Capacity Study of Two Potential Alternative Position Navigation and Timing (APNT) Technologies for Aviation

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1. INTRODUCTION

The Federal Aviation Administration (FAA) is seeking to develop alternative position navigation and timing (APNT) systems in order to minimize the impact of a degradation of the Global Positioning System (GPS) and other Global Navigation Satellite Systems (GNSS). The developed APNT system needs to have capabilities beyond those provided by currently existing FAA ground based navigation aids are needed. Ideally, the APNT system will be based on existing or soon-to-be existing FAA systems and infrastructure. Three promising technologies currently being investigated: 1) an improved distance measuring equipment (DME) infrastructure, 2) passive multilateration (MLAT), and 3) ground based "pseudolites".

As the purpose of APNT is to maintain operations for prolonged periods even in the absence of GPS, it must be able to handle the full capacity of future airspace. In 2025, it is anticipated the air traffic in the United States will increase at least twofold over the current (2010) levels. As both DME and MLAT are capacity limited, it is important to understand their capacity to fully consider these systems. We also need to consider potential changes to the system and how they may affect capacity. This paper examines the capacity of these systems, particularly in the context of APNT.

OUTLINE

The first section of the paper describes the goals of APNT and the need to support high density capacity. It outlines the architectures by which DME and MLAT based APNT would operate. The second section derives an analytical model for traffic on the each channel and implementation. The third section provides results on DME and MLAT from the analytic model and simulation. It also examines potential changes that could improve systems capacity. Sensitivity studies are performed to identify the effect of these changes.

2. BACKGROUND

The APNT group was formed to determine and develop promising solutions for providing navigation, surveillance and other FAA services in the event of a GPS degradation event. The need for APNT is particularly vital as aviation use of GPS will increase in the coming years. Under Next Generation Air Transport System (NextGen), GPS and GNSS will be the primary means of navigation and surveillance for aviation. GPS is what enables most of the operations needed to improve efficiency and handle the increased capacity anticipated in the 2025 time frame. In fact, GPS is often the only system capable of supporting many of the envisioned operations. Current terrestrial based navigation system either cannot provide the area navigation (RNAV) capabilities or the performance needed to support improved operations.

Hence, the FAA is working on developing an APNT system that is capable of sustaining operations in the event of GPS outage [1]. So not only will APNT provide safety and security, it will also minimize economic impact of a GPS degradation event. The system will provide RNAV capability. Additionally, the APNT must support en route coverage in CONUS and terminal coverage in major airspace. Currently, the APNT group is using the top 135 airports as a proxy for these terminal airspaces. For terminal operations, the APNT should be able to support Required Navigation Performance (RNP) operations down to RNP 0.3. The APNT system will provide the horizontal guidance for these RNP operations[1]. Additionally, to sustain operations and provide safety, it must be able to support the full level of air traffic anticipated in the future.

The ability of DME and MLAT based APNT to support future air traffic is a major unknown as these systems are both capacity limited. For both systems, supporting an additional aircraft adds extra burden to their transmission channels. To assess capacity performance, we need understand both the level of air traffic to be supported and

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[1] A baro-altimeter will be used should vertical guidance be necessary

how these systems operate. From that, we can develop a model to assess capacity. The model can then also be used to ascertain the benefits of various changes and configurations.

AIR TRAFFIC LEVELS

To understand whether DME or MLAT can support future air traffic levels, we need to determine what these anticipated levels may be. Several measurements and models are available. As our greatest concern is managing high density airspace of the future, we use the 2020 LA Basin model developed in the Technical Link Assessment Report from 2001 [2][3]. This model as presented in [3] is shown in Table 1. An additional column is added to show the airborne density.

While we use the LA Basin model as a reference, other traffic density models are also used. Fortunately, there is reasonable agreement between the models. The traffic collision alert system (TCAS) minimum operational performance standards (MOPS) targeted an average aircraft density (σ_o) of 0.3 aircraft per square nautical mile (NM) within 5 NM (R_o) [4][5]. The density (σ) steadily drops thereafter in portion to the distance as seen in Equation 1. The number of aircraft, $N(R)$, using the TCAS model is just slightly lower than in the LA Basin model. For example, at 50 NM, the TCAS and LA basin models indicate 235.6 and 260 aircraft, respectively.

Range (NM)	On-the-Ground	LA Basin 2020 Airborne Only	Total Units	Airborne Density (ac/NM^2)	Low Density Total Units
50	143	260	403	0.0331	4
100	190	520	710	0.0166	20
150	225	781	1006	0.0110	48
200	225	1045	1270	0.0083	88
250	225	1321	1546	0.0067	138
300	225	1648	1873	0.0058	203
350	225	2021	2246	0.0053	274
400	225	2469	2694	0.0049	360

Table 1. LA Basin Model & resulting airborne density

$$N(R) = \begin{cases} \sigma_o \pi R^2 & R \le R_o \\ \sigma \pi R^2 = \left(\sigma_o \frac{R_o}{R}\right) \pi R^2 & R > R_o \end{cases}$$

DISTANCE MEASURING EQUIPMENT (DME)

Distance measuring equipment (DME) has a long operational history within the national airspace (NAS). It is appealing as it can support area navigation with avionics such as a scanning DME. A scanning DME allows for horizontal positioning using multiple DMEs (DME/DME). However, under current FAA rules, DME/DME can only perform RNAV procedures if coupled with an inertial reference unit (IRU).

DME ground stations or beacons currently in the NAS are generally not capacity limited. Studies show that DME can handle current traffic level [6]. ICAO specifies that a DME beacon should be able to accommodate 100 aircraft [7]. However, given increases in future traffic, the current DME capacity limits will be tested, particularly in dense traffic areas. Capacity is partly limited by the number of replies a DME beacon will send. Current operational DME beacons transmit up to 2700 replies regardless of the number of interrogation requests. This is the maximum reply rate and the beacon will set a threshold on received signal power such that it will respond to at most 2700 interrogation requests. Newer DME transmitters can have reply limits of up to 5400 replies.

It has been suggested that increasing the limits on the number of DME ground transponder replies can increase capacity. However, this increase may cause other problems. Hence the APNT team is studying the capacity issues when using DME and how changes such as increasing the reply limit affects the system and users.

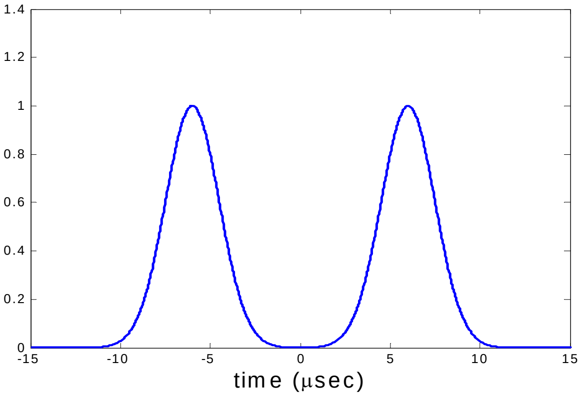

Figure 1. DME pulse pair (X channel)

A description of DME operations is useful in understanding how to model DME capacity. DME is a round trip ranging system based on request-reply. The aircraft initiates DME ranging. The avionics tunes to a specific DME station by selecting the station's frequency and then sends an interrogation request. The request, as with all DME transmissions, is a pair of pulses as seen in Figure 1. For standard DME (DME/N), these pulses are specified to have a Gaussian envelope. The DME station receives the request and responds after a fixed reply delay. The reply is also a pulse pair but on a different frequency. It is important to note that the DME station, upon accepting a valid request (reception of the second pulse), initiate its dead time gate thereby becoming non-responsive to other request. The dead time is typically at least 60 μsec [8]. The timeline of the response for DME operating on the X channel is seen in Figure 2. The round trip time minus the reply delay provides the range.

DME beacons are organized such that at any location, there should only be one station transmitting at a given frequency. This is true for both the uplink (request) and downlink (reply) frequencies.

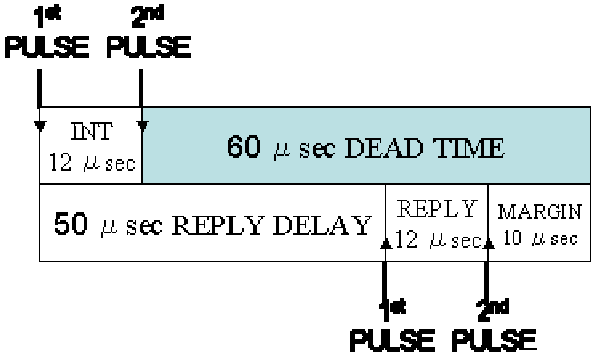

Figure 2. DME reply delay & dead time based on [8]

DME specifies several channels for transmission: X, Y, Z, and W. This paper mostly discusses the X and Y channels. W and Z channels were developed for the microwave landing system (MLS) and are not commonly used in the United States. The channels are identified by the delay between the first and second pulse in the pulse pair. For the X channel, both the request and reply pulse pairs are separated by 12 μsec. For the Y channel, the request and reply pulse pairs are 36 and 30 μsec apart, respectively. Additionally, the reply delays are 50 and 56 μsec for the X and Y channel, respectively. In each channel, the request and reply occur on different frequencies with the frequency difference typically being +/- 63 MHz. More details are given in [8].

One request/reply sequence is not adequate for ranging. Multiple requests are sent by the user (aircraft) to determine which DME transmissions are replies to the aircraft. Typically, the receiver looks over many requests to find a return time where there is consistently a reply. As some requests may not elicit a reply while there may be replies to requests by other aircraft, the identification process needs to be robust. With more requests-replies, the more confident one can be that the correct round trip time has been identified. In the search phase, the aircraft does not know the approximate round trip time and must search over a wide range of possible return times. In search mode, the aircraft sends about 150 pulse pairs per second (ppps) to determine which replies correspond to its requests. Search establishes strong certainty on identifying replies designated to the aircraft resulting in an estimated range. With this, the window in which possible reply pulses can exist is narrowed. Then the DME avionics enters track mode where a more modest 5-15 ppps can be used. A standard assumption is that 95% of aircraft using DME is in track mode. With this assumption, the average aircraft transmits 21.75 ppps (= .95*15 ppps + .05*150 ppps).

An important metric is the reply efficiency (RE). RE is the percentage of transmitted requests that elicit a reply from the ground station. Avionics should be able to perform with a RE of 70% [7][9].

MULTILATERATION BASED NAVIGATION

In passive multilateration (MLAT), the ground determines the position of an aircraft on using Automatic Dependent Surveillance Broadcast (ADS-B) transmissions of the aircraft. This is accomplished by examining the time of reception of the broadcast at multiple stations. Ground based transceivers (GBT) are the basic ground element supporting ADS-B. The GBT receive ADS-B broadcasts and sends the information to air traffic. These stations can simultaneously act as MLAT stations. The FAA currently plans to implement MLAT for back up surveillance. It may be possible to utilize this system to provide APNT service by having the ground-calculated position transmitted back to the aircraft. In this paper, we term this MLAT based navigation or APNT to distinguish it from the surveillance only MLAT.

Two physical layers exist to support ADS-B and MLAT in the US. For commercial airlines, ADS-B transmissions utilize the 1090 MHz channel as they already carry some 1090 equipment. It is envisioned that general aviation (GA) will use Universal Access Transceiver (UAT) on 978 MHz for ADS-B.

On 1090, ADS-B will be sent on Mode S extended squitter (Mode S ES), a version of the Mode S broadcast extended to 112 bits (from 56 bits for standard Mode S). The 1090 channel and Mode S ES can also be used for the uplink of the ground-calculated position to the aircraft, presumably using the Traffic Information Services – Broadcast (TIS-B) standard. Figure 3 shows the message structure of Mode S ES as used by ADS-B. The data bits are modulated by on off keying whereby the signal is only on for half of the bit interval. It is on for first (second) half if the data bit is “1” (“0”) [9].

Intersystem interference is an important issue on 1090 as the channel is also used by aircraft transponder replies to air traffic control radar beacon system (ATCRBS), Mode S, and TCAS. Transponder replies are generated to interrogations on 1030 MHz from ground assets such as secondary surveillance radars. For ATCRBS transmissions such as Mode A and C, the time between the beginning of the first pulse and last pulse is 20.3 or 24.65 μsec if there is a special purpose identification (SPI) pulse.

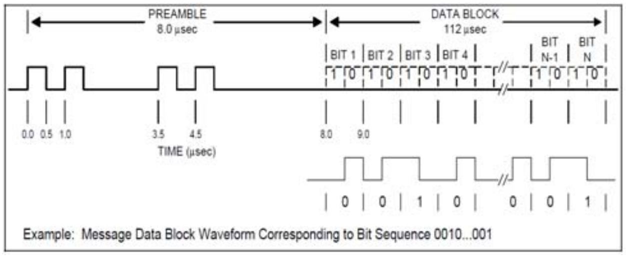

Figure 3. ADS-B Message Transmitted Waveform on 1090 Mode S ES [9]

The ATCRBS transmission can result in high levels of channel congestion. MIT Lincoln Lab examined such interference when it was studying Mode S ES for ADS-B. Table 2 presents interference environment scenarios used in these studies [10][11][12]. Case 1 represents the worst case ATCRBS and Mode S environment observed over large parts of the US. Case 2 is a more typical high-density environment case for the 1990s. Case 3 and 4 are future scenarios where ATCRBS has been completely replaced. Case 4 also assumes that TCAS operates only passively. As can be seen, the interference conditions depend significantly on many factors. Measurements of these conditions show that we generally fall within Case 1 and 2 in high-density conditions. Bernays, et al, while studying LA basin traffic, used 75 interrogations for aircraft with Mode S transponder (40% of aircraft) and 90 interrogations per second per aircraft with ATCRBS (60%) [13]. These levels yielded results that matched the measurements made. This works out to an average of 30 Mode S and 54 ATCRBS interrogations per aircraft per second. For this study, we used the first three cases in Table 2 as reference.

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
4	0	3	6

Table 2. Interference Cases with Replies per second per aircraft [10]

UAT operates on its own dedicated channel and thus the biggest concern is intrasystem interference. It utilizes time division multiplexing between ground and ADS-B segment transmissions as well as requiring that transmissions start at specific times known as message start opportunities (MSO) [14]. This set up is seen in Figure 4. The ground segment messages, seen in Figure 5, are transmitted in one of 32 MSO within the beginning 176 ms of the UAT frame. The message contains 4452 bits and has Reed Solomon forward error correction (FEC) parity. The message is divided into six blocks and the FEC is capable of correcting 10 code word symbols, with each symbol being 8 bits or 1 byte, per block. ADS-B messages, including those from the ground, are transmitted in the 800 ms UAT ADS-B segment. There are two messages, seen in Figure 6, both of which contain FEC parity check. The basic UAT ADS-B segment message has a payload of 144 bits resulting in a total size of 276 bits. The 96 bits of FEC parity allows for the correction of up to 6 incorrect bytes (symbol) of data per message. The long message has a payload of 272 bits and a total of 420 bits. It can correct up to seven bytes per message. TIS-B on UAT uses the same message formats and sent in the ADS-B segment. For both segments, continuous phase frequency shift keying (CPFSK) is used with each bit utilizing 0.96 μsec. Note that these transmissions are much longer than the Mode S ES.

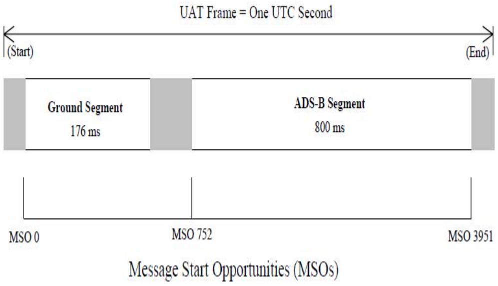

Figure 4. UAT Frame, grey areas are guard band [14]

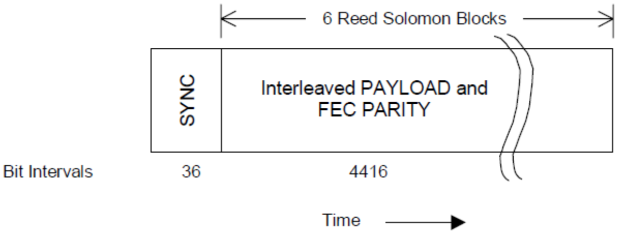

Figure 5. UAT Ground Segment Transmission [14]

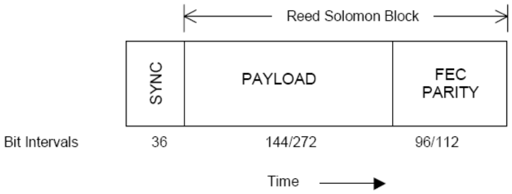

Figure 6. UAT ADS-B Segment Transmissions [14]

VARIATIONS

There are multiple concepts for implementing MLAT based navigation that may improve performance. This section describes some of these variants that can be studied using the developed model.

Channel congestion is also caused by using the same channel for both uplink and downlink. This is generally presumed as the most natural means to uplink is to use TIS-B, which is on 1090 MHz and UAT ADS-B segment, respectively. The congestion thus may be reduced if a different uplink channel is used. To reduce traffic on

1090, we examine the technical benefits of using 1030 MHz for the position information uplink. When using UAT, the use of the ADS-B segment for TIS-B also decreases performance. The study will examine the capacity improvements possible if the aircraft position uplink broadcast uses the ground transmission segment.

Another variation is the use of occasional two-way measurements to synchronize time with the aircraft. If the avionics and the ground are time synchronized, only two stations would need to receive the message to determine position. This increases redundancy and coverage.

3. ANALYSIS OVERVIEW

The study is conducted using an analytic model. The method models the key features of the channels. It allows for the rapid examination of many different scenarios and variations. Simulations are done to validate and verify performance of the model. This section discusses the derivation and limitations of the analytic model as well as the simulation methodology.

BASIC ANALYTIC MODEL

The analytic model was developed to assess the effect of intersystem and intrasystem interference on DME ranging and MLAT positioning. The model is based those developed in [5] and [15] to analyze TCAS performance. The derivation of the interference model is shown in Figure 7. The desired signal is assumed lost if there is an overlap between the desired and an interfering transmission. This assumption along with others results in the model being conservative.

The model is developed by examining the case where there is one desired and potentially interfering transmission. Define the time frame (t_f) over which we are examining the transmissions. For 1090, one second is generally used. Another transmission overlaps with the desire transmission if it arrives during the time segment of length t_m where there is a portion of the desired transmission. Additionally, if the interfering message is of length t_i, then it will interfere with the desired transmission if it arrives at a time $t < t_i$ before the arrival of the desired message. Interference effects are deterministic as any interference results in message loss. The probability of interference, seen in Equation 2, is then the probability of the overlap. The probability of clear reception (with one interferer) is given by Equation 3.

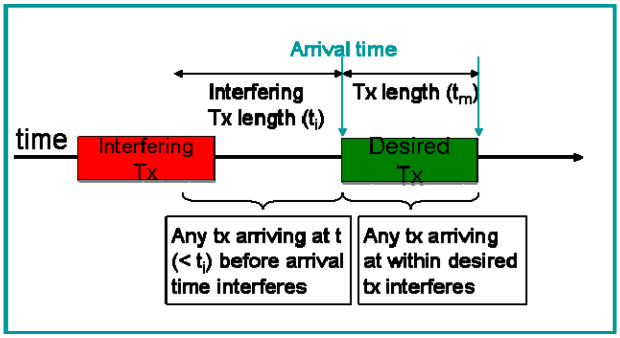

Figure 7. Basic Interference Model

$$P_{\text{int}} = \left(\frac{t_i + t_m}{t_f}\right) \qquad (2)$$

$$P_{clear} = 1 - P_{\text{int}} = 1 - \left(\frac{t_i + t_m}{t_f}\right) \qquad (3)$$

DME MODEL

For DME, one only needs to model the interrogation requests (downlink) component to examine capacity. There is no interference on the reply transmission once an interrogation request has been accepted. This is because, within a geographic area, each DME beacon is on a separate frequency and hence non-interfering with other DMEs.

Figure 8. DME downlink component

The model is modified to account for the ground beacon dead time (t_d). Assuming all DME transmissions in the channel require time t_m, an interfering DME request arriving at time $t < (t_m + t_d)$ before the desired request will trigger the dead time gate such that the DME beacon will ignore the desired request. The mechanism effectively prevents the beacon from being responsive to a request. Equation 4 shows the resulting probability of non-interference (clear ground reception) given the inclusion of a dead time gate.

$$P_{clear} = \left(1 - P_{\text{int}}\right) = \left[1 - \left(\frac{2t_m + t_d}{t_f}\right)\right] \quad (4)$$

For a given required reply efficiency (RRE), Equation 5 shows how to calculate the probability that an aircraft (Pac_{RRE}) will be at or above the RRE level for a given P_{clear} and N transmissions. This is essentially the availability of the DME for ranging assuming that the avionics needs RE ≥ RRE.

$$Pac_{RRE} = 1 - \sum_{k=0}^{\lceil N*RRE \rceil} \binom{N}{k} \left(P_{clear}\right)^{k} \left(1 - P_{clear}\right)^{N-k} \tag{5}$$

The probability of getting a horizontal position is the probability of having at least two stations with adequate RE (RE ≥ RRE). Assuming there are M DME stations, the probability of having at least two with RE ≥ RRE is given in Equation 6. With Equation 5 and 6, we have our final capacity relationship. These equations relate the probability of positioning with the number of transmissions (N), which depends on the number of aircraft for a given number of stations.

$$Ppos_{RRE} = \sum_{k=2}^{M} \binom{M}{k} \left(Pac_{RRE}\right)^{k} \left(1 - Pac_{RRE}\right)^{M-k} \tag{6}$$

Note that in this paper, we use the DME X channel as our example as it is the most common. However, the model applies to any channel with proper changes in parameters.

MULTILATERATION WITH ADS-B

While the MLAT analysis uses the basic model above, it is more complicated as there are three components to assess as seen in Figure 9. Additionally, we need to model and evaluate the both data channels as well as potential variants of the architecture for each data channel. This section discusses the modifications made to evaluate MLAT.

First, we need to examine the following three components: 1) probability of clear reception of a signal at the GBT (P_{rg}), 2) probability of determining position on the ground (P_{gndpos}) and 3) the probability of getting the position back to the aircraft (P_{ra}). Determining the first and second for MLAT is, in general, similar to the calculation made for DME. For the first, we must also model possible interference from the GBT as it may transmit on the same channel. For the second, passive MLAT requires three measurements for positioning. The third component, the probability of getting position back to the aircraft, depends on the channel used. If the typical TIS-B channels (1090 or UAT ADS-B segment) are used, then potential interference from ADS-B and other broadcasts need to be modeled.

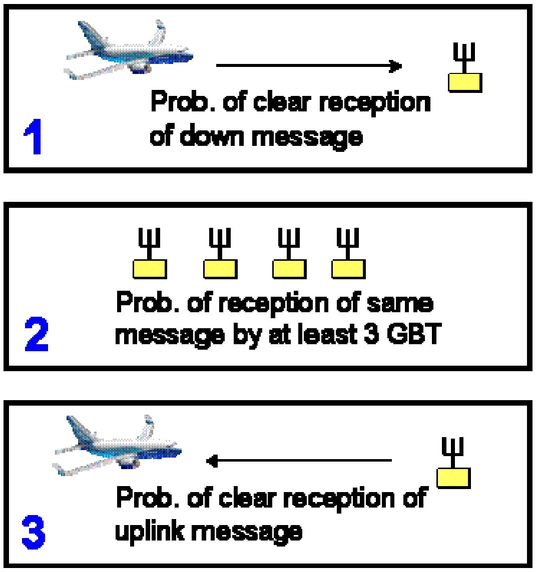

Figure 9. Three components needed to calculated availability (probability) of MLAT based navigation

MLAT BASED NAVIGATION MODEL FOR 1090

On 1090, we need to include the effect of transmissions from sources such ATCRBS as well as the GBT. Equation 7 shows the calculation of the probability of Mode A transmissions not interfering with the desired Mode S ES signal. In the equation, the Mode S ES and Mode A message have length t_{mSES} and t_{mA}, respectively. Each aircraft transmits N_{mA} mode A messages per time frame (t_f), typically one second, and there are Num_ac aircraft in interference range (including the aircraft transmitting the desired signal). It is assumed that the aircraft transmitting Mode S ES signal will not interfere with itself. The probabilities for the other transmissions not interfering with the desired signal follow the same form.

The GBT may transmit TIS-B uplink of the ground calculated MLAT position or it could be ADS-B rebroadcasts. Since these are all transmitted on 1090 MHz, they need to be modeled and the probabilities of interference from each transmission determined. The probability of non-interference from the GBT ($P_{clear,gbt}$) depends on implementation. For example, the number of transmissions may depend on the number of position fixes calculated or it can be fixed for a given period. In the worst case, we assumed that each Mode S ES received resulted in a GBT broadcast. For this case, the probability of clear reception on the ground (P_{rg}) and $P_{clear,gbt}$ are dependent on each other and thus is solved recursively. If the GBT transmits the ground calculated position on 1030 or another channel, then $P_{clear,gbt} = 1$.

$$P^{SES}_{clear,ModeA} = 1 - \left(\frac{t_{mSES} + t_{mA}}{t_f} \right)^{N_{mA} * (Num\_ac - 1)} \quad (7)$$

The overall probability of clear reception on the ground (P_{rg}) is the product of the probability of non-interference (clear reception) for each possible transmission type as each interference probability is independent of the others. The general result for when using signal *mode* for positioning is given in Equation 8.

More generically, we designate $P_{rg,mode}$ as the P_{rg} with the desired signal of type "mode" as seen in Equation 9. For example, if Mode S ES is the desired signal, then we will designate as P_{rgSES}.

$$P_{rg} = P_{clear,ModeA} * P_{clear,ModeC} * P_{clear,ModeS} * P_{clear,ModeSES} * P_{clear,gbt} \quad (8)$$

$$P_{rg,mode} = P^{mode}_{clear,ModeA} * P^{mode}_{clear,ModeC} * P^{mode}_{clear,ModeS} * P^{mode}_{clear,ModeSES} * P^{mode}_{clear,gbt} \quad (9)$$

The probability of deriving horizontal position on the ground using one aircraft broadcast requires that at least three GBT receive the same broadcast. Equation 10 gives the probability of one Mode S ES broadcast resulting in a position derived on the ground given that there are M GBTs. We assume that there are N_{mSES} broadcasts over time t_f. The probability of position on the ground over one second is just the probability that any of the broadcasts sent over that second is received by at least three GBTs. The probability using Mode S ES as well as using both Mode S ES and Mode S is given by Equation 11 and 12, respectively.

$$P^{M}_{gndpos,SES} = \sum_{k=3}^{M} \binom{M}{k} \left[P_{rgSES} \right]^{k} \left(1 - P_{rgSES} \right)^{M-k} \quad (10)$$

$$P^{M}_{gndpos,\sec} = 1 - \left(1 - P^{M}_{posSES} \right)^{\frac{N_{mSES}}{tf}} \quad (11)$$

$$P^{M}_{gndpos,\sec} = 1 - \left[\left(1 - P^{M}_{posSES} \right)^{\frac{N_{mSES}}{tf}} \left(1 - P^{M}_{posS} \right)^{\frac{N_{mS}}{tf}} \right] \quad (12)$$

The last part is to determine the probability of getting the position back to the aircraft. First, we derive the probability that a position uplink message is not interfered with by the *M-1* other GBTs. The result is given in Equation 13. From that result, the probability of non-interference for one uplink message is derived. It is given in Equation 14, which assumes the transmission is on Mode S ES and is the product of the probability of non-interference from aircraft and ground sources.

$$P_{ra,g} = \left(1 - \frac{k_m t_m}{t_f} \right)^{N_{reply} * (M - 1)} \quad (13)$$

Equation 13 has a factor k_m that is nominally 2 if all ground transmissions are independent. However, the term can be lower if there is some dependence between transmissions. For example, if all stations transmitted two messages one after the other, k_m would be 1.5 (for $t_m/t_f <<$ 1). The derivation for the result will not be discussed in this paper.

$$P_{ra,1,SES} = P_{rg,SES} * P_{rg,A} * P_{rg,C} * P_{rg,S} * P_{ra,g} \quad (14)$$

Finally, the probability of getting the position to the aircraft over a second is the product of the probability getting a position on the ground and the probability that at least one of the N_{up} uplink transmissions from the GBT is not interfered with. This is given in Equation 15.

$$P^{M}_{acpos,\sec} = P^{M}_{gndpos,\sec} \left(1 - \left(1 - P_{ra} \right)^{N_{up}} \right) \quad (15)$$

MLAT BASED NAVIGATION MODEL FOR UAT

The UAT channel differs from 1090 channel in a few important ways that must be captured in its model. A simple difference is that the frame length for UAT ADS-B transmission is 800 ms rather than 1 second used in 1090. Furthermore, the transmissions are random but slotted to start at specified times known as MSO. Within the ADS-B segment, there are 3200 MSOs.

Another difference is that the UAT utilizes FEC. To account for FEC in the analytic model, we modify the overlap time that can cause an error, resulting in a P_{int} that differs from that derived in Equation 2. The modification depends on the desired and interfering signal. Fortunately, UAT is a dedicated channel that only contains two transmission types (long and short) over the ADS-B segment. So we only need to look over for four combinations. However, we do need to account for the slotted nature of the transmission. Equation 16 and 17 show the modified overlap time when a long message interferes with a short and the new P_{int}. In the equation, R_{ac} is the maximum interference radius, c is the speed of light, and n_f is the number of slots or MSO (= 3200).

The modified overlap time takes into account the possible MSO and the time of propagation minus the number of bytes that can be corrected. A simplified explanation will be provided next rather the lengthy detailed derivation. The first term accounts messages sent at the same MSO, which is guaranteed to interfere. The second and third term account for messages sent at the previous and following MSOs which have a 50% chance of interfering. The last term accounts for modifications to the overlap time due to propagation effects.

$$t_{LS} = 1 + 2 * 0.5 - \frac{1}{R_{ac}^2}\left[\left(99\mu s * c + \frac{R_{ac}}{2}\right)^2 + \left(15\mu s * c + \frac{R_{ac}}{2}\right)^2\right] \quad (16)$$

$$P_{\text{int},LS} = \frac{t_{:S}}{nf} \quad (17)$$

The arrival times for interfering transmissions should still be independent. The probability of clear reception is given by Equation 18.

$$P_{clear,UAT} = 1 - \left(P_{\text{int},LS}\right)^{N_{mUL}*(Num\_ac-1)} \quad (18)$$

Given the modification to P_{int}, the calculation for the probability of positioning on the ground and uplink is similar to that for 1090. The result is Equation 19 where *U* represents the basic UAT ADS-B message and *UL* is the long UAT ADS-B message.

$$P_{rg,mode} = P_{clear,U}^{mode} P_{clear,UL}^{mode} P_{clear,gbt}^{mode} \quad (19)$$

The interference at different ground stations is more likely to be correlated on UAT than on 1090. This is because UAT transmissions are at least 2.2 times longer than Mode S ES messages and they are slotted. The result is that if the UAT broadcast is interfered with at one GBT, there is significant chance that the same signal will interfere with the broadcast at another GBT. Likewise, if the message is not interfered with at one GBT, it will likely not be interfered with at another GBT. Equation 20 gives the probability of position on the ground assuming no correlation. If we assume that there is perfect correlation, Equation 21 gives the probability of positioning on the ground. In actuality, we are somewhere between the correlated and uncorrelated cases.

$$P_{gndpos,U}^{M} = \sum_{k=3}^{M} \binom{M}{k} \left[P_{rgU}\right]^k \left(1 - P_{rgU}\right)^{M-k} \quad (20)$$

$$P_{gndpos,U}^{M} = P_{clear,U}^{U} P_{clear,UL}^{U} \sum_{k=3}^{M} \binom{M}{k} \left[P_{clear,gbt}^{U}\right]^k \left(1 - P_{clear,gbt}^{U}\right)^{M-k} \quad (21)$$

LIMITATIONS

While model is straightforward and provides an understanding of the desired channels, it does have some limitations. One limitation is that multipath, a potentially important interference source, is not accounted for. This phenomenon is difficult to capture in a general analytic model as it is location dependent. It also does not account for relative signal strengths between signals. Fortunately by not accounting for this factor, the model is conservative. We are developing a propagation-based model that does account for these relative signal strength effects. Additionally, for DME, most outages are due to the dead time. Relative signal strength is not factor in this form of interference. It occurs as long as the beacon is responsive to the interfering signal.

SIMULATIONS

Simulations modeling the behavior of DME and MLAT were also created. For DME, the simulation generated a given number of interrogations arriving at random times. The simulation analysis processed each signal received from earliest to latest and determined how the beacon would respond to that set of signals. An accepted signal then causes the dead time gate to trigger and all other signals received during that dead time interval are ignored.

Hence, simulation attempts to model the real world process and relationship between incoming signals. In contrast, the analytic model treats each interfering signal as independent, which results in it being overly conservative. One case where the difference is seen is when the dead gate modeled. In this case, a signal arriving within time t_m+t_d prior to our desired signal may not interfere as it may be within the dead time triggered by a previous signal. In other words, a would-be interfering signal is itself interfered with thereby cancelling its effect. The simulation accounts for this time dependence whereas the analytic model would not. As a result, the simulation yields a higher reply rates than the analytic model as the model. Another case occurs when multiple signals interfere with a given signal. The simulation more accurately treats this incident as one interference event. The analytic model counts this as multiple interference events as each is treated independently. The number of such incidents increases as we have more signals and interference. Both these effects result in the analytic model being somewhat overly conservative relative to the simulation.

For MLAT, simulations were created the downlink portion of each protocol. Each aircraft was modeled as transmitting its messages randomly or near randomly. In the latter case, the transmissions of the aircraft would be random about a given transmission rate.

Note that ten simulation runs are used to generate the MLAT plots shown in the paper. This seems adequate for our comparisons.

4. DME CAPACITY STUDY

The DME capacity study seeks to understand the effect of increased air traffic on DME beacon, particularly for a beacon that is operating beyond the current specifications. To handle the anticipated increased traffic, a DME beacon may need to transmit more than the current standard of 2700 ppps. Newer DME transmitter equipment can higher maximum reply rates going up to 5400 ppps [6]. However, we need to understand the effect of allowing the DME beacon to respond to more aircraft by increasing the number of replies sent per second.

REPLIES & REPLY EFFICIENCY

Allowing the beacon to reply to more incoming requests increases the interference level on any given requests. This is because there are more requests that can either interfere with or trigger the dead time gate making the beacon non-responsive to a given request. This result can be seen in Figure 10 which shows that the number of replies do not increase linearly with requests.

Figure 11 plots the analytic and simulation results of the average RE (probability of reply) versus the number of DME beacon replies. The plot shows that RE decreases as the number of DME beacon replies increases. This is an important observation as it means that increasing the reply limit comes at a cost to RE. At a reply limit of 2700 ppps, the average RE is still above the 70% standard. However, above 3300 ppps, the RE drops below 70% and at 5400 ppps, RE is well below 50%. So, simply increasing reply limit is not adequate for meeting future capacity levels. Note that in the figure, the actual independent variable is number of requests, from which we derive the number of replies using Figure 10.

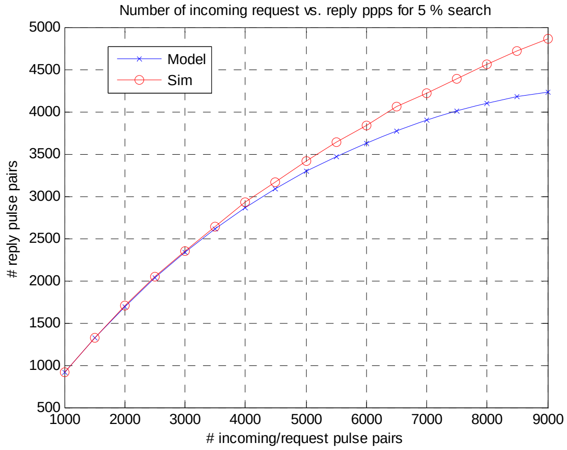

Figure 10. Total DME replies vs. total incoming requests (Nominal, 10 Sims)

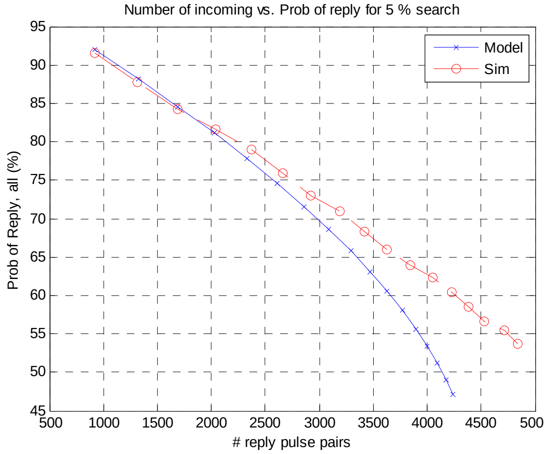

Figure 11. Reply Efficiency vs. total DME replies (Nominal, 10 Sims)

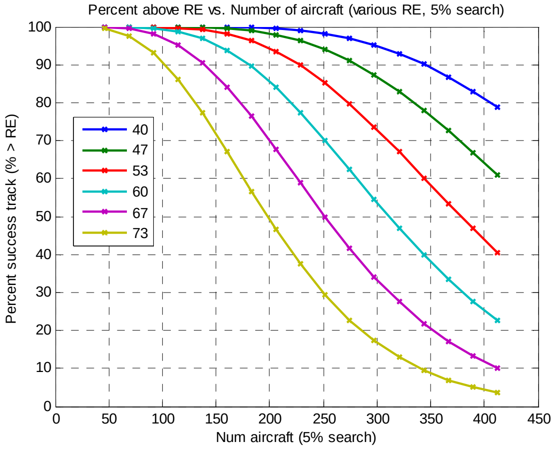

Figure 12. DME Ranging Availability vs. Number of Aircraft for Different RRE Levels (Nominal)

To understand what the results mean in terms of capacity, examine Figure 12, which shows the availability of a position solution versus number of aircraft for various levels of required reply efficiency. Successful tracking means that the RE experienced by the aircraft is greater than its RRE and so availability is the percent of aircraft experiencing an RE greater than their RRE. The number of aircraft is based on each aircraft transmitting an average of 21.75 ppps. From the figure, achieving 95% availability at 260 aircraft, means that the avionics must be able to track with RE of roughly 47%. This is significantly lower than the current specification of 70%. Alternatively, a RRE of 70% results in only 35% availability when there are 260 aircraft in the airspace.

DEAD TIME

A major reason why a beacon does not reply is because the request arrived during the dead time of the beacon. The dead time has significant impact on the DME beacon RE. We examined the sensitivity of DME capacity performance due to various dead time levels. As a limiting case, we show results for zero dead time. It should be noted that having no dead time may not be advisable or even feasible but it is shown to illustrate the limits of decreasing dead time.

Figure 13 to Figure 15 are the zero dead time results corresponding to Figure 10 to Figure 12 respectively. Figure 13 shows the number of replies as a function of incoming request. The number of replies is significantly higher than in the nominal case, especially for large numbers of incoming requests. Figure 14 shows that even at 5400 ppps, the reply efficiency is well above 70%.

The implications of the change are significant when we examine availability versus capacity in Figure 15. The figure shows that 95% availability can be achieved with a more modest 60% RRE. It also shows that having a RRE of 70% yields 85% availability.

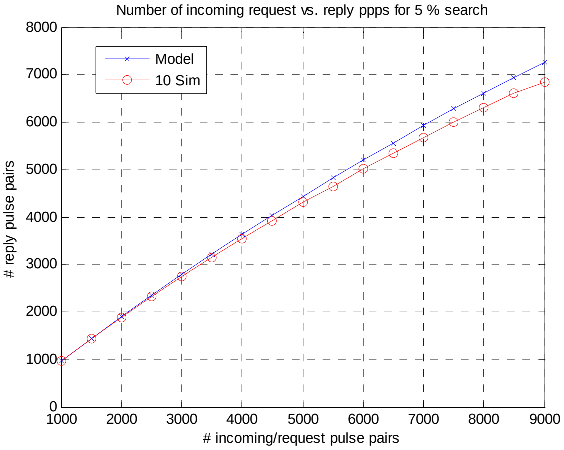

Figure 13. Total DME replies vs. total incoming requests (No dead time, 10 Sims)

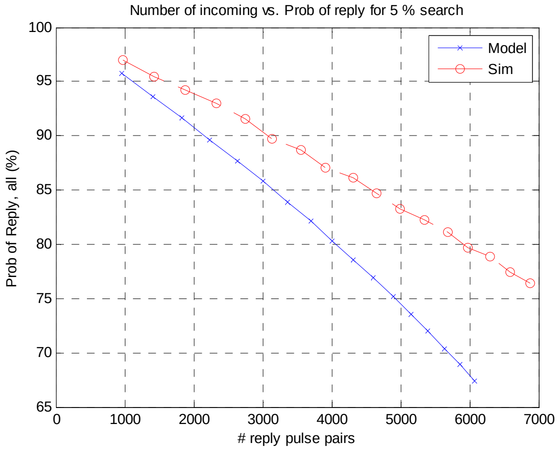

Figure 14. Reply Efficiency vs. total DME replies (No dead time, 10 Sims)

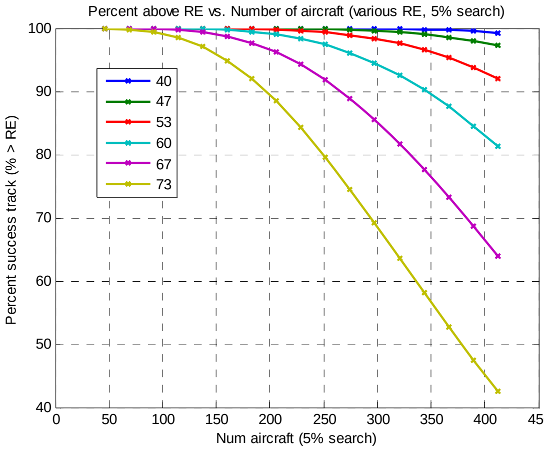

Figure 15. DME Ranging Availability vs. Number of Aircraft for Different RRE Levels (No dead time)

OBSERVATIONS

Our results indicate that increasing DME reply limit alone does not adequately increase capacity and comes at a cost of decreased reply efficiency. So increasing DME beacon reply limit is only part of the solution and it needs to be coupled with other changes to adequately meet APNT needs.

Changes in both airborne and ground equipment that could increase capacity are possible and can improve capacity. On the groundside, we showed that decreasing dead gate time can be useful. Another change is prioritization where the DME gives priority to closer (more powerful) traffic. This would alter the distribution of RE. In avionics, changes include being able to handle lower RE (having a lower RRE) and utilizing fewer requests per second for search or track. In fact, some of these features may already be incorporated in current DME avionics. For example, many the number of requests used for tracking is typically lower than the 15 ppps indicated.

5. MULTILATERATION CAPACITY

We will discuss the MLAT results by examining the probability of clear reception on the ground, the probability of positioning on the ground, and the probability of getting position on the aircraft. The results from each portion provide some insight into the capacity of MLAT and its limitations.

PROBABILITY OF CLEAR RECEPTION ON GROUND

First, we determine our likelihood of receiving an aircraft broadcast. This determination is also something studied while developing ADS-B and those results can be used to check the model.

Figure 16 shows the probability of clear reception on the ground per Mode S ES transmission versus the number of aircraft in range. The first three scenarios discussed in Table 2 are shown. For all cases, analytic and simulation (dashed line) results are in good agreement. When there are ATCRBS transmissions, the probability of clear reception is quite low by the time there are 50 aircraft. ATCRBS is a significant source of interference. Even with ATCRBS is gone, the probability of clear reception drops to about 45% at 260 aircraft. The results on UAT using the basic ADS-B broadcast are seen in Figure 17. In the figure, three cases are shown. The three numbers in the legend indicates the number of basic UAT ADS-B, long UAT ADS-B and ground UAT uplink broadcasts per second per aircraft. The UAT probability of clear reception is generally better than 1090.

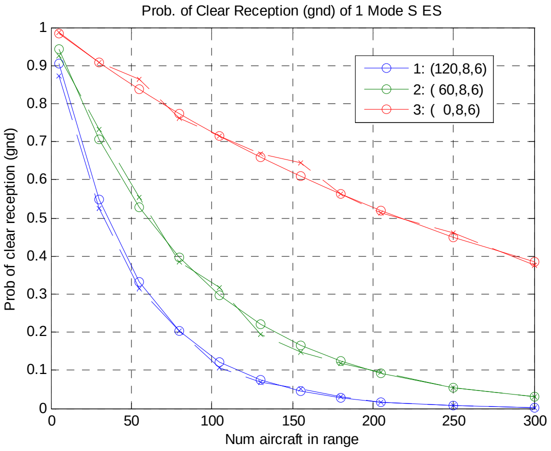

Figure 16. Probability of Clear Reception on the Ground of 1 Mode S ES broadcast (Dashed line is Simulation) vs. Number of Aircraft

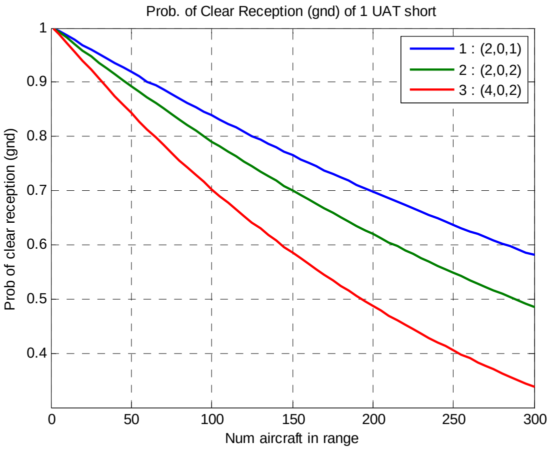

Figure 17. Probability of Clear Reception on the Ground of 1 UAT basic ADS-B broadcast vs. Number of Aircraft (Three cases)

The results are in reasonable agreement with [13] which showed a per squitter reception of 25% at up to 40 NM radius in the LA area. For the nominal case (case 2), 25% reception corresponds to about 120 aircraft is at 35 NM under the LA Basin model. These levels are quite adequate for ADS-B as only one message needs be received roughly every five seconds. In fact, Figure 16 and Figure 17 imply that the probability of receiving one ADS-B message over five seconds is quite reasonable for both channels even at high aircraft densities. This is because the ground has approximately 30 opportunities to clearly receive one broadcast. This is the presumably the same conclusion that led to the adoption of ADS-B.

PROBABILITY OF POSITIONING

Calculating the probability of determining position on ground follows naturally from the probability of clear reception. For horizontal positioning, reception of the same message at three or more stations is needed. This calculation is useful for several reasons. First, this probability represents the availability of MLAT for surveillance. Second, if we remove the effect of uplink transmissions, it is also the best case for MLAT based navigation. This represents the case where the position uplink is perfect and does not interfere with the reception of aircraft broadcast. Hence, it is the limiting case for using a different uplink channel.

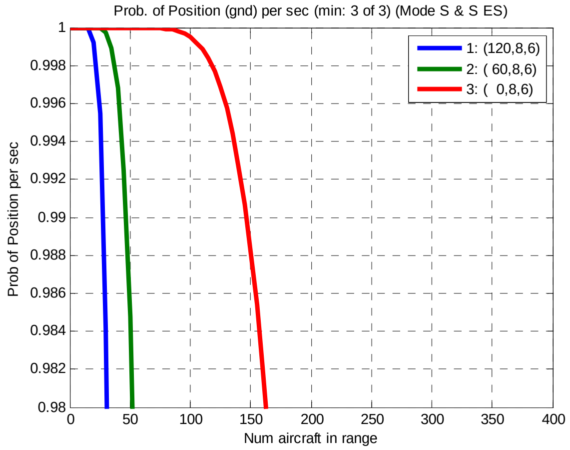

Figure 18. Probability of Deriving Position on the Ground over 1 second using Mode S and S ES broadcasts vs. Number of Aircraft (3 GBT, All uplink)

Figure 18 shows the probability of positioning on the ground over one second for 1090 assuming only three ground stations (GBTs). In this case, both Mode S and Mode S ES can be used for multilateration. So for position determination over one second, at least one of the 8 Mode S or 6 Mode S ES messages transmitted over the interval must be received by all three stations.

The probability of positioning on the ground also depends on the number of ground stations. More ground stations increases redundancy allowing for positioning even if some stations miss the message. Figure 19 shows the results if there are five ground stations. Significant improvements can be seen. For example, the aircraft capacity supported at 99% probability is more than doubled the three station case.

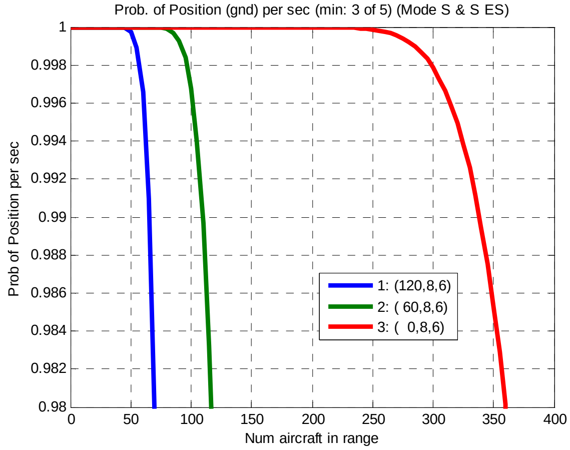

Figure 19. Probability of Deriving Position on the Ground over 1 second using Mode S and S ES broadcasts vs. Number of Aircraft (5 GBT, All uplink)

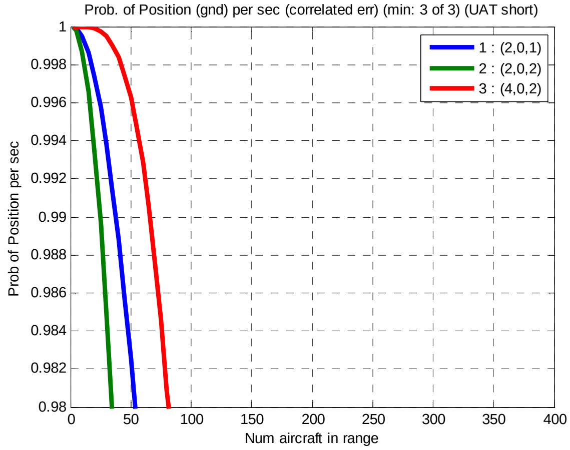

Figure 20. Probability of Deriving Position on the Ground over 1 second using UAT basic ADS-B vs. Number of Aircraft (3 GBT, All uplink, correlated)

Figure 20 and Figure 21 show the corresponding results for UAT. For UAT, we give the example where perfect correlation is assumed. The results are a bit worse for the uncorrelated case with three GBTs and are comparable to nominal (case 2) 1090 performance. For five GBTs, the performance is only slightly worse than the correlated case (as there is additional redundancy). UAT results are comparable to 1090 despite its better probability of clear reception. This is because there are 2-4 opportunities to receive a broadcast on UAT versus 14 on 1090.

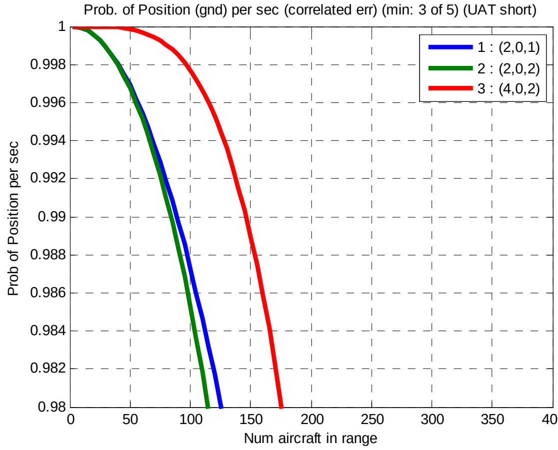

Figure 21. Probability of Deriving Position on the Ground over 1 second using UAT basic ADS-B vs. Number of Aircraft (5 GBT, All uplink, correlated)

PROBABILITY OF POSITION AT AIRCRAFT

The probability of position at the aircraft takes into account the position uplink transmission to the aircraft. If we use the same uplink as the downlink, then the uplink transmission can be interfered with and it can also interfere with the downlink. Figure 22 shows the probability of getting position to the aircraft assuming three GBTs with all GBTs transmitting two position messages per aircraft per second. The number and rate of ground stations providing position updates to the aircraft is one parameter that can be optimized for performance. More uplinks provide more redundancy but they also cause more interference. As seen from the figure, the aircraft capacity supported at 99% availability is low when there are only three ground stations. The result for five GBTs on 1090 is seen in Figure 23. Figure 24 and Figure 25 show the corresponding UAT results assuming correlation.

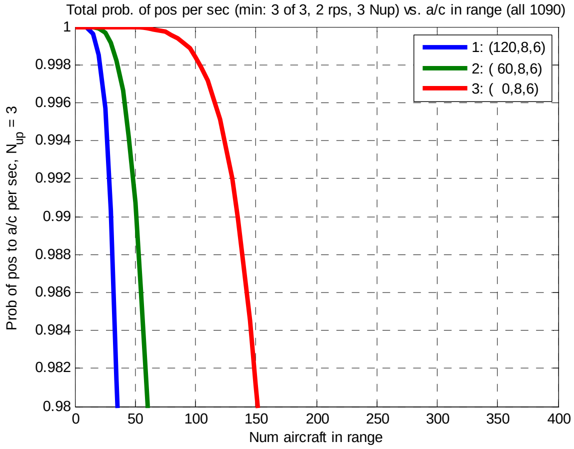

Figure 22. Probability of Getting Position to Aircraft over 1 second using Mode S and S ES broadcasts vs. Number of Aircraft (3 GBT, All uplink)

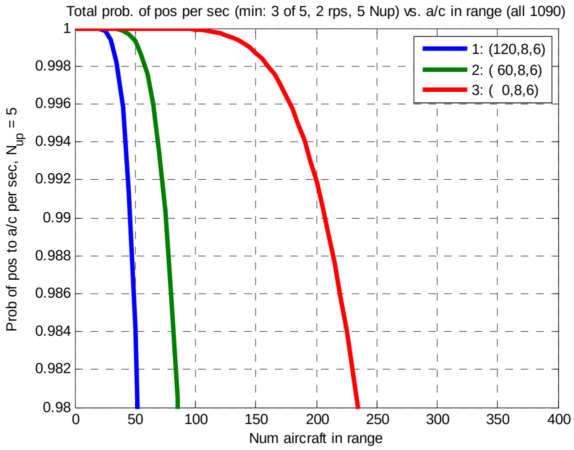

Figure 23. Probability of Getting Position to Aircraft over 1 second using Mode S and S ES broadcasts vs. Number of Aircraft (5 GBT, All uplink)

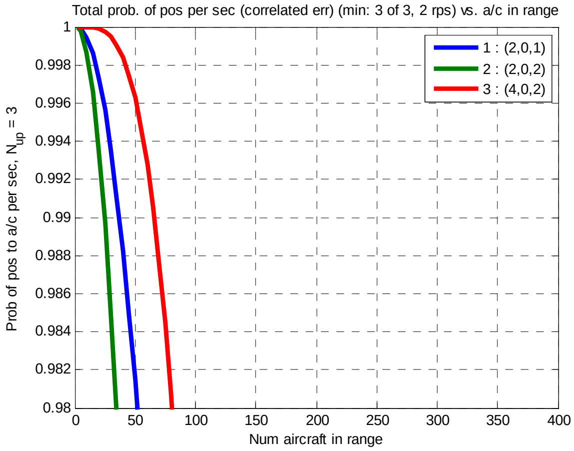

Figure 24. Probability of Getting Position to Aircraft over 1 second using UAT basic ADS-B broadcasts vs. Number of Aircraft (3 GBT, All uplink, correlated)

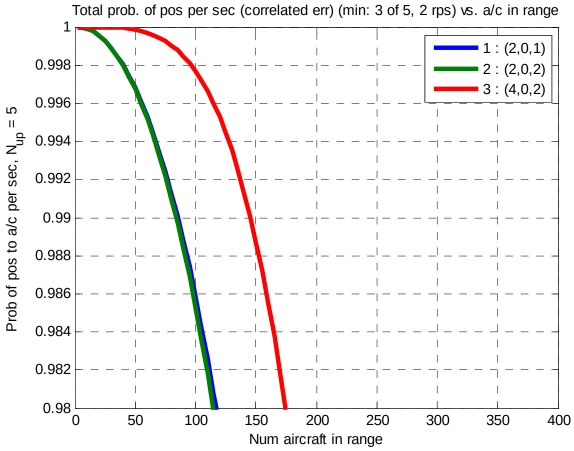

Figure 25. Probability of Getting Position to Aircraft over 1 second using UAT basic ADS-B broadcasts vs. Number of Aircraft (5 GBT, All uplink, correlated)

OBESRVATIONS

The results indicate that supporting MLAT based navigation on ADS-B channels is feasible but meeting the full capacity anticipated in the future will be challenging. While these channels are sufficient for surveillance, navigation has higher needs. But positioning requires the reception of the same message at three or more stations rather than one for ADS-B. Furthermore, an update rate of at least one hertz (Hz) is desirable, particular in terminal airspace. Surveillance rates are typically much lower. These two requirements place a much higher burden on the capability of the current system than required by ADS-B or MLAT surveillance.

It is important to note that the results are conservative. First, the model is conservative. Second, only a fraction of the traffic is on each channel as commercial aircraft use only 1090 and GA use UAT. Finally, there should be lower ATCRBS transmissions in the future as aircraft transition to ADS-B. The results show that in the limiting case of having no ATCRBS transmissions, capacity nearly triples at 99% availability.

Additionally, there are several means to improve the capacity of MLAT based navigation. The analysis shows that having more ground stations can significantly aid capacity. Another means is to use another uplink channel or optimizing the uplink rate. The uplink can cause significant interference and proper design can greatly improve capacity. Finally, we can prioritize transmission such that those aircraft needing the highest position availability and update rates transmit more frequently.

6. CONCLUSIONS

For DME capacity, the study shows that while newer DME transmitters can respond to more requests, this responsiveness comes at a cost of decreasing average reply efficiency. This can be an issue depending on the required reply efficiency in the avionics. Hence it is important to work with DME avionics manufacturers to understand the effects and limits of lowering reply efficiency. The analysis shows mean RE can be maintained at increased capacity with changes to the DME dead time. Additionally, DME transmitting logic may be created such that while the average RE remains, the distribution will be such that most aircraft will recover 70% or more replies. One way is to prioritize responses towards stronger requests. Other mitigations include improved avionics, some of which may already be implemented.

The analytic model indicates that MLAT based navigation is reasonable but channel congestion presents a significant challenge to using it to support the full capacity of the high-density airspaces of the future. This should not suggest that pursuing MLAT based navigation is not worthwhile. While APNT use of MLAT on transponder frequencies may be challenging, it is possible to improve the performance. Additionally, we can reduce the conservatism built into the model and requirements. For example, 1090 only needs to handle a fraction of the air traffic. Mitigating factors include lower ATCRBS transmissions. Additionally, even with limited capacity, MLAT may be useful to serve specific user groups such as GA or specific operational zones such as terminal airspace.

ACKNOWLEDGMENTS

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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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