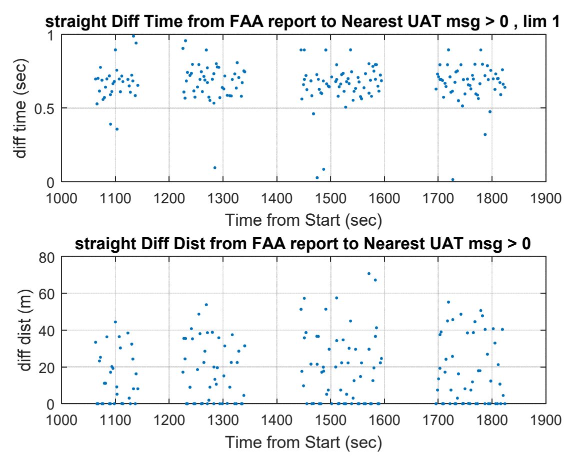

Figure 16. Time difference (top) & position difference (bottom) between FAA UAT from SDP & on-air TIS-B.

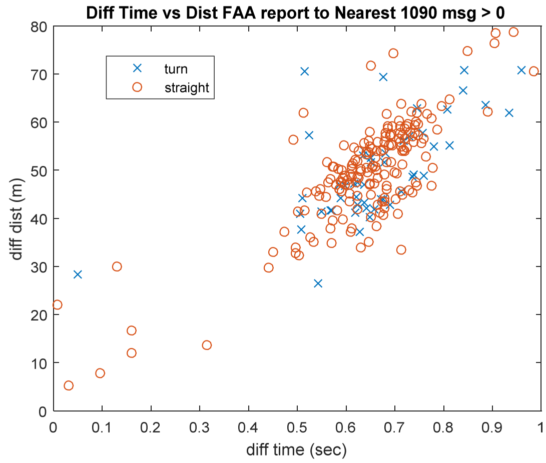

Figure 17. Relationship between time difference & position difference (bottom) between FAA Mode S ES from SDP & on-air TIS-B.

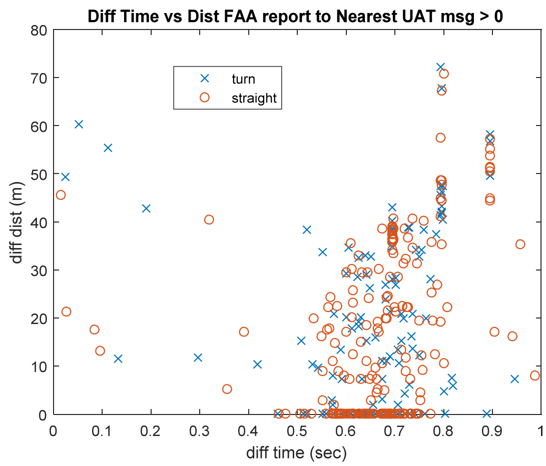

Figure 18. Relationship between time difference & position difference (bottom) between FAA UAT from SDP & on-air TIS-B.

Overall Accuracy

The overall accuracy of the TIS-B reports for the flight from both the FAA and our SDR is analyzed to examine the effects of the tracker. As the tracker is assumed to be linear, we divided the flight into straight/level and turn segments as seen in Figure 19. We then examined the error from the FAA reports and received reports for those segments. The result for the FAA report positions at ToA is seen in Figure 20. The figure shows the histogram of the error or difference between the FAA report and GNSS receiver position at ToA. The straight segment has mean and standard deviation of 48.7 m and 26 m, respectively. The turn segment error has a much larger mean and standard deviation (74.6 m and 39.3 m). This supports the belief that the tracker is linear. We also compared the result to the error of TIS-B position received by our SDR. These error are tabulated in Table 3. The straight and level errors for TIS-B and FAA report are similar. The extra latency in the TIS-B position does not add much error in a straight case. This suggest that the extrapolation done to mitigate the broadcast latency is good for linear movement. Furthermore, it suggests that the error measured is close to that of the initial radar position estimate as a linear estimator should not contribute much additional error in a root sum squared sense. Compare to FAA report, the TIS-B position has noticeably higher mean and standard deviation in the turn segments. This indicates that during turns, there remains significant errors when compensating for the broadcast latency.

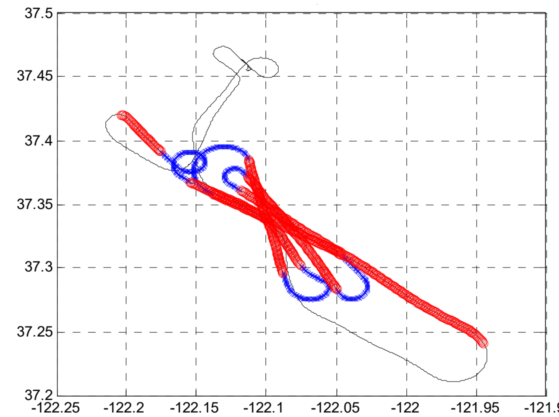

Figure 19. Flight path divided into straight (red) and turn (blue) segments

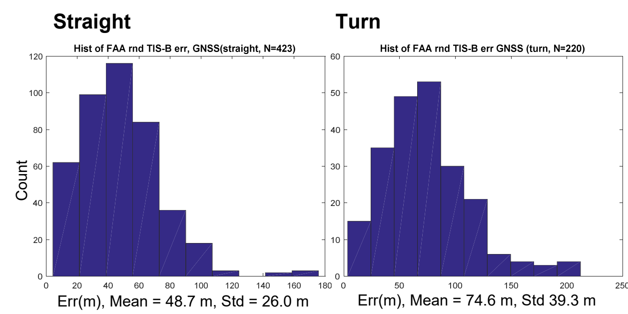

Figure 20. FAA report position error for straight and turn segments

Table 3. TIS-B position error statistics for straight & turn segments at time of applicability & reception

Segment (source)	Mean	Standard Deviation	Maximum Error
Straight & Level (FAA report/ToA)	48.7 m	26 m	~ 170 m
Straight & Level (TIS-B/broadcast)	47.7 m	27 m	~ 200 m
Turn (FAA report/ToA)	74.6 m	39.3 m	~ 200 m
Turn (TIS-B/broadcast)	90.3 m	46.3 m	~ 200 m

Analytically, we can examine the worst case. This is done by taking a worst radar measurement error of about 380 m with the tracker error from Figure 13 using the worst-case latency of 12 seconds for the radar and 1 second for transmission. For 280 m/s or roughly the cruise speed of a commercial jet, the root sum square of the error is about 1120 m (square root of $380^2 + 1050^2$). This is less than the target for RNAV 1.0. Additionally, our flight results are significantly better with the worst error being about 200 m. Hence, RNAV 1.0 accuracy levels should be achievable. However, RNAV performance such as 0.3 nm may be challenging to meet as the worst case radar performance already exceeds 307 m.

4. AVAILABILITY

The flight data also allowed us to examine reception availability. Figure 21 shows the time between Mode S ES TIS-B messages. The most common difference is nearly zero seconds because it takes two messages for a complete TIS-B transmission on Mode S ES. The next most common is between 1 and 4 seconds. There are a few instances where the gap exceeds 10 seconds either due to reception loss or more likely because the ADS-B RS did not need to transmit a TIS-B report. This is not representative of the worst case as the San Francisco bay area is not as challenging a radio frequency environment as the Los Angeles basin or New York. Nor are we currently operating in the densities expected in future airspaces.

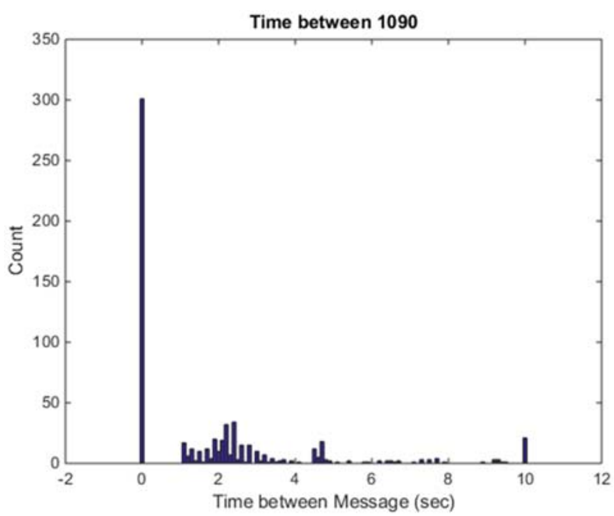

Figure 21. Time between Mode S ES TIS-B Messages

5. CAPACITY

The capacity of TIS-B for navigation is another consideration. Theoretically, an ADS-B radio station can send TIS-B broadcasts for many aircraft. With the UAT ADS-B Segment, about ~3000 basic messages per second can be supported. With Mode S ES, approximately 8000 Mode S ES messages can be sent. However, this channel is not organized, has many other transmissions and may require 2 messages per each TIS-B position report. All of these factors greatly reduce its capacity.

Additionally, to manage capacity, the transmissions from each radio station must be coordinated so that they do not interfere with transmissions from nearby ADS-B RS. We performed an initial assessment of the performance based on the modeling developed in [8]. We assess the probability of receiving a UAT or Mode S ES transmission given different number of aircraft in the airspace and assuming a specified number of transmissions per aircraft. For the purpose of comparison, we choose to use the capacity at the probability of reception is 50%. This results in 0.1% chance of getting TIS-B position over a 10 second period, assuming independent interference.

For Mode S ES case, we examined three cases with each case being shown in Table 4 which shows the number of each Mode (A or C, S, and S ES) transmitted per aircraft per second. Case 1 is the worst case ATCRBS and Mode S environment observed in the US [13]. Case 2 is a more typical high density airspace case typical of the 1990s. Case 3 represents a future scenario where ATCRBS has been replaced. These scenarios are based on traffic measured by [13] and used in [8].

Table 4. Traffic Cases on 1090 MHz

Case	ATCRBS 20.3/24.65 μsec	Mode S 56 bit/ 64 μsec	Mode S ES 112 bits/120 μsec
1	120	8	6
2	60	8	6
3	0	8	6

Figure 22 shows the probability of reception of one Mode S ES message. If only one Mode E ES message is needed per TIS-B navigation update then the capacity in Case 1 is slightly under 40 aircraft while case 2 capacity is about 60 aircraft. Case 3 is significantly better at 240 aircraft. If two consecutive Mode S ES messages are needed, the capacity becomes even worse. The capacity for each case is the number of aircraft where a probability of reception of greater than .7071 (√0.5) can be achieved.

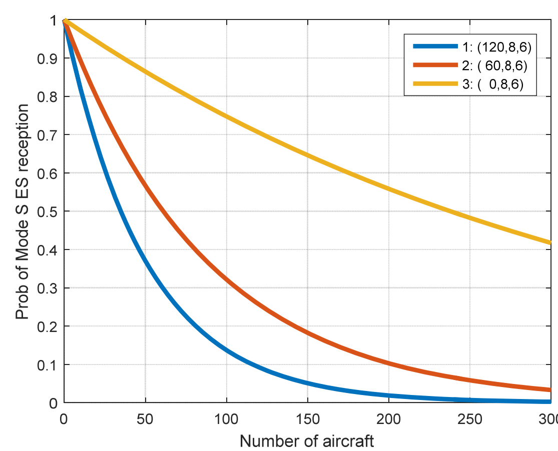

Figure 22. Probability of reception of Mode S ES transmission (TIS-B) vs. Number of Aircraft for 3 different cases (ATCRBS, Mode S, Mode S ES) per sec

For UAT, we examined three cases where there different numbers of UAT messages transmitted per aircraft per second. If we assume that a basic message is used for the

TIS-B uplink then examine the probability of clear reception of a basic UAT message versus the number of aircraft in the airspace. Figure 23 shows this analysis. The legend (*n*,*m*) indicates the number of basic (*n*) and long UAT messages (*m*) per aircraft per second. The figure shows that in the worst case used (2 basic and 4 long messages) per aircraft, 170 aircraft can be in the airspace and still yield a 0.5 reception probability. If TIS-B requires a long message, this level drops slightly to 132 aircraft. Other scenarios are much better and UAT has a lot higher capacity for supporting TIS-B. This is because UAT does not have other traffic to interfere with its transmission.

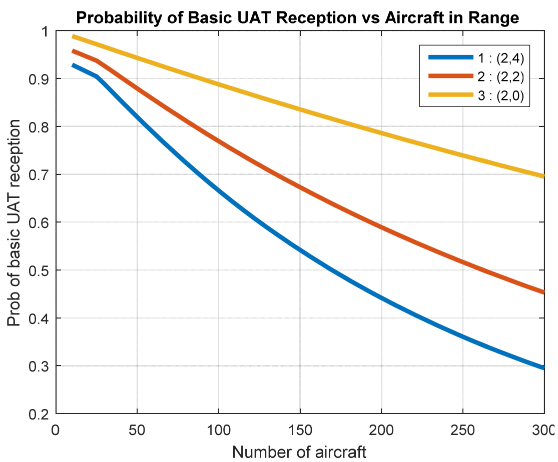

Figure 23. Probability of reception of a basic UAT transmission (TIS-B) vs. Number of Aircraft for 3 different cases (# basic, # long messages) per sec

6. COVERAGE

By definition, the coverage of the system is the intersection of the area where there is radar and ADS-B radio station coverage. Per the SBS contract for ADS-B, there should be ADS-B coverage everywhere with radar coverage. Hence, TIS-B for navigation coverage should then be equaled to the radar coverage area. Per discussion, radar coverage should be nearly 100% coverage at 5,000 feet (ft) above ground level (AGL). We have not examined coverage at 2,000 ft AGL where the instrument landing system (ILS) coverage starts.

7. LIMITATIONS

There are some limitations and challenges that need to be addressed as the concept is being developed. First, the integrity of solution needs to be better known as the TIS-B position estimator (tracker) is a black box. Also the integrity monitoring of radar measurements also needs to be examined. It is also desirable to communicate integrity within the current context of the TIS-B message. We may be able to use navigation integrity category (NIC) indicator to communicate integrity level.

Another challenge is integration into Flight Management System (FMS). ADS-B/TIS-B is not connected to navigation in FMS and so a means of integration needs to be assessed. Other questions include: "how would this system integrate into an autopilot?' and "could the latency, especially during turns and maneuvers cause unstable feedback to an autopilot?" This may not be a major issue as the target users, general aviation, typically do not have autopilots.

The integrity of uplink and the desirability of authentication is another major issue to examine. With today's TIS-B protocol, the aircraft position is transmitted without authentication. If it is being used for guidance, one can imagine an attacker spoofing the TIS-B for navigation. As the aircraft cannot authenticate the source, it may be guided in a dangerous manner.

8. SIGNIFICANCE & SUMMARY

A robust ground based navigation system is an essential component of the aviation infrastructure. ADS-B has many promising features allows it to provide significant value to an APNT system. This paper examined the use of TIS-B to provide navigation information to an aircraft. The accuracy assessed both from flight data and analysis suggests that RNAV 1.0 accuracy should be achievable. Latency is the largest driver of error and uncertainty. In the US, there is ADS-B/TIS-B coverage anywhere there is radar coverage. Capacity may be limited but it is not the main challenge as TIS-B for navigation service should only need to serve users without other means. Additionally, TIS-B for navigation on UAT has significantly more capacity. The major challenges with using TIS-B for navigation are its integrity, security and the performance levels it can support. Without RNAV 0.3, it does not have significant benefits over other means such as the minimum operating network (MON) for VHF omnidirectional range (VOR).

The analysis conducted here supported the FAA evaluation of technical APNT alternatives. In the end, the TIS-B for navigation did not make the current APNT roadmap. However, the analysis conduct here provided valuable insights into the capability of such a system and where improvements can be made. It also demonstrates the utility of smartphones for rapid and low cost in-air performance evaluation. We were also able to operate the modified Galaxy Note 3 in the middle seat of an Airbus A319 with high availability throughout the flight. While further work needs to done to in evaluating the smartphone performance, the ability to carry and operate such a device on most aircraft makes it versatile for analysis that do not require the accuracy of a professional or survey grade GNSS receiver.

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DISCLAIMER

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