Investigation of APNT Optimized DME/DME Network Using Current State-of-the-Art DMEs
Ground Station Network, Accuracy, and Capacity

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Abstract—An optimized DME/DME network is one of the Federal Aviation Administration’s (FAA) proposed Alternative Position, Navigation, and Timing (APNT) architectures. In comparison to other FAA-proposed APNT architectures, namely DME pseudolite network and passive Wide-Area Multilateration, airline operators find DME/DME more attractive for navigation back-up, as this solution requires no change to avionics used by nearly all commercial aircraft, thus reducing equipage costs to private companies. It is also advantageous because the absolute DME range measurements likely require a lower number of stations than the other architectures, thereby minimizing the cost to the public of installing new infrastructure. However, the insufficient range accuracy of the traditional DME (DME/N) has caused hesitation in actively pursuing this solution. U.S. and ICAO DME range accuracy standards of 0.2 nm is insufficient to support RNAV/RNP 0.3 nm operations, the performance the FAA has defined as needed for APNT. However, these standards are based on antiquated DME designs and have failed to account for advancements in both aircraft and ground station radio designs and performance. Recent flight inspections of DME range determined that the accuracy of the current state-of-the-art DME (DME/N) ground transponder is much better than 0.2 nm using current-day DME avionics. This enhanced accuracy presents an opportunity to leverage this technology and the network of DME ground stations for APNT. The DMEs in most stations in the National Airspace System (NAS) have been in service for more than 20 years and are due for replacement. It is thought that replacing DME legacy radios with modern state-of-the-art DMEs could support RNAV/RNP 0.3 operations, as well as optimize coverage with minimal addition to the DME network. This supposition leads to the feasibility study of the proposed APNT optimized DME/DME network. Using the expected range accuracy of the state-of-the-art DMEs, this paper investigates the feasibility of this proposed APNT solution by answering the following two key questions. First, what would be the optimal DME/DME ground station network that enables RNAV/RNP 0.3 operation for navigation and surveillance? Second, will the DME/DME network have sufficient capacity to support high density air traffic such as the 2020 LA basin model? The paper provides preliminary research results, by evaluating selected areas of the continental United States. Recommendations for network operation are based on the sample areas.

Keywords; APNT, DME/DME, Facility Location, Capacity

I. INTRODUCTION

Distance Measuring Equipment (DME) is a pulse ranging system used to measure the distance between the aircraft and the ground station based on the radar principle. There are three types of DMEs; DME/N (narrow), DME/W (wide) and DME/P (precision) [1]. Except for a few cases, the DME/N is predominantly used throughout the world. Traditionally, the DME (DME/N), collocated with a VHF Omnidirectional Range (VOR), was used for rho-theta navigation. In this navigation method, an aircraft flies the connected routes of the collocated DME/VOR stations by using the distance (rho) and azimuth (theta) provided from the stations. This rho-theta navigation is inefficient and no longer a preferred means of navigation. Another possible navigation method using DME is DME/DME positioning. This positioning technique computes aircraft horizontal position by using distance measurements from more than two different DME ground transponders and the known location of them. The DME/DME positioning is one of the enablers of Area Navigation (RNAV) that allows user-preferred and direct courses within the service area, and most large airline and business jets are equipped with and continue to use DME/DME avionics. Because RNAV is an important feature in the U.S. Next Generation Air Transportation System (NextGen), the FAA is expanding the DME/DME positioning service at Flight Level 180 by filling coverage gaps in the current DME infrastructures in Conterminous U.S. (CONUS) [2].

NextGen relies on RNAV with Required Navigation Performance (RNP) to meet future air traffic capacity and efficiency demands because RNAV/RNP allows for closer spacing between aircraft and flexible flight procedures. To enable RNAV/RNP in the NAS, NextGen primarily uses the Global Navigation Satellite System (GNSS). However, the GNSS service is susceptible to interruption by manmade and atmospheric effects. If a GNSS outage occurs for a significant time, air traffic management will be severely disrupted. For this reason, FAA has recently initiated a program pursuing an Alternative Position, Navigation, and Timing (APNT) service that will continuously provide RNAV/RNP capability during the GNSS outage. From FAA’s preliminary study on possible APNT systems, an architecture utilizing DME/DME
positioning was proposed [2]. The architecture is referred to as the APNT optimized DME/DME network and is to provide the RNAV/RNP capability through DME/DME positioning using a network of 1100 currently deployed DMEs and by leveraging 800 potentially usable Automatic Dependence Surveillance-Broadcast (ADS-B) Ground-based Transceiver (GBT) facilities. Additional sites may need to be added to provide seamless APNT coverage over CONUS.

The APNT optimized DME/DME network presents the least impact to operator equipage and to ground infrastructure compared to the other proposed architectures such as a pseudolite network or passive Wide-Area Multilateration [3]. In spite of these important benefits, the relatively poor ranging accuracy of 0.2 nautical miles (nm) in the DME standards makes this alternative seem infeasible for the anticipated APNT performance [4]. However, today’s state-of-the-art DME ground transponder and airborne interrogator are expected to be significantly improved such that their ranging accuracy greatly surpasses 0.2 nm. Recent flight tests and the evaluation of today’s DME performance by FAA’s APNT team support the improved range accuracy [5, 6]. Therefore, the feasibility of the APNT optimized DME/DME architecture can be more properly evaluated when the state-of-the-art DME performance is taken into account.

The two key elements to be analyzed in the feasibility analysis are the required ground network/infrastructure and the DME capacity. Focusing on these two questions, this paper presents a preliminary feasibility analysis of the APNT optimized DME/DME network using the state-of-the-art DMEs (DME/N) in a selected area of CONUS. Section II first reviews basic DME operations and the projected performance of the current state-of-the-art DMEs. In Section III, the APNT navigation and surveillance requirements and the corresponding airspace performance zones are discussed. Within the context of a feasibility analysis, a coverage analysis method is employed to determine an optimal DME/DME network that requires minimal augmentation to existing ground infrastructure [7]. Using the coverage analysis method, two resultant optimal DME/DME networks are presented for the selected region: one for APNT navigation and one for surveillance requirements. Furthermore, a DME capacity analysis in Section IV investigates whether the DME transponders in the resultant optimal networks can process the expected interrogation loading. The strategy of the capacity analysis in this paper is to calculate the reply efficiency using the simulated interactions between a given aircraft distribution and the resultant optimal ground networks. This approach is motivated by the fact that the realistic DME interactions can be simulated by using the known DME/DME network geographic layout, thus it leads to a reliable estimate of reply efficiency given an air traffic distribution. Using the calculated reply efficiencies, DME/DME positioning availability for the two resultant DME/DME networks is presented. Lastly, conclusions and recommendations are provided based on this research.

II. DME OPERATION AND PERFORMANCE

A. Overview of DME

The DME operation frequencies are in the range of 960 – 1215 MHz. These frequencies are divided into 252 channels with 1 MHz separation. A fixed channel is assigned to each ground transponder, with aircraft DME interrogators able to tune to any transponder DME frequency. The interrogator initiates communication with the ground station by sending randomly jittered interrogations of 120 – 150 pulse pairs per seconds (ppps) to one transponder frequency. The purpose of jittering is to distinguish valid replies from the DME replies to other interrogators. Once the interrogator confirms proper communication with a ground transponder, it enters into a tracking mode in which the interrogator sends interrogations (also randomly jittered) at a lower rate 24 – 30 ppps. The normal single aircraft interrogator is adequate for rho-theta navigation when used in conjunction with a VOR because the navigation method only needs one transponder at a time. Multi-channel or scanning DME avionics use interrogator architectures capable of simultaneously obtaining multiple DME distance measurements. The number of available channels in a scanning DME is typically between two and six [1]. In a six channel design, five of the channels are used in the foreground mode to provide slant range distance measurements for position computation. The sixth channel is assigned to the background mode which is used for an acquisition of new transponder stations. The average interrogation rate of a scanning DME is limited to 48 ppps for all frequencies [9].

The DME interrogation (in X-mode) consists of a pulse pair whose pulse shapes are approximately Gaussian with a separation of 12 μs for both of interrogation and reply. There exist other modes such as Y, W, and Z, but they are not considered in this paper because they are rarely used in today’s systems. When the ground transponder receives a valid X-mode interrogation, it sends a reply with the same type pulse pair arrangement after a 50 μs time delay. In addition to reply pulses, the ground transponder transmits squitter and facility identification signals. These two signals also use the same type of pulse pair. The squitter signal consists of random transmissions at a rate of 700 ppps to 850 ppps and is used for the automatic gain control of the interrogator. The identity signal consists of the transmission of the assigned beacon code for the transponder in the form of dots and dashes of identity pulses (International Morse Code) and should be transmitted at least once every 30 seconds [4].

B. DME (DME/N) Ranging Accuracy in the Standards and State-of-the-Art DMEs

The current DME specifications require range accuracy better than 0.2 nm for 95% of time including any performance degradation contributed by airborne interrogators, propagation effects, and ground transponders. The error contribution of an airborne interrogator should not be more than 0.17 nm (315 m, 95%) [4,10]. Previous analysis on propagation effects reported that multipath error could be as large as 0.04 nm (74 m, 95%) [1]. Taking this value as the multipath error contribution, the transponder range error contribution can be up to 0.10 nm (180 m, 95%).
Recent testing has shown that the state-of-the-art DME significantly outperforms the required range accuracy in the current standards. Fig. 1 shows the histogram of the averaged range error during flight tests of a state-of-the-art DME in Qabala, Azerbaijan [5]. The inspection aircraft was orbiting the DME transponder at 10 nm radius and 6000 ft Above Ground Level (AGL). The range errors shown in the histogram were averaged values per 10 degrees arc of the circle. The truth source determining the range error was differential GPS. The DME range measurement has a bias about 12 meters and a standard deviation of 4 meters. The standard deviation of 4 meters may not properly represent the true noise level of the DME slant range during the test because the DME range measurements have already been averaged by the flight inspection system. Instead, the standard deviation may come primarily from the remaining multipath after the averaging. It can also be inferred that the range error introduced by the airborne interrogator could be quite minimal in the data because a typical flight inspection practice is to measure and calibrate a bias that could be introduced by the inspection system itself. Therefore, the bias of 12 meters may largely be caused from the ground transponder system. A DME antenna survey error could be a probable error source, as well.

The FAA APNT team has recently surveyed the performance of the state-of-the-art DME airborne interrogator and ground station transponder [6]. The projected ranging accuracies (95 %) of the DME/N transponder and interrogator are 30 meters and 46 meters, respectively. Recent modeling suggests that multipath could be close to 43 meters (95 %). As a result, the Root-Sum-Square of the three major error sources is 70 meters (95 %). Although this claim needs to be verified with further analysis and experimental testing, the flight inspection data indicates that the actual state-of-the-art DME transponder range accuracy could be close to the transponder error allocation in the projected DME/N range accuracy. Assuming that the other projected error allocations also closely represent the true error distribution, this paper investigates the APNT optimized DME/DME network with the projected range accuracy.

III. APNT OPTIMIZED DME/DME GROUND NETWORK

A. APNT Requirements

The FAA’s APNT performance requirements are summarized in TABLE I for the operation of en route, terminal, and lateral navigation (LNAV). The airspace performance zones of each case are depicted in Fig. 2 [2]. For example, RNP 0.3 (or LNAV) performance is required within 5 Statute Miles (SM) radius of an airport at 500 ft AGL. Also, RNP 1.0 (or Terminal) is required in the entire airspace of Zone-3 following the 2 degree slope relationship between altitude and airport radius up to FL 180 and 89 SM.

<table>
<thead>
<tr>
<th>Navigation</th>
<th>Surveillance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>Containment</td>
</tr>
<tr>
<td>En Route</td>
<td>4 nm</td>
</tr>
<tr>
<td>Terminal</td>
<td>1 nm</td>
</tr>
<tr>
<td>LNAV</td>
<td>0.3 nm</td>
</tr>
</tbody>
</table>

The accuracy requirement for navigation, i.e. Total System Error (TSE), is further allocated to Navigation System Error (NSE) and Flight Technical Error (FTE). The accuracy requirement can be translated to Horizontal Dilution of Precision (HDOP) using the relationship

\[
\begin{align*}
\text{HDOP}_{\text{NAV}} = \sqrt{\frac{\text{TSE}^2 - \text{FTE}^2}{4\sigma_{\text{range}}^2}}. \\
\end{align*}
\]

Assuming 0.25 nm (95 %) FTE [6] and the projected state-of-the-art DME range accuracy of 70 meters (95 %), the minimum required HDOP value for RNP 0.3 navigation is \(\text{HDOP}_{\text{min}} = 4.39\). Assuming 0.5 nm (95 %) FTE for RNAV/RNP 1.0, \(\text{HDOP}_{\text{min}} = 22.91\) is required for RNAV/RNP 1.0 navigation. The minimum required HDOP value for surveillance is found by using the relationship between position and ranging source uncertainty as shown in (2).
This will not always be the case. When the coverage gaps extend to a large area, a station placement becomes a complex problem. This facility location problem has been a research subject for several decades in the areas of mathematics, computer science, and management science [11]. In computational complexity theory, the problem is classified as NP-complete. Loosely speaking, ‘NP-complete’ means that there are no known general efficient algorithms that output an exact solution(s) other than an (almost) exhaustive search. When faced with the problem of NP-complete, the focus normally shifts from seeking an exact solution to an approximation by using heuristics that can be applied to a particular problem [12]. Following the same philosophy, a solution to the APNT station placement problem will be sought based on heuristics that are discussed below.

In searching for an efficient ground station network that provides good accuracy coverage with a minimum number of stations, the two important heuristics are the preferred location of a candidate station and the required geometrical separation between stations. The preference of the candidate station locations is exemplified in Fig. 4. In the figure, the entire area is the airspace projected onto the ground and consists of Region 1 and Region 2. Region 1 is the area requiring the highest accuracy such as RNP 0.3, while Region 2 requires the lower accuracy such as RNP 1.0. These two heuristics are motivated from the observations that an optimal station network with a minimum number of stations has the most stations in Region 2 with a large separation between them to provide a good azimuth angular diversity to the area requiring the highest accuracy [7]. An additional heuristic is preference for the use of the existing stations. The existing stations are the red ‘X’s in Fig. 4, and they could currently be located in either Region 1 or Region 2. It is clear to see that there could be numerous station layouts yielding the same number of stations that meet the coverage requirement. In such case, it is always beneficial to choose the station layout that includes the largest number of existing stations to minimize build-out cost.

Taking advantage of those heuristics, the coverage analysis method uses a two-step Binary Integer Linear Programming (BILP) formulation to search for valid solution sets. The two steps are iterated until a termination criterion is met. The first step or baseline formulation is expressed as

\[
\min Z = \sum_{i \in T} w_i x_i = w^T x
\]

subject to:

\[
Ax \geq b
\]

\[
Cx \leq d
\]

\[
Fx \leq g
\]

\[
x_i \leq Z_{\text{min}}
\]

\[
x_i \in \{0,1\}
\]

where \(Z\) is the cost function to be minimized and \(x\) is the index vector of the candidate station location corresponding to a grid of the given area. If \(x_i = 1\), then it contains a candidate station. Otherwise, \(x_i = 0\). The vector \(w\) is a weighting factor on the values in \(x\) and is lower for the preferred candidate station locations. For example, if \(x_i\) is in Region 2 and is one of the existing stations, \(w_i\) takes the lowest value. On the other hand,
if \( x_i \) is in Region 1 and would be a new station site, then \( w_i \) takes the highest value. The matrix \( A \) is a visibility matrix and has the information about the radio propagation line-of-sight between an aircraft in a given location and the candidate station locations. The \( i^{th} \) row of \( A \) corresponds to an aircraft location grid and the \( j^{th} \) column to a candidate station location grid in a given area. The elements of matrix \( A \) also take on values of 0 or 1. If the aircraft at the \( i^{th} \) row location “sees” the station at the \( j^{th} \) column location, \( A_{ij} \) is equal to 1. Otherwise, \( A_{ij} \) is 0. Each element of the vector \( b \) is the required minimum number of visible stations at the corresponding aircraft location.

In the second constraint, \( C \) and \( d \) control the minimum separation between stations. If the distance between \( i^{th} \) and \( j^{th} \) stations is less than the minimum separation, \( C_{ij} \) is equal to 1. Otherwise, \( C_{ij} \) is equal to 0. The vector \( d = 1 \) is a vector of all 1s, which means that only one station is allowed to be inside the separation limit of another station location. The matrix \( F \) contains records of the previous solution sets \( x \), and the vector \( g = (x^T - 1) \) has all of its values equal to one less than the number of stations in the previous solution sets in \( F \). This constraint forces the BILP formulation to yield a unique solution for each iteration. Finally, \( Z_{\min} \) is the minimum cost among the valid solution sets found through previous iterations. Thus the last constraint, \( w^T x \leq Z_{\min} \), reduces the search space such that the BILP only looks for a new solution having a cost that is less than or equal to \( Z_{\min} \).

The second step of (4) is repeated until a solution set meeting the required HDOP is found or no solution is found due to the conflicts with the constraints. The impact of the vector \( b_{\text{mod}} \) is that the airspace locations with an insufficient HDOP value need visibility to at least one more station to improve the HDOP value. The matrix \( C_{\text{mod}} \) relaxes the separation between stations at small steps for each iteration, and \( F_{\text{mod}} \) is used only for the updated BILP formulation.

With the two-step BILP formulation, the block diagram in Fig. 5 shows the overall coverage analysis method to determine an optimal station network for a region having multiple major airports. This process is used to generate the APNT optimized DME/DME network in southern Florida discussed in the next subsection.

\[
\begin{align*}
\text{min } Z &= \sum_{i=1}^{n} w_i x_i = w^T x \\
\text{subject to: } A x &\geq b_{\text{mod}} \\
C_{\text{mod}} x &\leq d \\
F_{\text{mod}} x &\leq g \\
w^T x &\leq Z_{\min} \\
x_i &\in \{0,1\}
\end{align*}
\]

where \( b_{\text{mod},i} = \begin{cases} b_i + 1 & \text{if } \text{HDOP}_i > \text{HDOP}_{\text{req}} \\ b_i & \text{if } \text{HDOP}_i \leq \text{HDOP}_{\text{req}} \end{cases} \).

Note that (3) does not have the accuracy requirement as a constraint because it cannot be directly incorporated into the formulation. Therefore, the solutions from (3) do not necessarily satisfy the accuracy requirement. For this case, the coverage analysis method implements the second step or updated BILP in (4).
D. APNT DME/DME Optimized Network with State-of-the-Art DMEs

In this section, the APNT optimized DME/DME network with the state-of-the-art DMEs is investigated for the southern Florida region using the coverage analysis procedure. It is assumed that the aircraft is equipped with a scanning DME having 5 channels available for DME/DME positioning. When more than 5 DME transponders are available to the aircraft, it is also assumed that the scanning DME can choose a set of channels that will minimize the HDOP value, which may require a change to the way some flight management systems operate. This section first shows the geographic locations of the existing DME, GBT, and major airports in southern Florida. Then, the DME/DME positioning performance is examined for navigation and surveillance with the currently deployed DME network to identify the area requiring the station augmentation. Then, it will present the resultant APNT optimized DME/DME networks, one for navigation and one for surveillance.

1) Current DME/GBT Station Layout and DME/DME Positioning Performance in Southern Florida

Fig. 6 depicts 23 DME transponders and 14 GBT stations identified in southern Florida. The figure also indicates the location of 8 international airports, where RNP 0.3/LNAV is expected to be achieved. It should be noted that the DME/GBT stations shown in Fig. 6 may not represent all of the existing stations.

Figure 5. Overall Coverage Analysis Methodology Process

Figure 6. DME/GBT Stations and 8 International Airports in Southern Florida

Fig. 7 shows the airspace altitude profiles simplified in three levels for the region following the airspace performance Zone 3 depicted in Fig. 2. The accuracy requirement in the airspace follows the APNT requirement in TABLE I. For example, the RNP 0.3/LNAV accuracy is required in the gray color region of 500 ft AGL. The rest of the region having green and blue colors requires RNAV/RNP 1.0 accuracy. However, note that the surveillance requires the same level of accuracy (96.2 m, NACP 8) at all of the defined altitudes. Fig. 8 shows the coverage gaps against navigation and surveillance accuracy requirement using the currently deployed DME network with the state-of-the-art DMEs. Most of the coverage gaps exist in the area where the aircraft altitudes can be low such as RNP 0.3/LNAV region.

Figure 7. Performance Zone Altitude Profiles in Southern Florida
2) APNT Optimized DME/DME Ground Network relative to Navigation Accuracy Requirement

Fig. 9 shows the resultant APNT DME/DME network relative to the navigation accuracy requirement. The coverage analysis method equally preferred existing DME and GBT stations and chose a network with a lower HDOP among the same number of total stations and new sites. The resultant optimal network has 8 DMEs, 4 GBTs, and 2 new sites. The resultant network satisfies the navigation accuracy requirement in the entire region of the map as shown in Fig. 10.

3) APNT Optimized DME/DME Ground Network for Surveillance

The resultant network for surveillance includes 14 DMEs, 6 GBTs, and 5 new sites as shown in Fig. 11. The position accuracy parameterized by HDOP is shown in Fig. 12. The northern part of the map shows some coverage gaps having HDOPs larger than the required HDOP of 1.32. Those coverage gaps are acceptable at this point because their HDOP will be lower once the other stations outside the map are taken into account. Note that the network for surveillance can be used for navigation because the surveillance network provides better accuracy than the one required for navigation.

To take full advantage of the accuracy that can be provided from these two resultant networks, the ground DME transponders must provide minimum reply rates. This capacity problem is analyzed in the next section.
4) Discussion of the Optimality of the Resultant Optimized DME/DME Networks

In general, it is often difficult to verify if a solution from an optimization process is really optimal because the global or even local optimality cannot be easily determined due to the complexity of the problem. The same is true for this facility location problem. This subsection discusses the optimality of the resultant optimized DME/DME networks.

The optimal solution that the coverage analysis method seeks is the network having the minimum total number of stations using as many of the existing stations as possible, thus requiring a minimum number of new sites. Therefore, the optimality of a solution should be inspected by considering the following two factors: the total number of stations and the number of new sites. First, the minimum total number of stations can be approximated by finding the minimum number of stations required to provide the appropriate coverage in the low-altitude airspace near an airport. The reason is that the required set of stations for the low-altitude airspace mostly determines the entire network layout. The high-altitude airspace usually has no impact because aircraft can typically have a line-of-sight to many stations at that altitude. Assuming that the low-altitude airspace ranges from the center of an airport out to a 15 SM (0.22 degree angular distance) radius and a range source accuracy of 70 m (95%), the minimum number of stations could be as low as 2 or 3 for navigation depending on the geometry of stations relative to the airport. The three airports in Fig. 9 have 2 stations each except for the airports having common low-altitude airspace with other airports. This case will be further discussed below in this section.

The minimum number of new sites can be approximated by evaluating the coverage gaps from utilizing every possible existing station as shown in Fig. 15. Even with all of the existing stations, there still exist 2 localized coverage gaps for navigation and 4 for surveillance near the airports. Those coverage gaps exist in low-altitude airspace. Considering the low altitudes in those airspaces and the considerable distance among the coverage gaps, it would be ideal if only one new site is required to meet the required HDOP for each localized gap. In fact, the optimization process in the coverage analysis allocates 2 new stations in the network for navigation and 5 for surveillance as shown in Fig. 9 and Fig. 11, respectively. The network for surveillance needs one more station than the number of the localized coverage gaps because only two existing stations are available for the airport in the north-east region of the map.
Figure 13. HDOP Contour Plot with 3 Stations (red dots). The Area with White Color Represents the Coverage for Surveillance Accuracy Requirement

Figure 14. HDOP Contour Plot with 4 stations (red dots). The Area with White Color Represents the Coverage for Surveillance Accuracy Requirement

As discussed in this section, the two factors of the optimality criteria are well satisfied in the resultant networks for navigation and surveillance. In general, there could be various ways of checking the optimality of the solution and further research would be needed for a tighter optimality inspection.

IV. CAPACITY ANALYSIS

The important metric for DME capacity is the reply efficiency (RE) that is the percentage of replies provided by the transponder relative to valid interrogations. The minimum RE of the current specification is 70% [4]. To evaluate the REs of the DMEs in the two resultant networks from the above analysis, a Monte Carlo simulation is used. This test calculates the REs based on the simulated interactions between the DME transponders in the networks and the randomized air traffic distribution. Because a high air traffic density is expected in southern Florida, the 2020 Los Angeles (LA) Basin air traffic model is used to generate the aircraft distribution [8]. It is assumed that all aircraft have the same kind of scanning DME as used to develop the optimized DME/DME network.

A. AIR TRAFFIC MODEL

The parameters of the 2020 LA Basin air traffic model are summarized in Table II. The aircraft on the ground are ignored in this analysis because they do not generate interrogations. The aircraft moves in random directions with some assigned velocity. As was the case in the previous analysis of [8], 75 percent of the traffic over the sea was redistributed to be near or over the terrain. Fig. 16 shows an example snapshot of the air traffic distributed over the southern Florida region.

<table>
<thead>
<tr>
<th>Air Traffic Model Parameters</th>
<th>Aircraft Density</th>
<th>Altitude Distribution</th>
<th>Average Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parame-ter Ranges</td>
<td>5.25 aircraft/nm from the center of the area to 225 nm</td>
<td>Exponential distribution with a mean altitude of 5000 ft</td>
<td>130 knots at 0 – 3000 ft</td>
</tr>
<tr>
<td></td>
<td>0.00375 aircraft/nm² from 225 nm to 400 nm</td>
<td>200 knots at 3000 – 10000 ft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0025 aircraft/nm³ from 400 nm to 600 nm</td>
<td>3000 knots at 10000 – 25000 ft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.00125 aircraft/nm⁴ from 600 nm to 1000 nm</td>
<td>450 knots at 25000 – up ft</td>
<td></td>
</tr>
</tbody>
</table>

B. DME INTERACTIONS BETWEEN INTERROGATOR AND TRANSPONDER

The DME interaction is initiated from the airborne interrogator. A scanning DME interrogates at an average rate of up to 30 ppps for one frequency and can interrogate up to 48 ppps over all frequencies [9]. The interrogation rate is basically determined from the ratio of the maximum number of allowable interrogations and the number of channels in use by an aircraft. For example, with a 6-channel scanning DME using 5 channels for position computation, the minimum interrogation rate is 8 ppps. For this capacity analysis, the
number of channels in use is up to 6 by employing the same type of scanning DME as used in the coverage analysis.

Although an airborne interrogator sends valid interrogations to the ground transponders, not all of the interrogations will be processed by the transponder. There are several factors that inhibit the transponders from processing the interrogations. The first factor is the possibility of a dead time interval which is a period of time following the decoding of an interrogation pulse pair during which the transponder receiver is prevented from decoding other interrogation pulse pairs. The dead time interval can take about 60 µs when receiver blanking is used during ground facility transmissions [1]. Another factor is the possible overlap of interrogation pulses at the receiver which is known as the downlink garbling. When garbling occurs, it is unlikely that the receiver can properly decode the received pulses. To avoid a systematic garbling among airborne interrogators, an interrogator deliberately jitters the timing of its interrogation interval [13]. Of course, downlink garbling can still occur. In contrast, uplink garbling can be ignored because the RF frequency of a reply should be different among the ground transponders in view of the aircraft. A third factor is interrogation loading due to the internal monitoring function. The monitor in a transponder generates self-interrogation pulse pairs to check for proper operation in the reply functions. The self-interrogation pulse pairs can also prohibit the reception of an interrogation signal from the aircraft. It is assumed that the monitor generates self-interrogation pulse pairs to check for proper operation in the reply functions. The average RE of the DME networks is 70% for navigation and 80% for surveillance.

### C. DME Transponder Reply Efficiency in the Two Optimized DME/DME Networks

A 5 minute simulation period is used to estimate the REs of the two APNT DME/DME optimized networks. Fig. 17 shows the RE levels of the DMEs in the APNT optimized DME/DME network for navigation. The green markers in Fig. 17 represent DME stations having a good RE of greater than 75%. The yellow markers represent DMEs having a marginal RE of between 70% and 75%. The red markers represent DMEs having an insufficient RE of less than 70%. Fig. 18 shows the REs of the DMEs in the optimized network for APNT surveillance. The same colors were also used to indicate the RE levels. Note that the DMEs in the northern region have the lowest REs in Fig. 17 and Fig. 18. The reason is that those particular DMEs suffer a heavy interrogation loading because a denser air traffic distribution was allocated on the northern part than the southern region surrounded by sea. However, once the DMEs outside the shown map are taken into account, the loading will be reduced. Thus, REs for those transponders will also improve. The average REs of the DME networks are 70% for navigation and 80% for surveillance.

### D. DME/DME Positioning Availability Analysis

The REs obtained in the above analysis can be used to calculate a DME/DME positioning availability as follows. For the positioning availability analysis, it is assumed that the avionics only needs to obtain at least one slant range measurement within a given time interval or position update rate from each transponder to which a scanning DME is tuned. This assumption is based on the fact that a navigation computer has a decent capability of extrapolating the previous measurement to the current within the given short time interval. It is also reasonable to assume that the number of transponders in use by a scanning DME is typically 3 or 4 due to the required HDOP value. Using an averaged RE, denoted as $\text{RE}_{\text{avg}}$ of the DMEs in the optimized DME/DME networks, the

![Figure 16. High Density Air Traffic from 2020LA Basin Air Traffic Model Applied in Southern Florida](image)

<table>
<thead>
<tr>
<th>Parameters of DME Interaction Factors</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{NC} = \begin{cases} \text{Number of Channels in Use (up to 6)} , \ \geq 30 \text{ pps} \end{cases}$</td>
<td></td>
</tr>
<tr>
<td>Rate = $\frac{\text{4800}}{\text{NC}}$ , Interval = $\frac{1}{\text{Rate}}$ ± random jittering</td>
<td></td>
</tr>
<tr>
<td>$\text{Dead Gate Interval}$</td>
<td>60 µs</td>
</tr>
<tr>
<td>$\text{Monitor Self-Interrogation}$</td>
<td>100 ppps</td>
</tr>
<tr>
<td>$\text{Maximum Reply Transmission}$</td>
<td>4800 ppps</td>
</tr>
<tr>
<td>$\text{Downlink Garbling}$</td>
<td>$A = \text{Maximum pulse amplitude}$, First Pulse: Pulse overlap within 12 µs from the time at 0.1 A (leading edge), Second Pulse: Pulse overlap within 7 µs from the time at 0.1 A (leading edge)</td>
</tr>
</tbody>
</table>
probability of not receiving a reply from a transponder in the given time interval is

$$\Pr_{no\_reply} (IR) = (1 - RE_{avg})^{IR}$$ (5)

where $IR$ is the number of interrogations determined from the number of channels in use. Using $\Pr_{no\_reply}$, the positioning availability is computed as

$$\Pr_{re} (M) = 1 - \sum_{i=1}^{M} \binom{M}{i} (\Pr_{no\_reply})^{i} (1 - \Pr_{no\_reply})^{M-i}$$ (6)

where $M$ is the number of transponders in use by a scanning DME.

![Figure 17. Reply Efficiency Levels of the Optimal DME/DME Network for Navigation Calculated from the Monte Carlo Simulation](image)

![Figure 18. Reply Efficiency Levels of the Optimal DME/DME Network for Surveillance Calculated from the Monte Carlo Simulation](image)

The value of $RE_{avg}$ was found to be 70% for the DMEs in the optimized network for navigation and 80% for surveillance. Taking $M = 3$ for navigation, the value of $Pr_{re}$ is 99.98% for a position update every 0.5 seconds. In turn, taking $M = 4$ for surveillance, the value of $Pr_{re}$ is 99.97% for the same position update rate.

V. CONCLUSIONS

The state-of-the-art DME (DME/N) provides much higher range accuracy than the requirements in the current DME standards. The projected range accuracy of the state-of-the-art DME is expected to be as low as 70 meters (95%). Recent flight inspection data show that the presumable range error caused by the state-of-the-art DME transponder has a bias about 12 meters. Comparing the bias with the error allocation of 15 meters (1 sigma) to the transponder in the projected range accuracy, the flight inspection data indicates that the actual state-of-the-art DME transponder range accuracy could be close to the allocation of 15 meters. Although the projected range accuracy must be validated by further evaluation, this projected range accuracy was used here to investigate the APNT optimized DME/DME network.

Optimized DME/DME networks were presented for APNT navigation and surveillance service and analyzed with respect to capacity for southern Florida region of CONUS. The two optimal networks were found from using a coverage analysis method based on binary linear integer programming. The resultant optimal network meeting the navigation accuracy requirement has 8 DMEs, 4 GBTs, and 2 new sites. The resultant optimal DME/DME network for surveillance has 14 DMEs, 6 GBTs, and 5 new sites. Two factors have been suggested to check the optimality of the resultant network, and the optimality analysis showed that the two factors were overall well satisfied in the resultant DME networks. The capacity analysis was performed on the two resultant networks by simulating the DME signal interactions between the transponders of the network and randomized aircraft distribution based on the 2020 LA Basin Air Traffic Model. This simulation facilitated the calculation of Reply Efficiency (RE) of the DMEs. The average RE was observed to be 70% for navigation and 80% for surveillance. Using the average RE, the DME/DME positioning availability of the networks was found to be 99.98% for navigation and 99.97 % for surveillance.

From the above results, it can be concluded that the two networks do not require a significant number of new stations, 2 for navigation and 5 for surveillance. However, the capacity of the network for navigation was found to be either insufficient or marginal particularly in the upper region of southern Florida. The unused existing DME and GBT stations in the region could be utilized to reduce the interrogation burden. In contrast, the network for surveillance had no problem in providing good (above 75%) reply efficiency by taking advantage of the additional 11 transponders. Therefore, the optimal network for surveillance is preferred to the network for navigation because it provides much better performance benefit in accuracy and capacity with a small cost increase by considering that the driving cost factor is the number of new sites.
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