TECHNICAL MEMORANDUM
OU/AEC 06-24TM15689/0003-3

REVIEW OF THE FEDERAL AVIATION ADMINISTRATION'S DISTANCE MEASURING EQUIPMENT – AREA NAVIGATION (DME RNAV) FLIGHT INSPECTION REQUIREMENTS, CONCEPTS, AND IMPLEMENTATION PROPOSED FOR THE NEXT GENERATION AUTOMATED FLIGHT INSPECTION SYSTEM

This report provides results of a review of the Federal Aviation Administration's distance measuring equipment – area navigation (DME RNAV) flight inspection requirements, concepts, and implementation proposed for the next generation automated flight inspection system. The DME RNAV route requires the availability of two or more DMEs although limited gaps in coverage are tolerated. RNAV route and procedure design is facilitated by FAA RNAVPro software. The software determines if suitable DME coverage exists for the procedure based on inter-site geometry and generalized assumed coverage characteristics. Flight inspection of the designed route is performed to assess actual DME coverage. The algorithm used in both RNAVPro and the flight inspection prototype Automated Flight Inspection System (AFIS) software is assessed and data from both implementations of the algorithm is compared to ensure compatibility between procedure design (RNAVPro) and FAA prototype AFIS software. The FAA AFIS equipped fleet (with prototype software) is conducting DME RNAV flight inspection missions using the software for data collection but not DME RNAV route approval.

by

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I. INTRODUCTION

Distance measuring equipment (DME) has been traditionally used in the United States national airspace system (NAS) to provide the slant range between the aircraft airborne interrogator and ground-based transponder antennas. The DME distance information may be used to support en-route, terminal, approach, landing, and departure operations when it is used in conjunction with other navigational aids (navaids), e.g., Very High Frequency Omni-directional Range (VOR) and Instrument Landing Systems (ILS).

In addition to the traditional applications, avionics have been developed that can interrogate multiple DME transponders thus enabling determination of aircraft position solely from DME facilities and an associated facility database. This application is referred to as scanning DME, or DME-DME Area Navigation (DME RNAV).

The future NAS architecture is expected to heavily utilize satellite-based navigation and landing systems [1]. One should note that RNAV procedures can be supported using satellite-based navigation systems. Any backup to satellite-based navigation must also provide support for RNAV. The positioning capability provided by DME RNAV makes DME a candidate backup system for satellite-based navigation. In order to use DME to provide RNAV, the service volumes of DME facilities will likely need to be expanded. However, before a DME can be used beyond the currently specified service volume, flight inspection of the extended service volume, among other things, must be performed to ensure that a safe, suitable signal exists within the extended volume.

DME facilities are typically installed with associated navigation and landing equipment (e.g., ILS or VOR). The DME service volume is typically defined by the service volume of the associated equipment. All DME facilities used to support DME RNAV procedures are also used to support other NAS functions. As such, they are subject to commissioning and periodic flight inspections as required to support typical NAS functions such as en-route, STAR, SID, approach, landing, etc. [2]. The purpose of this study is to evaluate the need for flight inspection of DME/DME and DME/DME/IRU RNAV procedures not necessarily the DME facilities involved. The findings of this study indicate that flight inspection of said procedures is required, particularly when aircraft containment along such procedures is required.

The Federal Aviation Administration (FAA) office of Aviation System Standards (AVN) has requested that the Ohio University Avionics Engineering Center (AEC) conduct an independent review and assessment of flight inspection requirements for DME RNAV operations. The following tasks are included: review DME RNAV flight inspection requirements and methodology, review resource requirements for supporting DME RNAV flight inspection, assess the impact of expanding the DME SSV to provide service for DME RNAV procedures, methods to maximize effectiveness of the flight inspection fleet, and review of the DME AFIS position estimation error (PEE) algorithm implementation.

II. BACKGROUND

This section presents a brief history of navigation techniques to give the reader a sense of the progression of aircraft navigation over time. A graphical comparison between the navigation characteristics of ground-based navigation equipment is presented. Discussion of the NAS designs and effect of the advent of RNAV equipment is then presented.

Early aviators used ground-based navaids to maneuver their aircraft from point A to point B. Usually this meant going through points X, Y, and Z to reach the destination in instrument meteorological conditions. Systems such as the non-directional radio beacons (NDB) and VOR provided this guidance between points with the "points" being the ground-based navaid facility. Emergence of advanced electronics and navigation techniques enabled users to begin navigating from point-to-point without being tied to the location of the ground-based navaid. The following discussion provides a brief description of some of the methods of navigation used from NDB to DME/DME RNAV.

To navigate using NDB involves flying "to" or "away" from the beacon. NDB provides an electronic indication of "which way to fly" to head "towards" or "away from" the beacon (Figure 1). It provides limited situational awareness in terms of the user's position or location. The aircraft can be located at any point along a line extending to/from the beacon. Travel beyond the operational range of the NDB requires that the aircraft travel from beacon to beacon.

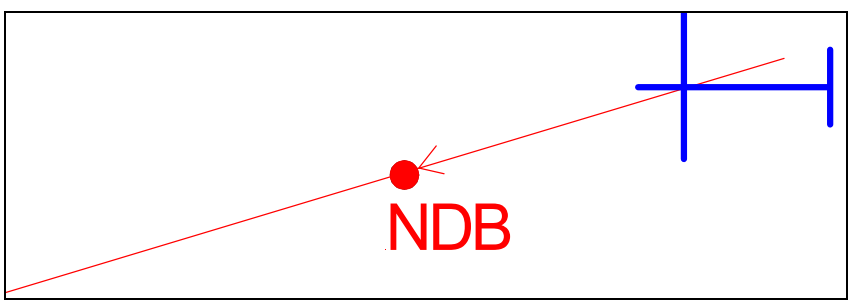

Figure 1. NDB Navigation

With VHF Omni-directional radio range (VOR) the user receives an electronic indication of theta (θ), which is analogous to compass bearing (Figure 2). Again, like NDB, VOR by itself does not provide information as to where the aircraft is along/on the radial. However, VOR does provide angular (radial) information to the aircraft which can be used to determine a general area of operation (position) of the aircraft on an aeronautical chart.

A single DME facility can provide the user with a slant-range measurement between the facility and the aircraft as shown in Figure 3. With this measurement the user knows the range from the DME facility. On its own the range measurement is of limited usefulness since the user could be anywhere on the circle defined by a radius equal to the range. When coupled with other navigational aids the DME becomes indispensable because of this ranging function.

When an aircraft has both VOR and DME the user can receive an electronic indication of their angle (θ) and range from a VOR/DME facility (see Figure 4). The user can determine their exact position relative to a VOR/DME facility and if the latitude and longitude of the VOR/DME facility is known the user can calculate the aircraft latitude and longitude. This gives a fairly precise indication of the user's location on an aeronautical chart.

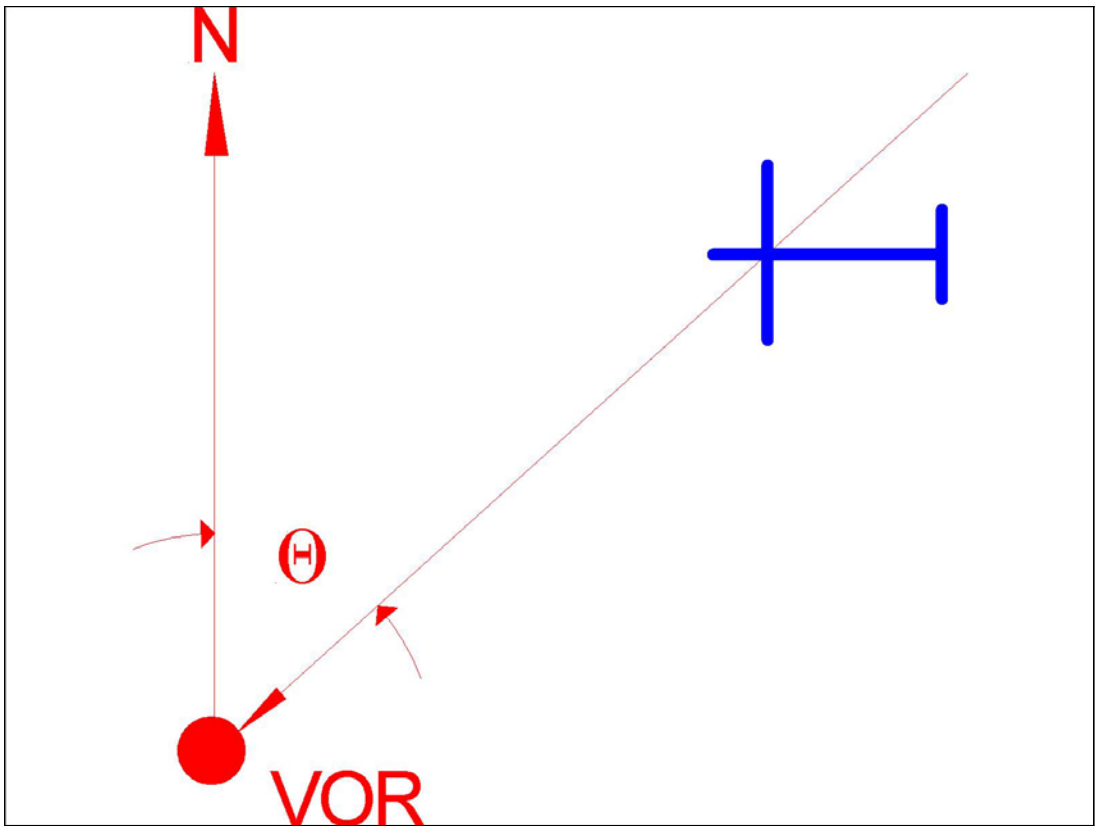

Figure 2. VOR Navigation

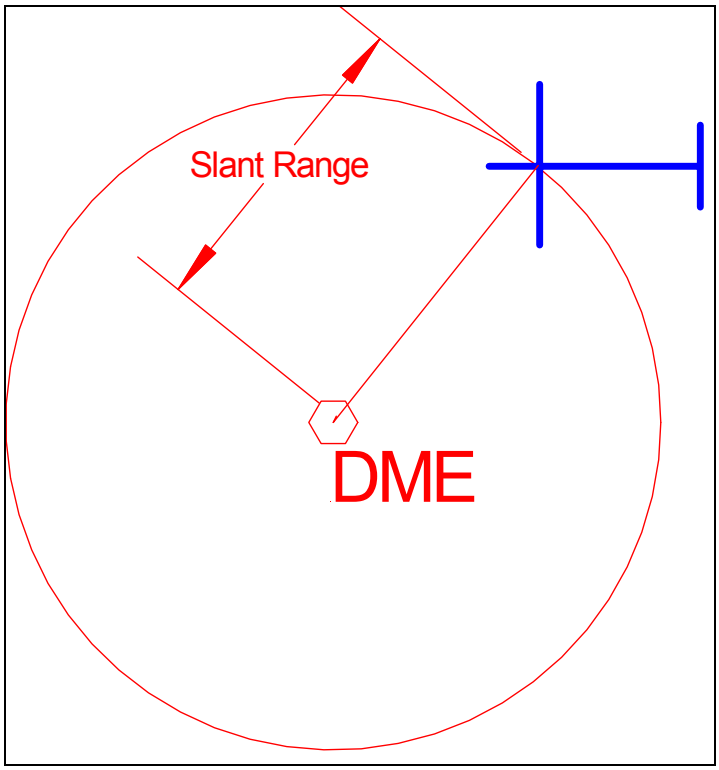

Figure 3. DME Navigation

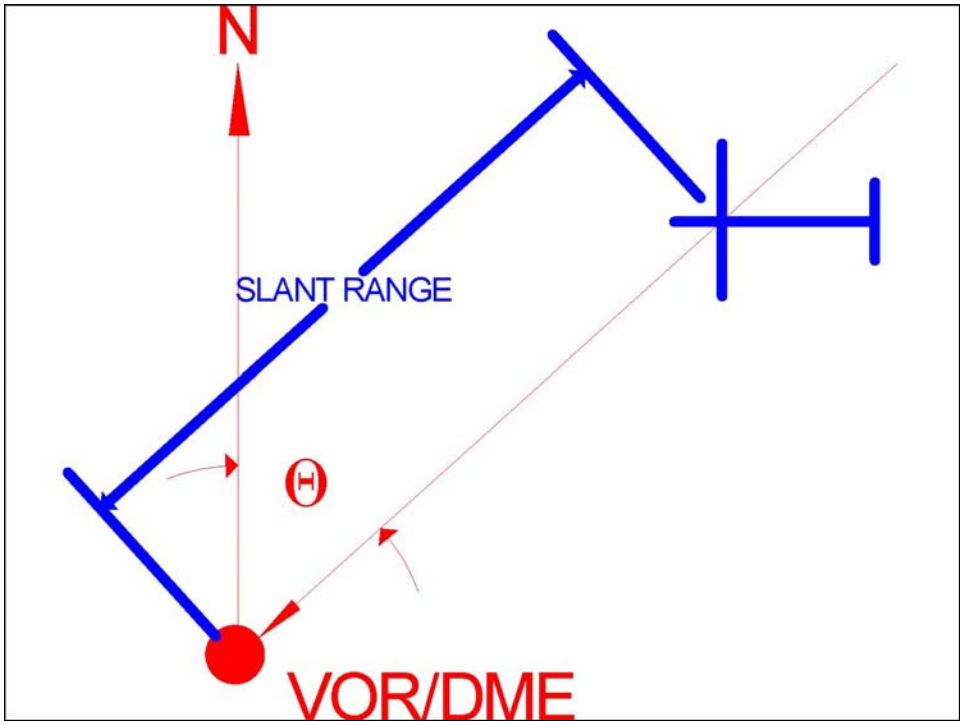

Figure 4. VOR/DME Navigation

DME range information from one facility can be combined with range information from a second DME facility to provide an accurate position of the aircraft if the locations of

the facilities are known as shown in Figure 5. DME fixes may be defined using this method on aeronautical charts and used for navigation. However, the real benefits of DME/DME ranging are realized when the range information is used by an RNAV computer or FMS. These will be discussed in relation to area navigation below.

NAS designs have depended to a degree upon ground based navigational aids to provide specific guidance to aircraft based on their fixed earth position. Procedures used to support movement of aircraft in the NAS have been, in the past, limited to routes, airways, and paths that are coincident with and dependent on guidance from these navaids. Avionics developments led to systems that could use guidance from these navaids in combination to provide an aircraft position in locations not directly served by the NAS defined routes. Procedures were developed to make use of this area navigation (RNAV) equipment.

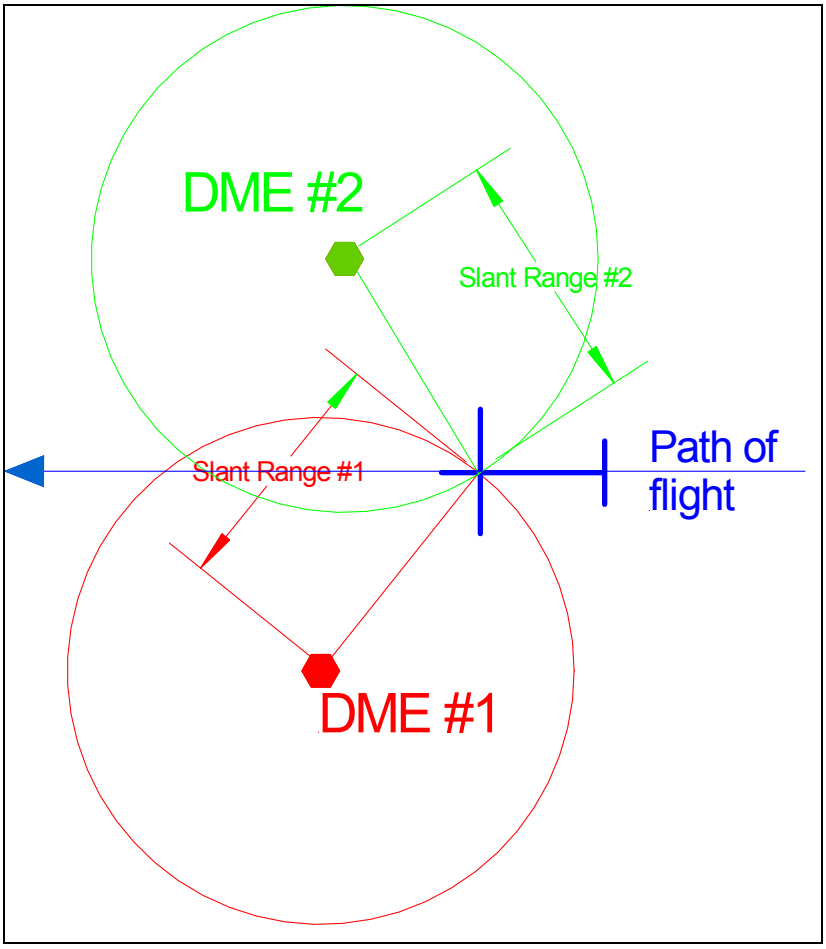

Figure 5. DME/DME Navigation

RNAV is, as described in Ohio University Technical Memorandum OU/AEC 02-15TM 00078/5-1, "The use of a microprocessor-based navigation system provides a means for conducting area navigation operations. The flight path is generically defined by waypoints that may be entered manually or loaded from a navigation database, depending on the criticality of the operation. The requisite navigation information may be provided

by a single system, or any combination of different systems that provide the performance necessary to conduct the operation. GPS, combined with fault detection and exclusion (FDE) algorithms, WAAS, LAAS, multiple VOR/DME, and DME/DME integrated with inertial are all examples of systems, or combinations of systems, that may be used to support RNAV operations. For the purpose of the discussion presented herein, a system or combination of systems/sensors that may be used to support RNAV operations will be generically referred to as an RNAV system" [3].

RNAV systems were greatly enhanced with the advent of microprocessor-based navigation systems and space-based navigation. Air carriers and corporate aircraft now take advantage of RNAV procedures to expedite their travel from point-to-point. It is essential that RNAV procedures remain operational for safety and efficiency of the national airspace and the flying public. The benefits of using an RNAV system are shown graphically in Figure 6. Benefits of RNAV include: enabling of shorter flight times and distances, reduced fuel consumption, reduced saturation of specific waypoints leading to busy air terminals, and more.

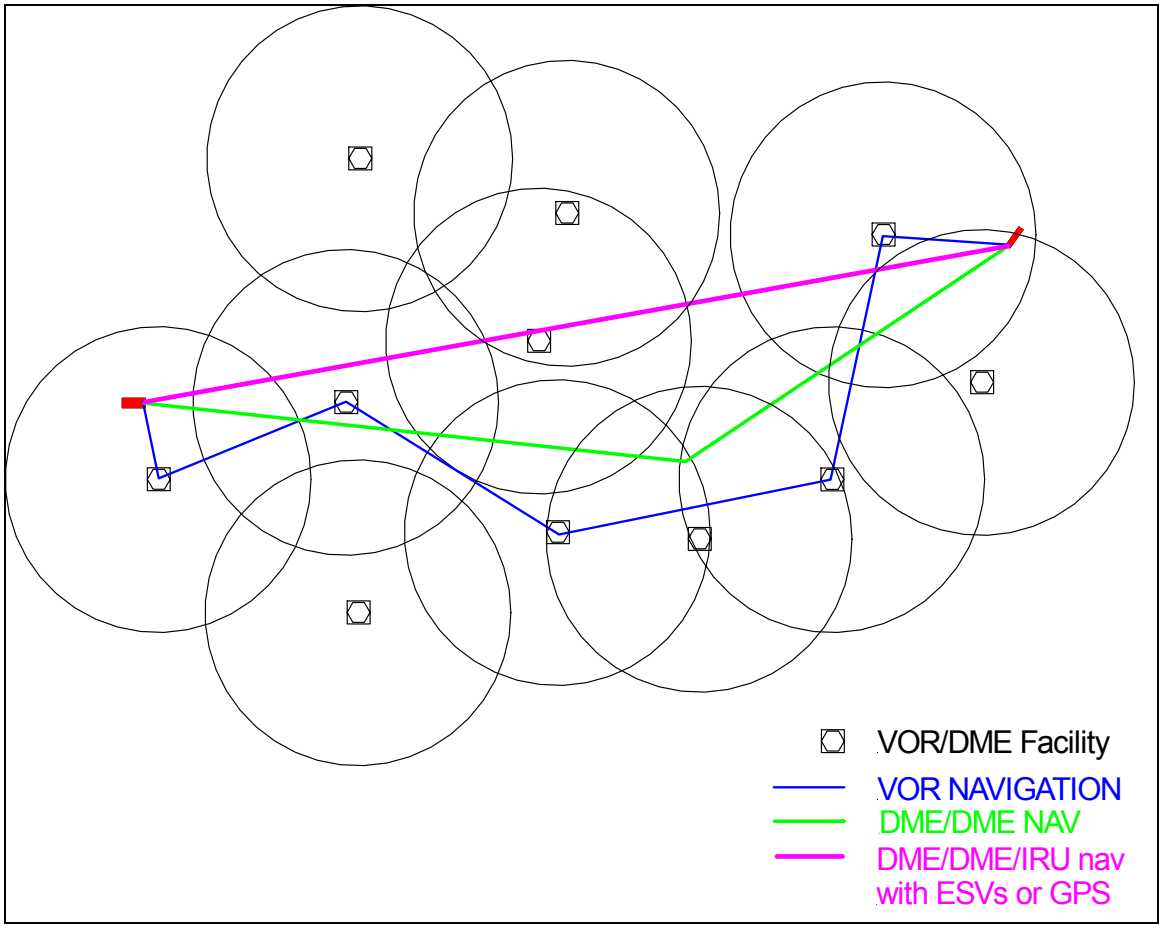

Figure 6. Navigation Characteristics of Legacy and RNAV NAS Systems

Many flight management systems (FMS) use multiple DME facilities as a ground-based network of range measurements. The FMS combines range information from two or

more DMEs to determine a geographic location based on information stored in its database. This database contains the coordinates for all of the DME facilities in the NAS.

A basic summary of the DME principle of operation is provided in Figure 7. Typical DME operation is described as follows. An airborne interrogator transmits a pair of precisely formed pulses and the ground transponder receives these pulses after a period of time. This time period (known as the propagation delay) is the time that it takes for an electronic signal to travel from its origination point to the point of reception. Upon reception and verifying that the incoming (received) pulses are valid the transponder waits a predetermined amount of time and transmits a set of pulses from the ground. The airborne equipment receives these pulses and then determines the total time from the transmission of its original pair of pulses to the reception of the reply pulses from the ground transponder. The total time, minus the predetermined delay on the ground is then used to compute a slant range from the aircraft to the ground transponder thus providing the aircraft user with a measure of distance from the aircraft to a specific geographic point.

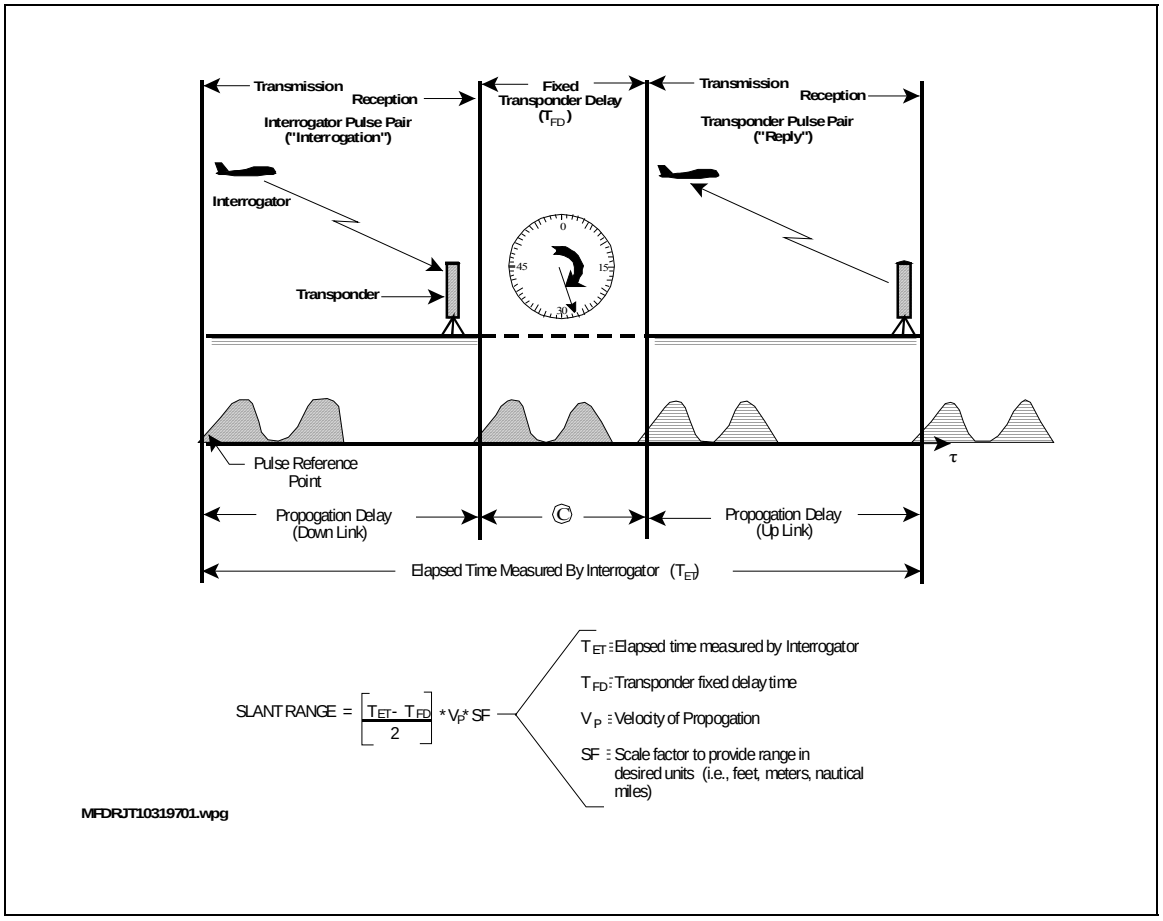

Figure 7. DME Principle of Operation [4]

The FAA has issued Advisory Circular (AC) 90-100A to "provide operational and airworthiness guidance for operation of aircraft on U.S. Area Navigation (RNAV) routes…" while providing "a series of performance and functional criteria necessary to

conduct RNAV procedures" [5]. This document addresses RNAV systems using "positioning inputs" from GPS/GNSS, DME, and IRU. The FAA is developing DME RNAV procedures and conducting flight inspections of these procedures throughout the NAS daily.

The primary goal of this effort and report is to provide an independent review and assessment that flight inspection of these new RNAV procedures with the next generation AFIS provides sufficient characterization of the DME environment including confirmation of DME facility identification, accuracy, and coverage. Additionally, an assessment of the compatibility of the algorithms used for procedure development and flight inspection is undertaken. Flight inspection results confirm that there are no false locks or unlocks (acquisition and tracking of the DME transponder by the DME interrogator) due to multipath or signal shadowing. Flight inspection results also confirm that sufficient DMEs are available to support the procedure and that the location of these DMEs provide adequate geometry to meet the accuracy requirements.

III. DME RNAV FLIGHT INSPECTION REQUIREMENTS REVIEW

This section provides information related to the review of FAA DME RNAV flight inspection requirements. Documents reviewed, requirements, methodologies, and procedures are identified. Brief discussions of FAA resource requirements and "expanded" service volumes (ESV) as they relate to DME RNAV flight inspection are provided.

The DME RNAV flight inspection kick-off briefing was held at the Mike Monroney Aeronautical Center in Oklahoma City on June 23, 2006. FAA AVN personnel provided AEC with documents and materials related to the task after the meeting. Directions for obtaining access to the FAA's RNAVPro software and associated documentation were provided. RNAVPro is a software package used to create and evaluate DME RNAV procedures. The FAA had flown DME RNAV procedures in Florida and near Cleveland, Ohio and provided test data from the flight inspection missions. Copies of intra-FAA correspondence related to the development and testing of FAA DME RNAV flight inspection capability were also provided.

The documents used for this project are listed in Table 1. Updates for several of the documents were received during the review process and are used herein. Format changes as well as content changes were included in some of the new versions of documents.

A. Requirements, Methodologies, and Procedures

DMEs associated with other NAVAID facilities are subject to flight inspection of the tolerances given in FAA Order 8200.1C. These tolerances are provided in Table 2. The columns C and P denote commissioning and periodic flight inspection requirements, respectively. Flight inspection for DME RNAV procedures differs from the requirements in the table in a few instances. These differences will be discussed in the following

paragraphs. Periodic inspections for DMEs associated with other navigation facilities are inspected at the same interval as the associated facilities. Thus, periodic DME flight inspections can be as often as every 270 days (when associated with ILS or MLS) or as long as 1,080 days when associated with certain VOR/TACAN equipment. A period of 540 days is used for specific configurations. These inspections occur regardless of the DME facility's use in RNAV procedures.

The flight inspection procedures of interest for this study are those for RNAV procedures supported by DME. AC 90-100A defines RNAV as "a method of navigation which permits aircraft operation on any desired flight path within the coverage of station-referenced navigational aids or within the limits of the capability of self-contained aids, or a combination of these" [5]. The AC states that "the specified RNAV accuracy must be met 95% of the flight time". Two accuracies are then defined as given in Table 3.

Table 1. DME RNAV Flight Inspection Requirements Review

DOCUMENT	NAME / DESCRIPTION
FAA Advisory Circular 90-100A	US Terminal and En Route Area Navigation (RNAV) Operations
FAA Order 6050.32B	Spectrum Management Regulations and Procedural Manual
FAA Order 8200.1 (revisions B & C)	United States Standard Flight Inspection Manual
FAA Order 8240.52 (Eff. Date 10/01/05)	FAA Flight Inspection Standard Operating Procedures
NXT TM3500-071 Rev J	System Description FAA AFIS
NXT TI 4040.55 Change 10	Technician User Manual FAA AFIS
OU/AEC 02-15TM00078/5-1	WAAS Flight Measurement
RTCA/DO-236B	Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation
RTCA/DO-283A	Minimum Operational Performance Standards for Required Navigation Performance for Area Navigation
Other	Additional correspondence with FAA offices (electronic and paper)

Table 2. DME Flight Inspection Tolerances [6]

PARAMETER	C	P	TOLERANCE/COMMENT
Identification	√	√	Morse code and voice identification must be correct, clear, and identifiable.
Signal Strength	√	√	> -80 dbm
Distance Accuracy	√	√	0.20 nmi
Receiver Checkpoints	√	√	Distance must be within 0.2 nmi of measured distance.
Coverage	√	√	Solid stable lock-on is preset throughout all ***areas*** of intended use.

Table 3. RNAV Accuracies

RNAV ACCURACY	DEFINITION FROM AC 90-100
RNAV 1	the total system error may not exceed 1 nmi for 95% of the total flight time
RNAV 2	the total system error may not exceed 2 nmi for 95% of the total flight time.

In Table 3, RNAV 1 is equivalent to Required Navigation Performance (RNP) 1.0 and RNAV 2 is equivalent to RNP 2.0. Two basic DME RNAV systems are defined in AC 90-100A, they are a DME/DME RNAV system and a DME/DME/IRU RNAV system. As the names imply the first system receives inputs from two or more DME facilities to determine aircraft position while the second, DME/DME/IRU RNAV, integrates an inertial reference unit (IRU) with the DME range functions to provide for more accurate guidance and guidance during outages due to coverage gaps (not equipment service outages) from DME facilities. There are limits to the duration of the outages that can be supported by DME/DME/IRU equipment and the limit is derived from the IRU drift rate and procedure accuracy requirement. The present perception is that the current DME infrastructure is not robust enough to support DME/DME RNAV procedures, thus the FAA requires DME/DME/IRU equipage for all existing and planned procedures. However, DME/DME RNAV procedures may be developed in the future.

From FAA AC 90-100A, RNAV 1 procedures are required to have a total system error (TSE) (see Section IV.b. for an explanation of TSE) bounded by 1.0 nmi while DME/DME equipment, meeting the requirements of Appendix 1 of the circular, are required to provide a position estimate error (PEE) "better than or equal to" 1.75 nmi. DME/DME RNAV equipment can not demonstrate compliance with the requirements for RNAV 1 procedures. Thus, there is no entry for a DME/DME RNAV system for the RNAV 1.0 entry in Table 4.

The total system errors given in Table 3 are for RNAV 1 and RNAV 2 types. Table 4 contains a summary of PEE and AFIS TSE tolerances based on the total system errors provided in Table 3. AC90-100 & 100A both indicate that for flight technical error DME/DME and DME/DME/IRU systems must assume a 1.0 and 0.50 nmi error, respectively. Assuming that these values are to be taken at face value the following must

hold. For RNAV 1 the TSE to be allocated outside the FTE component is 0.86 nmi and 1.73 nmi for RNAV 2 type procedures.

Table 4. RNAV System Types and Related Tolerances [7]

RNAV (Total allowed navigation error for 95% of total flight time)	RNAV SYSTEM Capable of providing required navigation performance	TOLERANCE (95%)	
		PEE (maximum)	AFIS TSE[1] (maximum)
0.3 nmi	DME/DME/IRU	N/A	Note 2
0.5 nmi	DME/DME/IRU	N/A	Note 2
1.0 nmi	DME/DME/IRU	N/A	0.86 nmi
2.0 nmi	DME/DME/IRU	N/A	1.73 nmi
2.0 nmi	DME/DME	1.73 nmi	1.73 nmi
4.0 nmi	DME/DME	Note 2	Note 2
[1] AFIS TSE consists of the last valid PEE value and IRU drift value since the last valid time.			
[2] Future needs due to expansion of RNAV to support DME RNAV approach procedures and navigation routes greater than RNAV 2.			

1. Requirement for DME RNAV Flight Inspection

ICAO and RTCA documents do not require flight checks for commissioning of en-route RNAV procedures (airways) beyond that already required for the DMEs. However when the DMEs are to be used to support approach and departure operations flight inspection is recommended in ICAO Document 8071 (Volume 1, Chapter 3) because "DME performance at lower altitudes can be expected to be degraded due to the effects such as multipath, terrain, and masking" and "For approach and departure procedures, it is also necessary to confirm that there is adequate signal strength and that there are no false locks or unlocks due to multipath." The ICAO document says "it is therefore highly desirable to conduct a flight inspection of the RNAV procedure". The FAA currently performs commissioning flight inspections for DME RNAV including procedures using post-flight data analysis.

2. Present DME RNAV Flight Inspection Technique

DME RNAV procedures are designed using various software tools. The primary tool is RNAVPro. RNAVPro, as a tool, is used to determine what procedure design is likely to work given the modeling of the established DME infrastructure [8]. It performs these modeling calculations based on a formulated DME error budget and facility geometry with respect to an aircraft flying along the desired route.

RNAVPro assumes full DME coverage is achieved with the exception of those areas previously identified by DME flight inspection missions as unusable. RNAVPro cannot account for site specific blockage or interference due to multipath that is manifest in areas not checked during standard DME or other DME RNAV flight inspections.

The large number of DMEs deployed in the United States NAS *does not guarantee* that a sufficient number will be available for any particular DME RNAV procedure. One method of alleviating the lack of facilities on a given route may be to request an ESV (Section III.C. contains additional information on DME ESV) for one of the facilities already under consideration for use. This permits use of a particular facility's signals beyond the normal or "standard" service volume for that facility. The ESV is generally restricted to specifically designated areas [9]. Requests of this type pass through several FAA organizations to ensure that, if approved, the DME signal in the ESV will be frequency protected from other facilities in the area [10]. Flight inspection is the *only means available* for accurate assessment of actual conditions along the designed route and is thus an essential step in the DME RNAV procedure authorization process. These conditions include items like source signal accuracy and coverage, interference, obstruction clearance, and flyability.

The process FAA AVN currently uses to perform a commissioning flight inspection of RNAV procedures involves a pre-flight, in-flight, and post-flight phase. Once the design is complete, RNAVPro uses the leg/segment data, specifically designed to support the AFIS, to create CSV files containing up to five DMEs to consider along each segment of the procedure [8]. The AFIS then uses this list to determine the "desired" DMEs along a given route which are then given priority with respect to other DME facilities within range. Other DMEs are not precluded from use if conditions warrant. In addition, RNAVPro may determine that one or more DME facilities in a segment are "critical" to a valid RNAV solution, and therefore must be operational for the route to be flown using DME RNAV. Any such DME facilities are marked as critical in the CSV files. Flight checks begin with the transfer of the CSV files generated by RNAVPro to the AFIS. Once the files are loaded and verified the aircraft is prepared for the inspection mission of the associated RNAV procedure.

The mission involves flying the aircraft along the various segments of the RNAV routes using the developed RNAV procedures and verifying items such as DME availability, suitability, obstructions, etc. For example, one segment may be used in multiple procedures so the inspection of it is conducted during the most opportune flight inspection run. During flight inspection of the DME RNAV procedure the AFIS software is used to collect data on aircraft positioning relative to the selected DMEs, the state of DME facility lock or unlock by the interrogator DME range error, and additional items typical to stand-alone DME flight inspection. The data (DME signal status and range) used for post-flight analysis and the ultimate approval or denial of the procedure is the same previously validated data utilized by the AFIS when conducting DME facility flight inspections. The 'prototype' aspect of this AFIS software does not affect the collection of this data.

Upon completion of flight inspection activities for a DME RNAV procedure the recorded data is copied from the AFIS. The data is then used in a post-flight analysis by RNAVPro. RNAVPro is re-run using actual aircraft range from facilities and whether or not the interrogator is locked or unlocked. This does not take into account actual DME range error, but rather assumes a DME range error proportional to the range (minimum

one-sigma value of 0.099nmi). This is a conservative approach as observed DME range error is typically much smaller. Based upon passing results from the RNAVPro post-flight analysis and other procedure criteria the DME RNAV procedure is then approved.

3. Next Gen AFIS Flight Inspection of DME RNAV

In the Next Generation AFIS the decision for a procedure passing or failing is based upon the PEE and TSE values recorded throughout segment(s) of the RNAV procedure assuming all other criteria are met (e.g., flyability, obstructions, etc.). A decision to pass the procedure confirms the presence of suitable DME signals of sufficient coverage, accuracy, and geometry, along the desired RNAV procedure flight path that are capable of providing the required navigation performance. Additionally, a "pass" may be assigned when the TSE indicates allowable inertial drift is not exceeded when DME coverage is not available for calculating an RNAV position solution. Again, inspection is necessary because unknown interference sources could be located along the procedure path, new obstacles may have been erected, and signal sources could be partially blocked or be affected by multipath.

B. Resource Requirements

Chapter 13 of FAA Order 8200.1C provides the policy, procedures, and criteria for the flight inspection of area navigation or RNAV procedures. Its content is the combined version of what was formerly contained in Sections 209 and 210 of 8200.1B. The inspection of RNAV procedures has been harmonized to minimize unnecessary overlap of flight inspection functions when procedures are designed to be supported by both DME RNAV and WAAS RNAV.

The FAA operates a fleet of approximately 31 flight inspection aircraft [11]. The aircraft are equipped with the AFIS although not all are capable of DME RNAV inspections, and not all of those can simultaneously conduct the GNSS RNAV portion of an RNAV procedure inspection [12]. The fleet is summarized in Table 5. Flight inspection aircraft that are capable of inspecting both the DME/ DME and GNSS parts of an RNAV procedure simultaneously will save time and fuel by not having to fly the entire route twice. Mission planning and workload for these aircraft will be increased with tasking to conduct DME RNAV flight inspection missions.

C. Expanded Service Volumes (ESV)

The standard service volume (SSV) types for DME in the NAS are depicted in Figure 8 [13]. Flight Inspection Standard Service Volumes (FISSV) are defined as orbits centered on the facility with a 40-nmi radius for high- and low-power DMEs and a 25-nmi radius for terminal DME equipment. These orbits are conducted at specific low altitudes where the transmission pattern is more susceptible to interference and signal blockage [14].

When RNAV procedures are developed they may include expansion of a nearby DME SSV in order to conduct the procedure. These ESVs are first submitted to the Frequency

Management Office (FMO) for approval. Once the FMO grants an ESV for a DME, AVN must inspect the ESV prior to certifying the procedure. Inspection of a waypoint, supported by a DME ESV, is conducted by flying certain geometries as shown in Figure 9 [15] from FAA Order 8200.1C that bound the area of extended service. When an ESV is used to support portions or entire segments/legs of an RNAV procedure the inspection is different. A potential DME ESV example is presented in Figure 10.

Table 5. FAA Flight Inspection Resources -Aircraft

AIRCRAFT TYPE	NUMBER OF AIRCRAFT	AFIS TYPE	EQUIPPED FOR DME RNAV INSPECTIONS	Equipped for Simultaneous Inspection of GNSS
Challenger 601	3	FAA	Yes	Yes
Challenger 604	1	FAA	Yes	Yes
Hawker	3	2 - Sierra System 1 - FAA	No Yes	N/A Yes
King Air	18	FAA	Yes	No
Lear 60	6	FAA	Yes	Yes

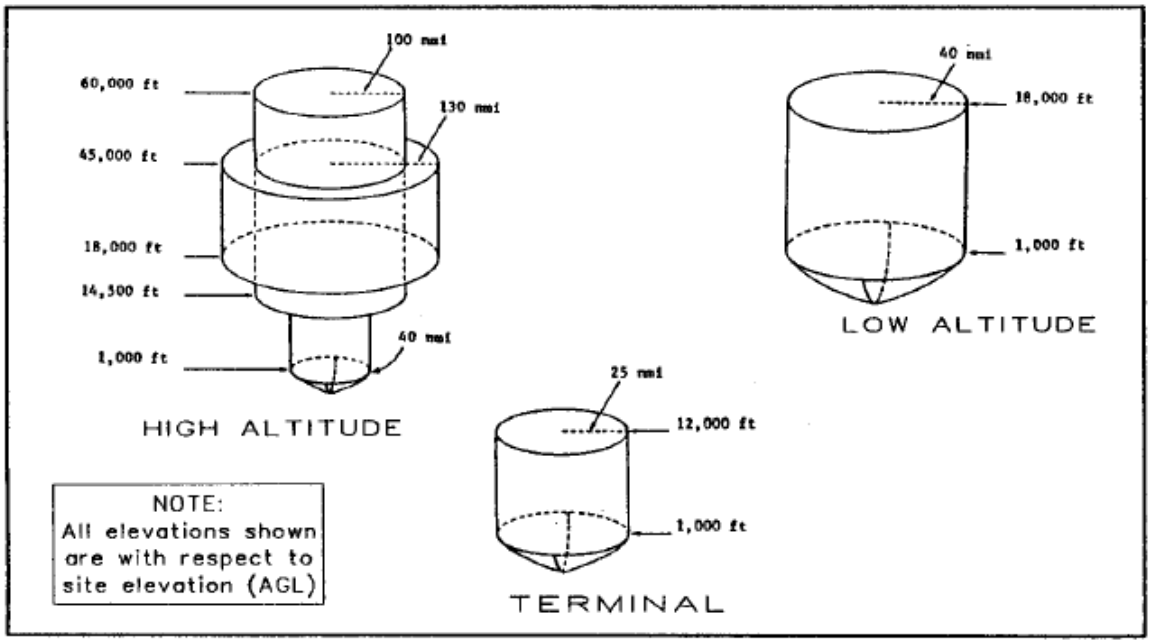

Figure 8. Standard Service Volumes

According to FAA Order 8200.1C, DME range accuracy, coverage, and identification are checked when inspecting a DME ESV independently of an associated facility. This is the

case when inspecting ESVs that are used to support DME RNAV procedures. FAA philosophy is to fly the RNAV ESV at the lowest procedure altitude on centerline. The ESV for an RNAV segment is specific to the segment. New procedures developed that transit the same path will not need an additional ESV established. Because the ESV is not a 360° radial expansion of the SSV, those new procedures that do not transit the same path through an existing ESV will need additional ESV(s) to be defined and flight inspected. RNAVPro simulation is used to assess the extremities of the RNAV procedure volume and higher altitudes [16].

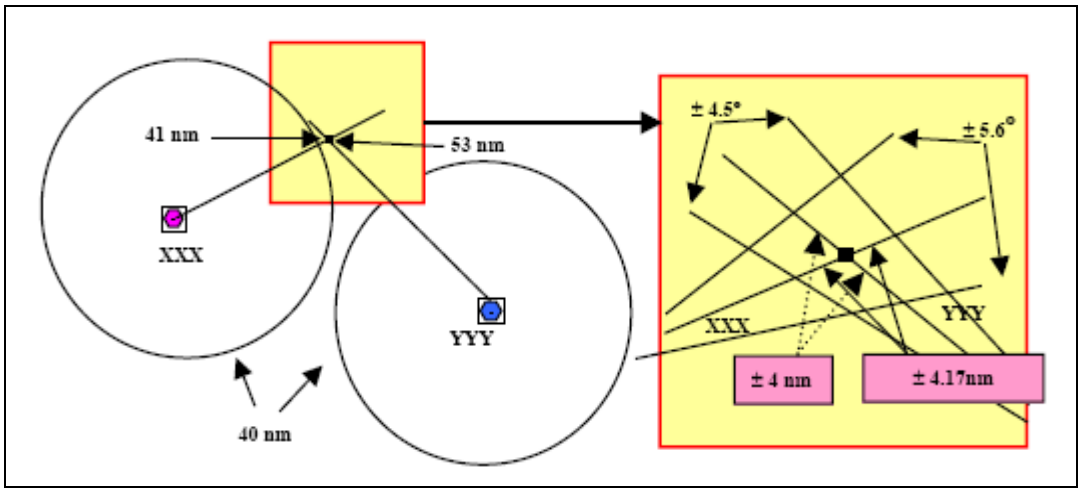

Figure 9. Stand-Alone DME Fix Inspection Beyond the FISSV (ESV)

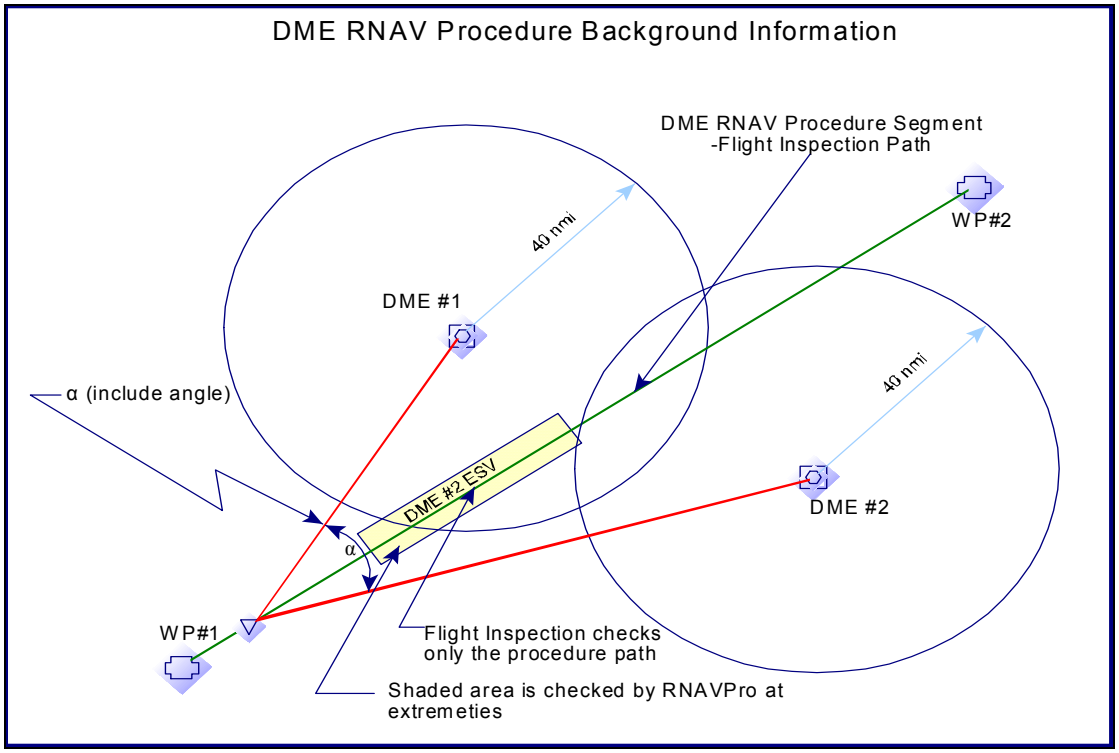

Figure 10. DME RNAV ESV Flight Inspection

For all navaids, once an ESV is established it is not scheduled for periodic flight checks. Instead, only when a change of equipment or location occurs, or when user complaints are received, is the ESV re-inspected. The DME facility with one or more ESVs is still subject to periodic flight inspection and any facility or environmental changes that could affect the ESV should be identified during the facility's periodic inspection. Because there is no periodic inspection requirement for DME ESVs supporting DME RNAV, the effect on the overall flight inspection workload is minimal.

Future US NAS plans may include DME facilities in a stand-alone configuration. This action may change procedures and notations for standard DME inspections and DME ESVs. These changes may increase FAA resource workload.

IV. DME RNAV AFIS ALGORITHM REVIEW

The following material provides a description of the RNAVPro software and its interface with the AFIS, discussion of the AFIS DME algorithm review, and the analysis results of FAA provided data. Comments related to the DME RNAV flight inspection mission that AEC personnel were invited to observe are provided. General observations about these items are provided at the conclusion of Section IV.

Tasking was added to this task order (Number 0003) to assess the DME RNAV algorithm implementation in the FAA prototype AFIS during the project kick-off briefing. Interest was specified to be in the implementation of the PEE and later the TSE algorithms. Proper implementation of these algorithms will result in cost and time savings when the FAA begins commissioning new and updated DME RNAV procedures using "officially released" AFIS software. A discussion of the research and data analysis follows.

The FAA is using installed prototype AFIS software during DME RNAV inspections to collect DME RNAV data but the prototype software is not used for determination of a DME RNAV route "Pass" or "Fail". Data is collected on aircraft positioning relative to the selected DMEs, the state of DME facility lock/unlock along the RNAV route, and prototype PEE/TSE values in addition to typical DME flight inspection data. Current DME RNAV flight inspection procedures require the transmittal of this data (collected by the prototype AFIS software) to other FAA offices after the flight inspection mission for post-flight analysis. A post-flight analysis of the data is performed to determine success or failure of the procedure, and this analysis includes re-running RNAVPro using the actual range of the aircraft from the DMEs. This does not take into account actual DME range errors [16]; however, DME unlock information collected by AFIS is used to remove a DME from consideration in RNAVPro for the portion of the procedure that it is unlocked.

It is highly desirable for FAA Flight Inspection to be able to declare success or failure of the procedure as soon as the airborne inspection is complete. If the algorithms used by the AFIS to calculate the PEE and TSE are correct and validated, the maximum values would be a more accurate assessment of the procedure navigation performance. The PEE

and TSE values can then be used in determining the success or failure of the DME RNAV procedure by comparing it to the associated required navigation performance value (PEE for DME/DME procedures and TSE for DME/DME/IRU procedures).

A. FAA vs. RTCA Position Estimation Error Formulas

Validation of the AFIS algorithms includes ensuring the PEE equations are properly formulated and implemented. Such equations are provided in RTCA DO-236 and DO-283. However, the FAA discovered what is believed to be an error in the position estimation error equation in both RTCA documents (DO-236B and DO-283A). The FAA equation for the two-sigma PEE value is given in equation 1 [17]. The equation as given in RTCA DO-236B is presented in equation 2 [18] and the corresponding two-sigma equation is provided in equation 3. In these equations: $\sigma^2{}_{x,air}$ is the error due to the airborne DME component and $\sigma^2{}_{x,sis}$ is the error due to the DME signal-in-space which includes the ground station error. When combined these represent the DME contribution to error (slant range) $\sigma^2{}_{DME(1or2)}$. The include angle is the angle formed by the line from DME_1 to the aircraft and the line from the aircraft to DME_2 and is represented by α. A diagram of the include angle is provided in the following section.

Equation 1. DME Two-Sigma Position Estimation Error (FAA RNAVPro)

$$2\sigma_{DME/DME} \leq 2\left(\frac{\sqrt{\left(\sigma^2{}_{1,air}+\sigma^2{}_{1,sis}\right)+\left(\sigma^2{}_{2,air}+\sigma^2{}_{2,sis}\right)}}{\sin(\alpha)}\right)$$

Equation 2. DME/DME Position Estimation Error (RTCA DO-236B, Appendix C)

$$\sigma^2{}_{PEE} = \frac{\left(\sigma^2{}_{DME,1}+\sigma^2{}_{DME,2}\right)}{\sin(\alpha)}$$

Equation 3. DME Two-Sigma Position Estimation Error (based on RTCA)

$$2\sigma_{DME/DME} \leq 2\left(\sqrt{\frac{\left(\sigma^2{}_{1,air}+\sigma^2{}_{1,sis}\right)+\left(\sigma^2{}_{2,air}+\sigma^2{}_{2,sis}\right)}{\sin(\alpha)}}\right)$$

A copy of the "Request for Clarification" memorandum [19] prepared, by W. Scales and C. Hegarty, for transmittal of information regarding this error to RTCA is included in Appendix A. The date of transmittal of this memorandum is unknown to the authors. It is unknown to the authors if any action has been taken by RTCA regarding this memorandum. A reference was cited in this memorandum supporting the FAA position that the denominator in the equations above is not under the square root. A limited literature search for this reference was conducted due to program scheduling and as of this writing a copy of the reference has not been located. The publication year for the reference is 1946 and will likely require a more intense search to secure a copy. This issue regarding the position estimation error must be resolved before using RTCA documents for guidance on avionics development.

B. RNAVPro / AFIS PEE/TSE Algorithm Implementation Review

A comparison of RNAVPro results with PEE values obtained during analysis of the LONNI-ZFP standard arrival (STAR) route data supplied by the FAA revealed some differences. The standard arrival route LONNI-ZFP is a route with non-optimum DME coverage that is flown over both land and ocean and was selected by the FAA as a test case. The major difference identified is that the RNAVPro algorithm (equation 1) computes the two-sigma value for PEE while the AFIS (equation 4) computes the one-sigma value. Additionally, the FAA AFIS software calculates both the position estimation error (PEE) and total system error (TSE) using actual DME range error values during the flight inspection mission. The AFIS presents the worst-case or maximum PEE and TSE values to the operator upon completion of each RNAVPro defined "leg" [20]. RNAVPro calculates the maximum value for the procedure based on geometry, formulated DME errors, and the PEE formula which, while protecting safety, can lead to denial of valid procedures for properly operating equipment and inadequately protects the user when actual DME errors are out of tolerance due to external factors (e.g., multipath).

Equation 4. DME One-Sigma Position Estimation Error (FAA AFIS)

$$\sigma_{DME/DME} \leq \left(\frac{\sqrt{\left(\sigma^2{}_{DME1} + \sigma^2{}_{DME2}\right)}}{\sin(\alpha)} \right)$$

Discussions between FAA, the FAA AFIS support contractor, and AEC personnel resolved that the AFIS software implements a one-sigma version of equation 1 (equation 4) and not equation 5 (given below). As a result of these discussions the FAA has coordinated with the AFIS support contractor to eliminate this difference. In accordance with this decision by the FAA, the PEE values retrieved from the AFIS data files and discussed in the following sections have been compensated to reflect the two-sigma values unless noted otherwise. Analysis using the AFIS data provided by the FAA led to suggestions for including information regarding which DMEs are being used to calculate the instantaneous PEE values in the data file for archival and data analysis purposes.

Equation 5. Desired DME Two-Sigma Position Estimation Error (FAA AFIS)

$$2\sigma_{DME/DME} \leq 2\left(\frac{\sqrt{\left(\sigma^2{}_{DME1} + \sigma^2{}_{DME2}\right)}}{\sin(\alpha)} \right)$$

FAA document AC90-100A defines TSE as "The difference between the true position and the desired position. The error is equal to the vector sum of the path steering error, path definition error, and position estimation error" [21]. From Appendix C in RTCA DO-236B the equation form for TSE is given as:

Equation 6. Total System Error (RTCA DO-236B) [22]

$$TSE^2 = PSE^2 + PDE^2 + PEE^2$$

Or

Equation 7. Total System Error

$$TSE = \sqrt{PSE^2 + PDE^2 + PEE^2}$$

Where: TSE = total system error
PSE = path steering error
PDE = path definition error
PEE = path estimation error

The AFIS System Description document [23] refers to the TSE calculation: "The NCU also computes the TSE where the derived DME PEE, a fixed Flight Technical Error (FTE) of 0.5 nmi, and progressive IRU drift rate of 8 nmi/hr are used." No reference is given as to the actual algorithm used. FAA's understanding of the AFIS algorithm is that it is simply a sum of the PEE error and IRU drift during periods of loss of DME [24]. Analysis of the flight check data provided by the FAA shows that the fixed 0.5 nmi FTE is not included in the AFIS calculations. The AFIS TSE data can not be replicated and without knowledge about the algorithm used the TSE data can not be verified or validated. Preliminary calculations show that the algorithm seems to be using a root-sum-square method to determine TSE with the inputs of PEE and IRU drift only. Converting 8 nmi/hr into nmi/sec, applying the apparent time since the last PEE update, and adding the last valid PEE value (RSS as in equation 8) does not result in an exact match for the AFIS calculated TSE value providing an indication that the RSS method may be in use. An unresolved issue is that the starting time value to use in calculating the IRU drift is not apparent in the data files given our review of the documentation, data, and tools.

Equation 8. Possible AFIS Implementation of AFIS TSE

$$AFIS_TSE = \sqrt{PEE^2 + (IRU_{driftrate} * T_{timefromlastvalidPEE})^2}$$

Since Equation 8 only includes navigation sensor error sources, the intention of the next generation AFIS software is to measure the total navigation system error (NSE_T) not TSE as defined in FAA AC 90-100A and RTCA DO-236B. Referring to this quantity NSE_T as TSE (in AFIS documentation, software, user interface, etc.) is confusing, particularly since TSE is a term defined in FAA AC 90-100A and RTCA documents which include additional error sources. The name for the value computed in the AFIS should be changed so that it is apparent that it does not refer to the typical meaning of "TSE" when used as an aviation acronym. The FAA will need to internally define the tolerances for NSE_T (such as provided in Table 4) that can be applied to the computed value in order to determine the passage or failure of the procedure (in terms of navigation sensor requirements).

In FAA AC 90-100A Section 4, paragraph b the accuracy for RNAV 1 and RNAV 2 type systems is required to be "met 95% of the total flight time." A strict interpretation of this requirement would allow the total system error for a flight over 60 nmi to be greater than 95% for a span of approximately 3 nmi. Previous navigation and landing systems have used "intervals" or "windows" to assess 95% criteria that allow the presence of errors that are large but short enough in duration to not affect the physical displacement of the

aircraft. A similar "windowed 95% criteria" for PEE and TSE values should be developed for these RNAV types that will protect the airway boundaries while not allowing extended deviations from the desired path. Adoption of a "windowed" criteria for flight inspection of procedures will protect the airways while not unnecessarily denying procedures due to momentary data spikes or events that will not impact the aircraft's position.

When the actions identified in the report are made to the AFIS software the PEE will be computed to provide the two-sigma value. Whether the value provided for the TSE or NSE_T is also a two-sigma value is presently undetermined. Information on how the TSE or NSE_T pass/fail flag is determined is necessary. The pass/fail flag may represent a single excursion beyond the defined tolerance for 95% or it may represent the 95% criteria over a period of time.

C. Test Cases

FAA AVN provided access to sets of test data from DME/DME RNAV flight inspection missions that were conducted in 2006. Three cases were reviewed and analyzed in an effort to characterize the AFIS-algorithm generated PEE data. A brief summary of the data sets, observations, and results are provided in the following sections. PEE data calculated by the AFIS during the flight inspection mission are stored electronically.

To enable a comparison of expected versus actual PEE data, manual PEE values are calculated from the basic data (DME range error, angle, etc.) stored in the same data file as the PEE data. It involves user selection of the best "include angle" (see Figure 11 [25] for an example) out of the combinations available from the up-to five DME facilities. This in turn selects which two DME facility range errors are used in calculating the PEE. The two criteria used to determine the "best" manually-calculated include angle in the data files were: first the include angle closest to 90 degrees and second the closer facility pair (if two pair matched the first criteria). AC 90-100A also includes the requirement: "the DME/DME RNAV system (referred to as FMS hereafter) must use, as a minimum, DMEs with a relative include angle between 30° and 150°" [26]. Section 4.b.2.a of AC 90-100A Appendix 1 includes an option for FMSs to use DMEs with relative include angles outside the range of include angles typically used to define an acceptable position solution geometry. It also suggests that accuracy "be evaluated under poor geometry scenarios" while considering the demonstrated DME sensor accuracy. Comparison of the AFIS generated PEE results with these manual PEE values is used to determine if the AFIS algorithm is performing as required. Results for each test case are provided in the following sections.

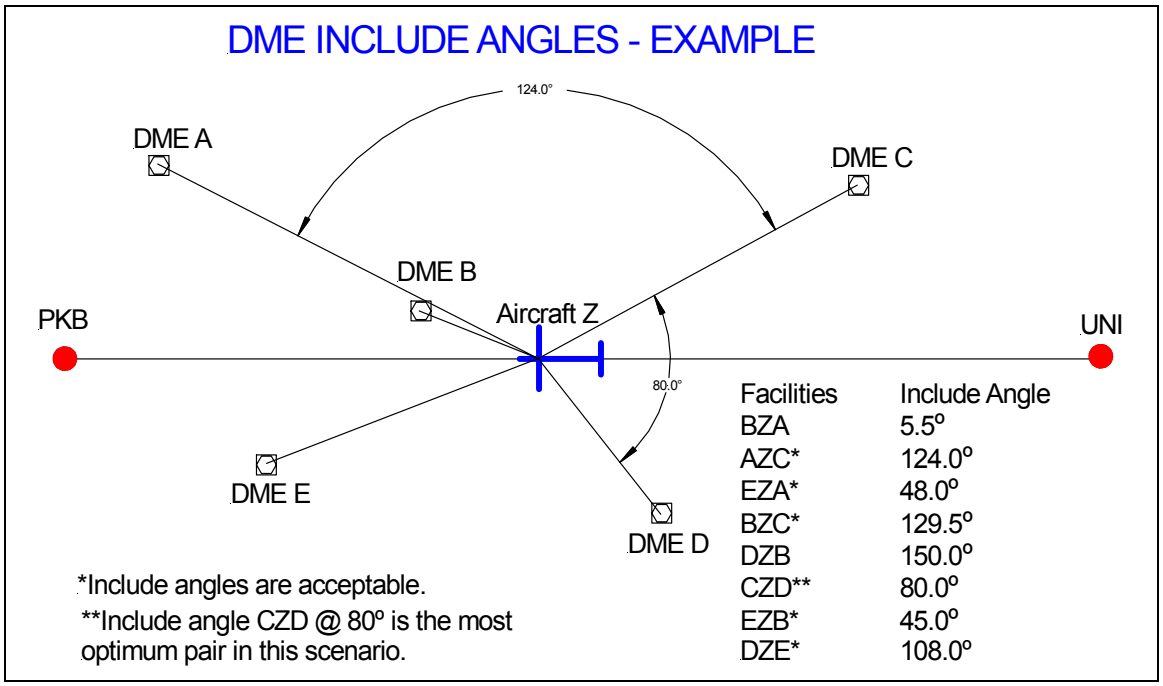

Figure 11. DME Include Angle – Example

1. LONNI-ZFP STAR Leg

The first set of test data analyzed and reviewed is from south Florida. The leg denoted "LONNI-ZFP" is part of a standard arrival route. It has non-optimum DME coverage that is flown over both land and ocean (Figure 12) and is the nearly horizontal leg from ZFP to LONNI as shown in Figure 12. The RNAVPro graphical output (for the entire LONNI STAR procedure) shows the predicted DME/INS error (Figure 13). The predicted error includes two regions of significant INS drift (due to predicted DME outages) which can be identified as the two slanted parts of the predicted error trace. The slanted region on the left of Figure 13 corresponds to the region in Figure 14 from 20:18:30 to 20:24:20. Figure 14 shows there are no areas indicating INS drift due to lack of DME updates (i.e., the flight inspection results do not show any DME outages).

The initial review of the test data revealed differences between the RNAVPro and AFIS implementations of the PEE. Comparison of the original PEE errors revealed the presence of a factor of two between the RNAVPro and AFIS PEE magnitudes. These differences were suspected to the result of RNAVPro calculating the two-sigma (95%) PEE error and the AFIS calculating the one-sigma value. FAA and AEC personnel met with the AFIS support contractor in Oklahoma City to solidify an understanding of the AFIS implementation of the PEE. As previously discussed, the FAA has coordinated with the AFIS support contractor to eliminate this difference. Additionally, a minimum of two DMEs (the actual number was four) were available to the prototype AFIS throughout the LONNI-ZFP leg negating the 30-nmi INS drift region predicted to occur, by RNAVPro, between LONNI and ZFP.

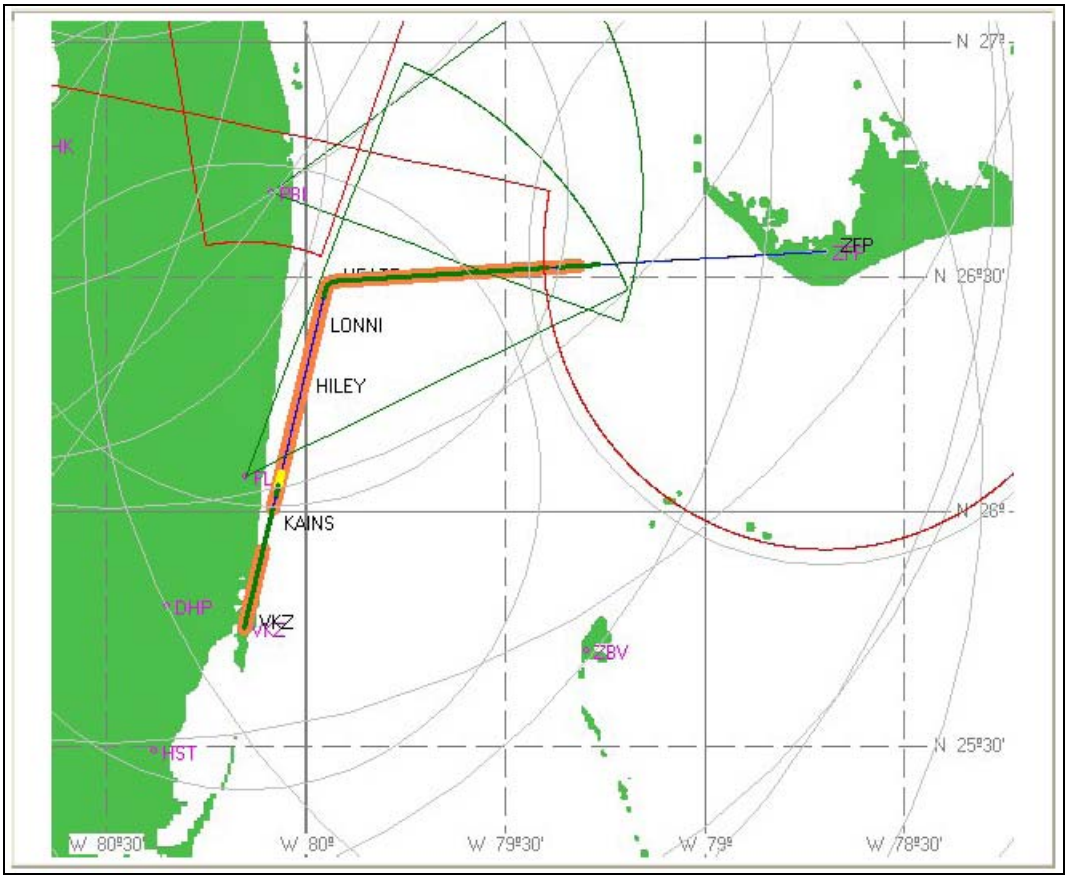

Figure 12. RNAVPro LONNI-ZFP STAR Output

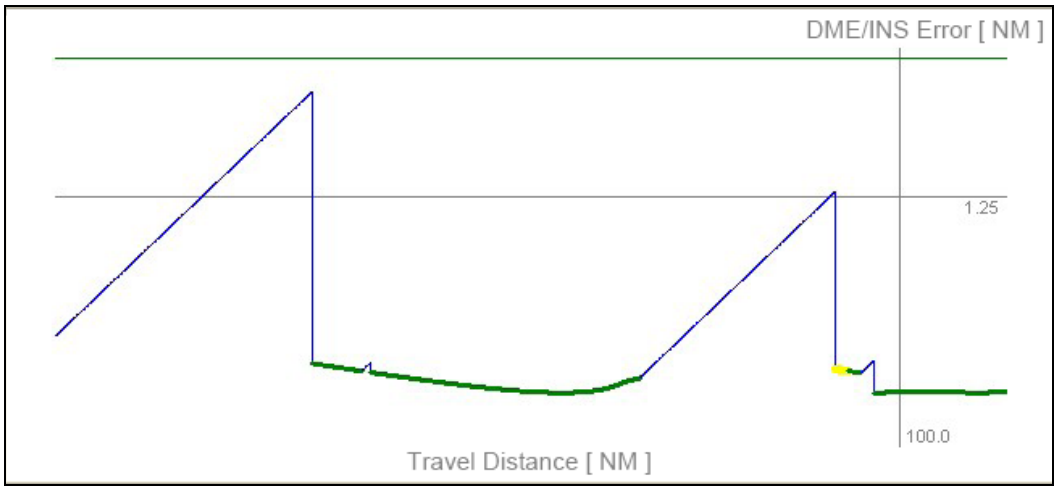

Figure 13. RNAVPro Predicted DME/INS Error for LONNI-ZFP

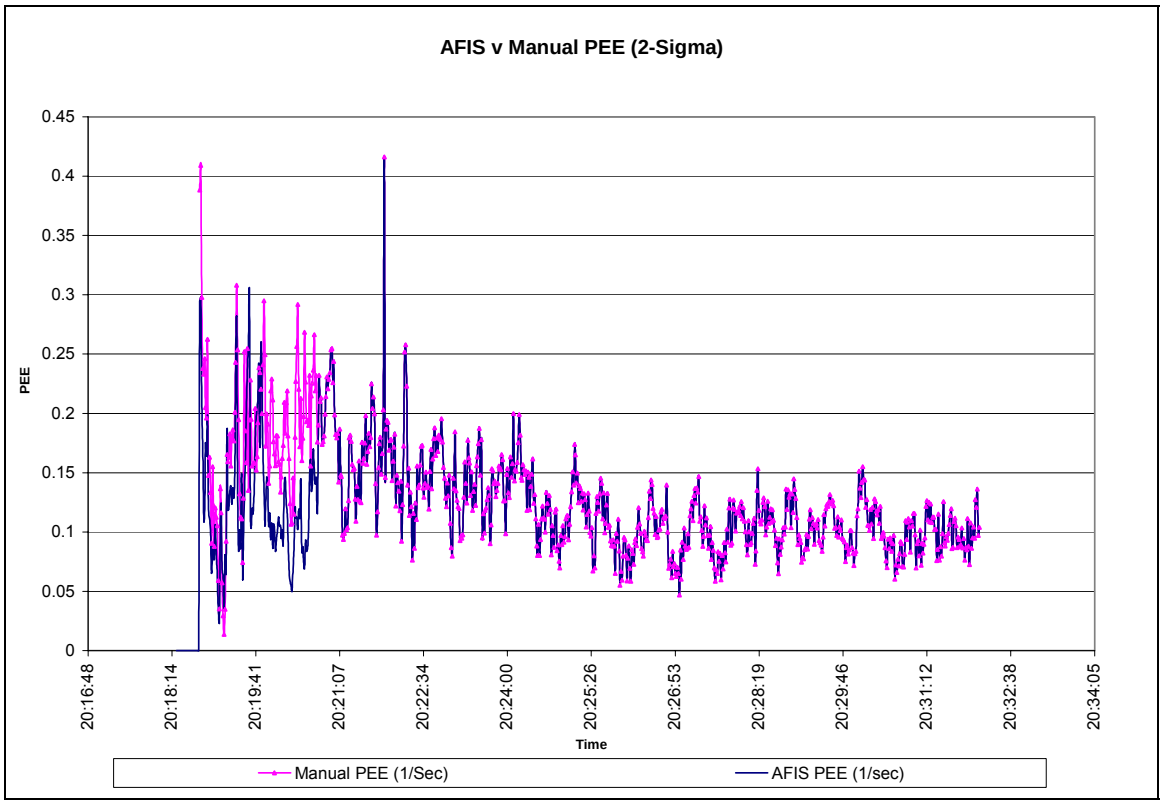

Figure 14. Two-Sigma LONNI-ZFP Manual vs AFIS PEE

Figure 14 data reveal relatively large PEE values were obtained during the initial 1/3 of the data set and is expected since the include angle is less than 50 degrees. Although larger, the PEE levels show that acceptable performance is obtained. Although the difference between the manually calculated and AFIS values is large for this initial region, an acceptable level of agreement is still achieved. Early analysis results only contained AFIS PEE data at a rate of 0.1 Hz. In Figure 14, data provided for the AFIS PEE (extracted from the original data file at the full rate) and the manual PEE values are provided at 1-Hz intervals. The region in Figure 14 from 20:18:30 to 20:24:20 is where RNAVPro predicted that the DME/DME RNAV procedure would require INS thus having an INS drift component in the error. The DME facility ranges were as high as 99 nmi at a flight level of 10,000' for this region and would require the establishment of one or more ESVs to support this procedure. As the flight progressed (20:22:30 and later) and the include angle geometry improves to greater than 50 degrees the differences between the manual and AFIS PEE values become negligible. Throughout the flight inspection procedure the PEE values remain well below the RNAVPro predicted 1.774 nmi error (Figure 13) as evidenced by the actual maximum value of approximately 0.42 nmi in Figure 14. There were no portions of the LONNI-ZFP leg with significant INS drift due to loss of DMEs.

2. ALPHE-RDVA STAR/SID

Results from a standard terminal arrival route/standard instrument departure (STAR/SID) procedure in the vicinity of Cleveland, Ohio, have been analyzed and reviewed as the

second set of test data. In this procedure the manually calculated PEE matches nearly identically to the corresponding AFIS generated PEE value as shown in Figure 15. In fact, the traces overlay completely with the scaling of the graph shown in Figure 15 and differences can only be identified if the vertical scale is changed to show less data (i.e., from +0.3 to -0.3 nmi). The graphical output of RNAVPro is provided in Figure 16 with the predicted DME/INS error shown in Figure 17.

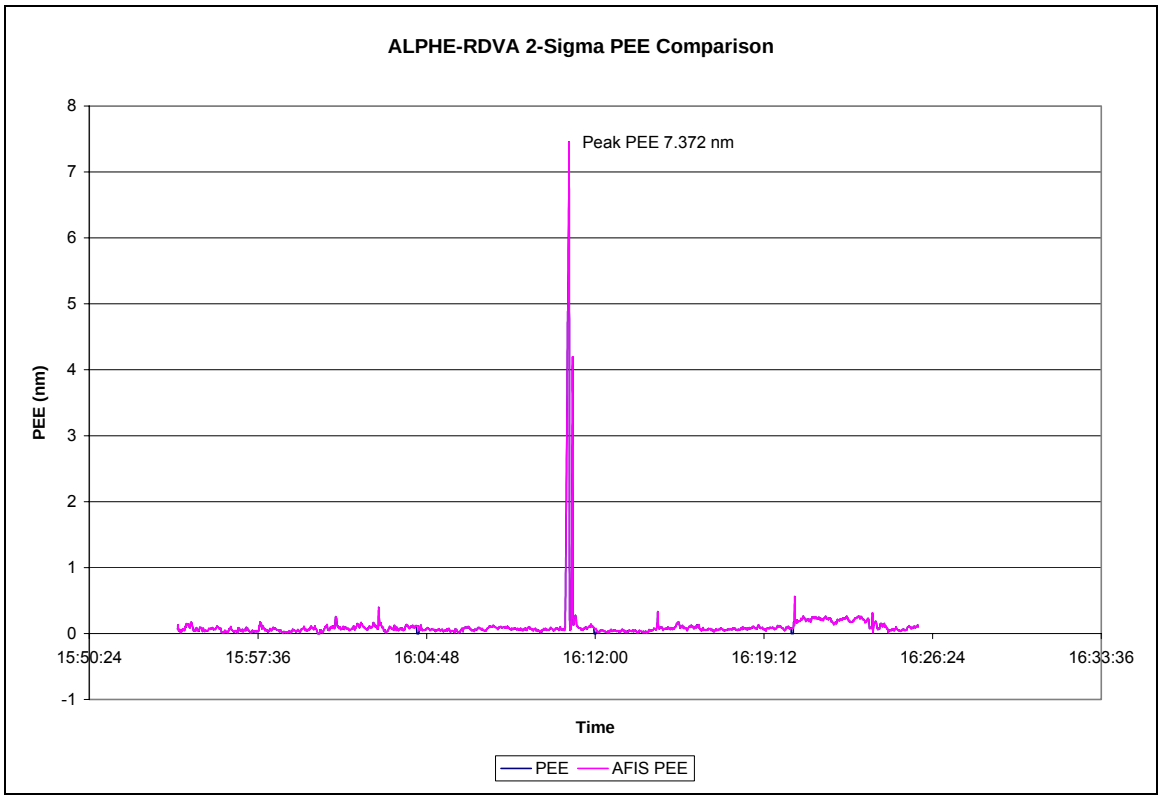

Figure 15. ALPHE-RDVA Manual vs AFIS PEE

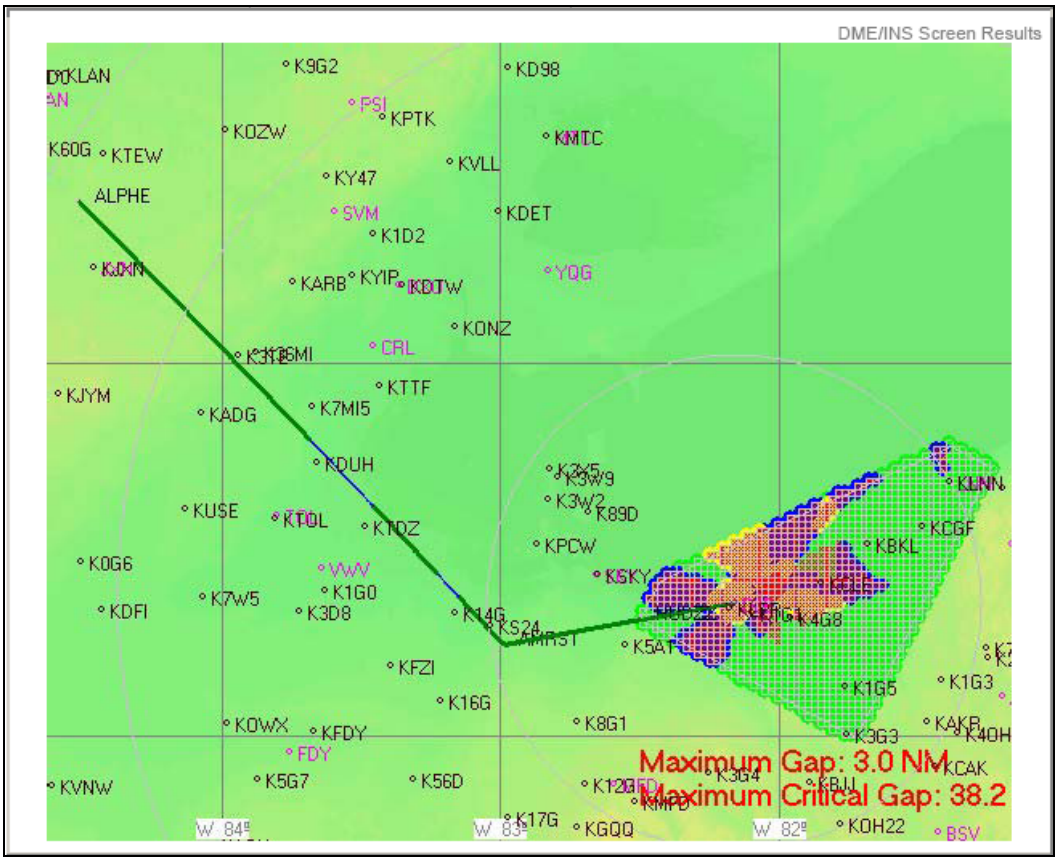

Figure 16. RNAVPro ALPHE-RDVA Output

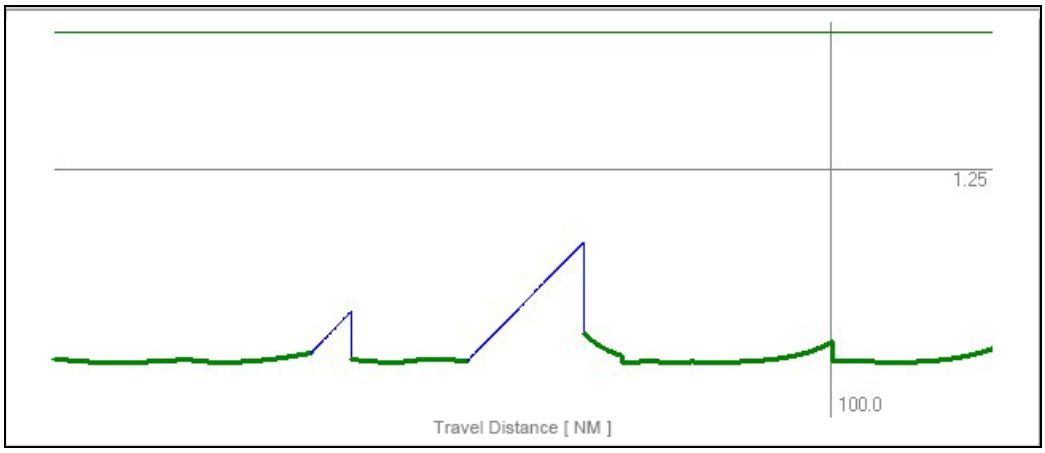

Figure 17. RNAVPro ALPHE-RDVA DME/INS Predicted Error

In the pre-inspection data set there is a portion of the flight where RNAVPro indicates that use of the IRU would be required implying that a gap in DME coverage is predicted to be encountered. During this portion DME facilities continue to be received at the aircraft and recorded by the AFIS. At one point the "SKY" DME facility's error value jumps to a two-sigma value of approximately 7.4 nmi (the one-sigma value is 3.7 nmi). A scanned copy of the actual flight inspection "leg summary report" is provided in

Figure 18. The worst (WST) PEE value (one sigma) for the leg of interest is recorded as 3.69 nmi which agrees with the "worst" PEE value in the recorded data set of 3.68576 nmi.

```
                    DME/DME LEG SUMMARY REPORT
                                          |
ROUTE NAME      ALPHE                     | CRITICAL DME FAILURE
WAYPOINT NAME   ALPHE                     |
LOGFILE NAME    DMMCW18_.008              |
CSV OUT FILE    DMOUT008.CSV              |
                                          |
                                          |
-------------------------------------------------------------------------------
ESV ID |FROM BRG/  RNG/  MSL/  HAF  | TO BRG/  RNG/  MSL/  HAF  STATUS
MFD    |   144.7/029.4/06994/05784  |  103.6/044.8/09001/07791  PASS
DJB    |   084.3/038.7/06994/06214  |  059.5/048.5/09001/08221  PASS
SKY    |   054.8/026.5/09002/08422  |  073.8/046.9/08984/08404  PASS
SKY    |   073.8/046.9/08985/08405  |  074.0/047.5/08992/08412  FAIL
SKY    |   074.0/047.5/08992/08412  |  074.1/047.8/08990/08410  PASS
SKY    |   074.1/047.8/08990/08410  |  074.2/048.0/08990/08410  FAIL
SKY    |   074.2/048.0/08990/08410  |  075.5/051.2/08995/08415  PASS
VWV    |   133.6/021.4/08999/08339  |  112.6/050.3/09001/08341  PASS
CRL    |   066.4/034.0/09009/08379  |  070.4/038.8/09004/08374  PASS
SVM    |   025.8/029.7/09009/08059  |  052.6/040.7/09001/08051  PASS
CRL    |   070.4/038.8/09004/08374  |  070.6/039.1/09001/08371  FAIL
CRL    |   070.6/039.1/09001/08371  |  076.6/052.3/09001/08371  PASS
       |   ***.*/***.*/*****/*****  |  ***.*/***.*/*****/*****  PASS
       |   ***.*/***.*/*****/*****  |  ***.*/***.*/*****/*****  PASS
       |   ***.*/***.*/*****/*****  |  ***.*/***.*/*****/*****  PASS
       |                            |
-------------------------------------------------------------------------------
        AVG    WST/DIST/STATUS
PEE    0.06   3.69/57.2 FAIL
TSE    0.06   3.69/57.2 FAIL
```

Figure 18. AFIS Leg Summary Report – ALPHE-RDVA Flight Test

Of particular interest in this test case is the rate at which the DME error increased. In Figure 15 the one-sigma error between 16:10:45 and 16:10:53 ramped from 0.734753 nmi to 3.68576 nmi. During this time, the DME computed range progresses normally as shown in Figure 19. The computed range is obtained from a GPS/IRU solution and is used as the truth reference for determining the DME range error. This means that the error change is due primarily to the DME range error. For the range error to change by 2.951 nmi in 8 seconds results in a DME range rate of approximately 1328 knots. This rate exceeds the stated dynamic tracking abilities of the Collins DME-900 [27]. The DME channel appears to be in coast mode from flight inspection data shown in Figure 20. Discussions between AEC and FAA AVN have not yet resulted in a determination of whether or not filtering of data may have played a role in this event. The status of "coast" information in the electronic copy of the data needs to be determined. If it is not presently included, serious consideration should be given to the future inclusion of this information.

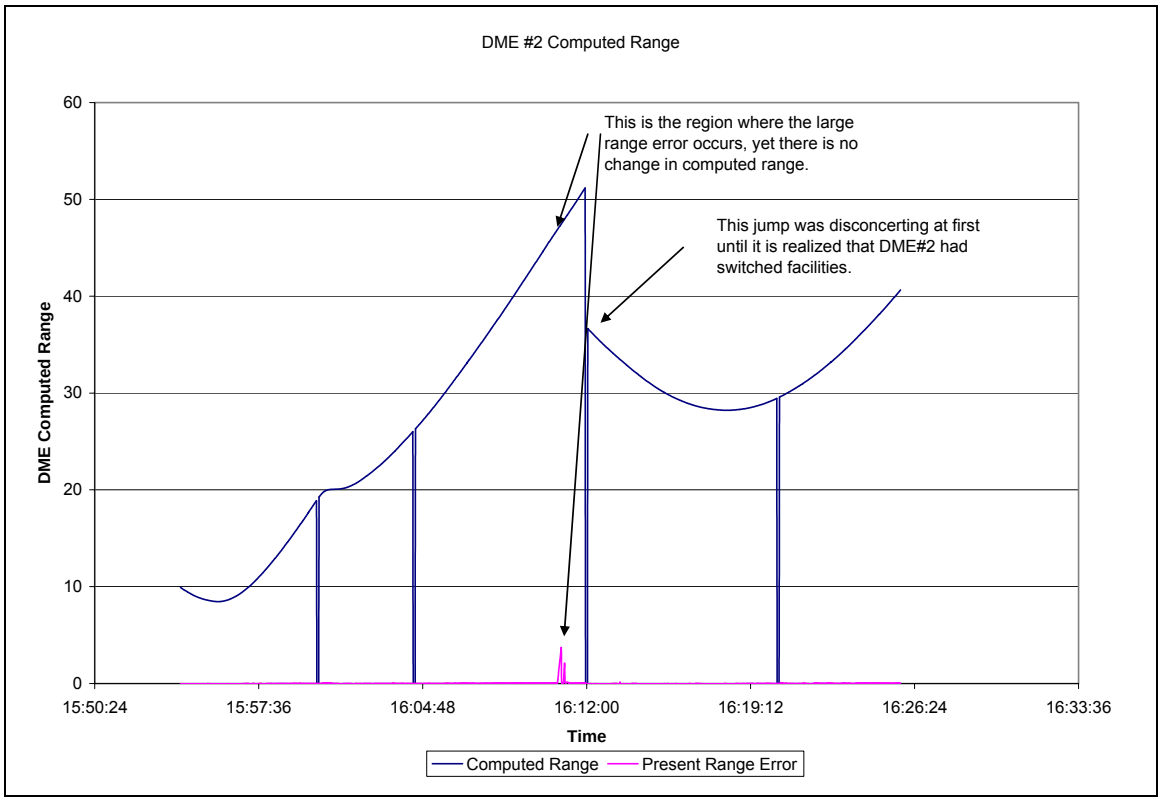

Figure 19. ALPHE-RDVA DME #2 (SKY) Range Error

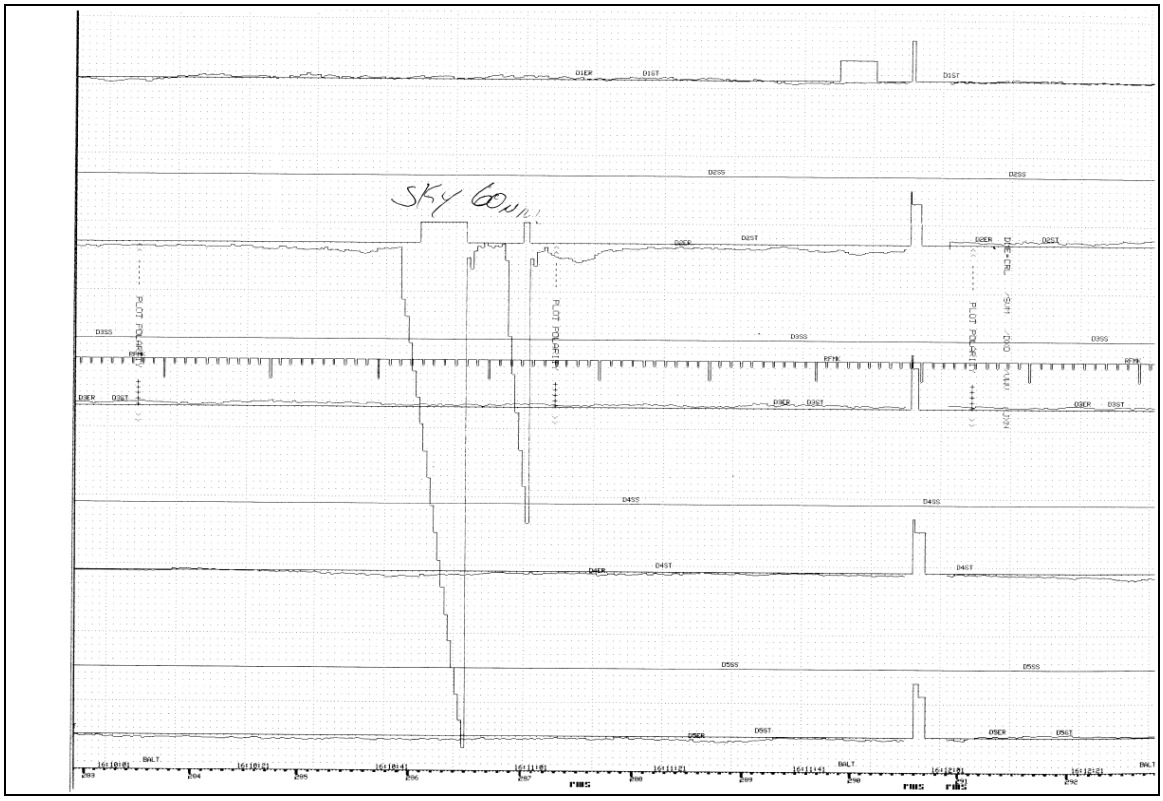

Figure 20. ALPHE-RDVA "SKY" DME Coast Data Plot

3. HOLTZ (KLAX)

In early December 2006, the FAA provided an additional data set from flight inspection missions out of Los Angeles, California. The data files are identified as HOLTZ. Figures 21 and 22 below are from the RNAVPro output for the HOLTZ missions. The data file for the run named "DMLAX24L.064" has been analyzed and the results presented in Figures 23 and 24. Figure 23 presents a plot containing both the "Manual PEE" and "AFIS PEE" data (i.e., both sets of data are plotted against time). The AFIS PEE results overlap the Manual PEE data nearly completely. To obtain a better representation of the difference between the value for the Manual PEE and AFIS PEE at each point in time the actual difference is calculated and is presented in Figure 24. The maximum difference (magnitude) between the two-sigma Manual PEE and AFIS PEE values is approximately 0.0058 nmi.

The RNAVPro output file indicated that the maximum DME error would be 1.018 nmi [28]. From Figure 23 the maximum PEE value is approximately 0.9 nmi and is less than the predicted maximum. In this case, RNAVPro provided an upper bound that was also representative of the actual performance, i.e., not excessively conservative.

All of the following observations pertain to an observed event or data displayed on the AFIS software user interface screen unless otherwise noted.

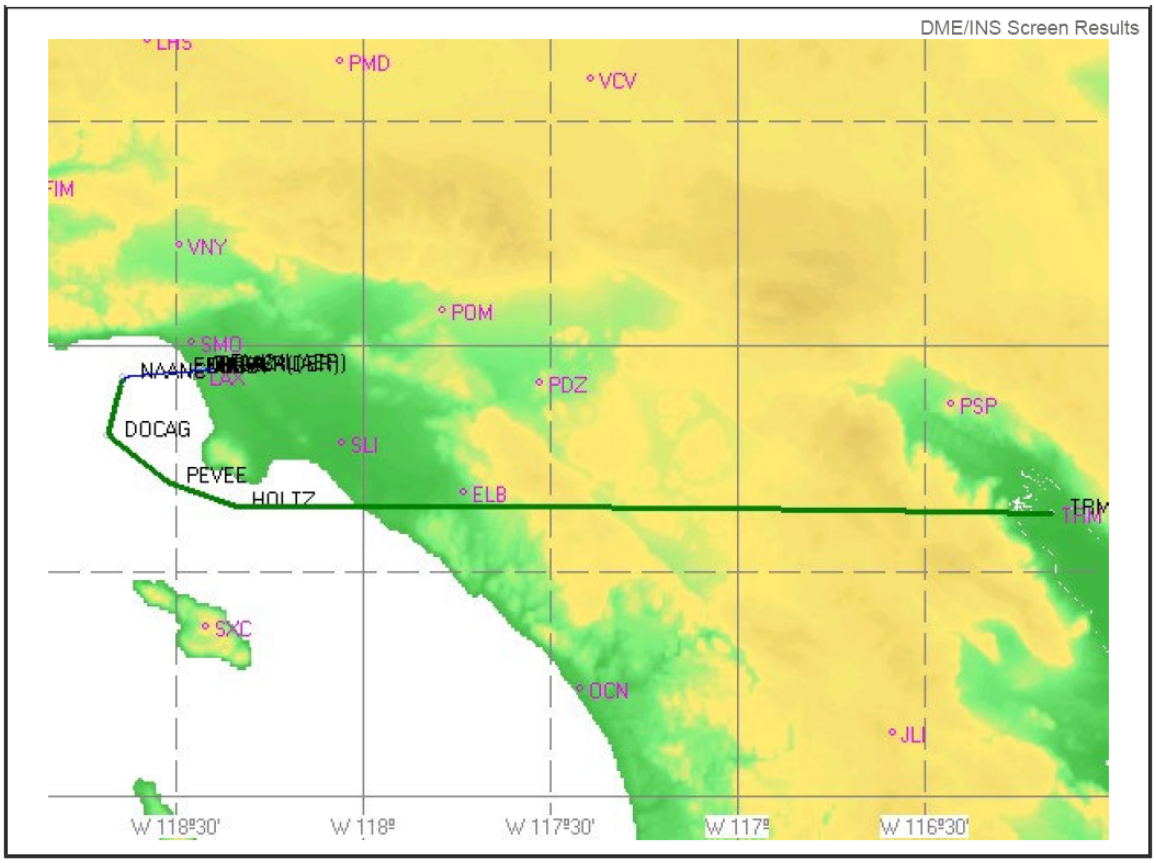

Figure 21. RNAVPro HOLTZ 24L Output

Figure 22. RNAVPro HOLTZ 24L DME/INS Predicted Error

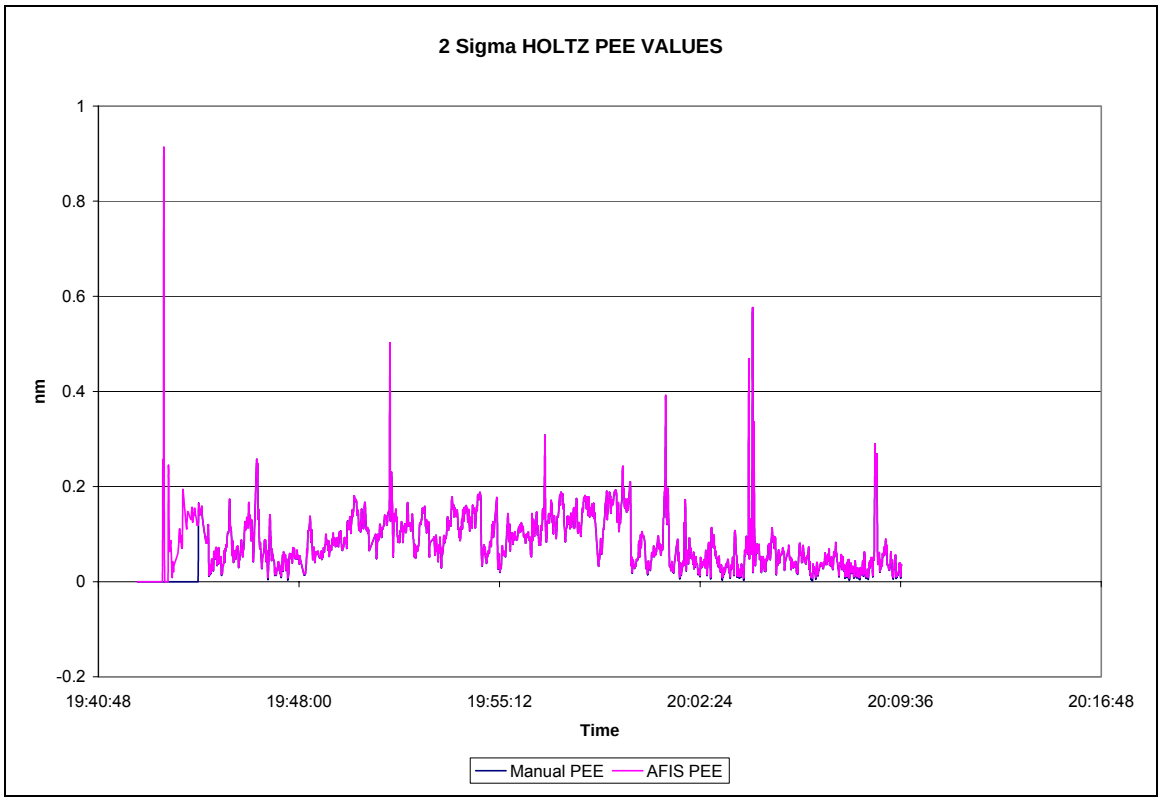

Figure 23. HOLTZ Two-Sigma Manual vs AFIS PEE

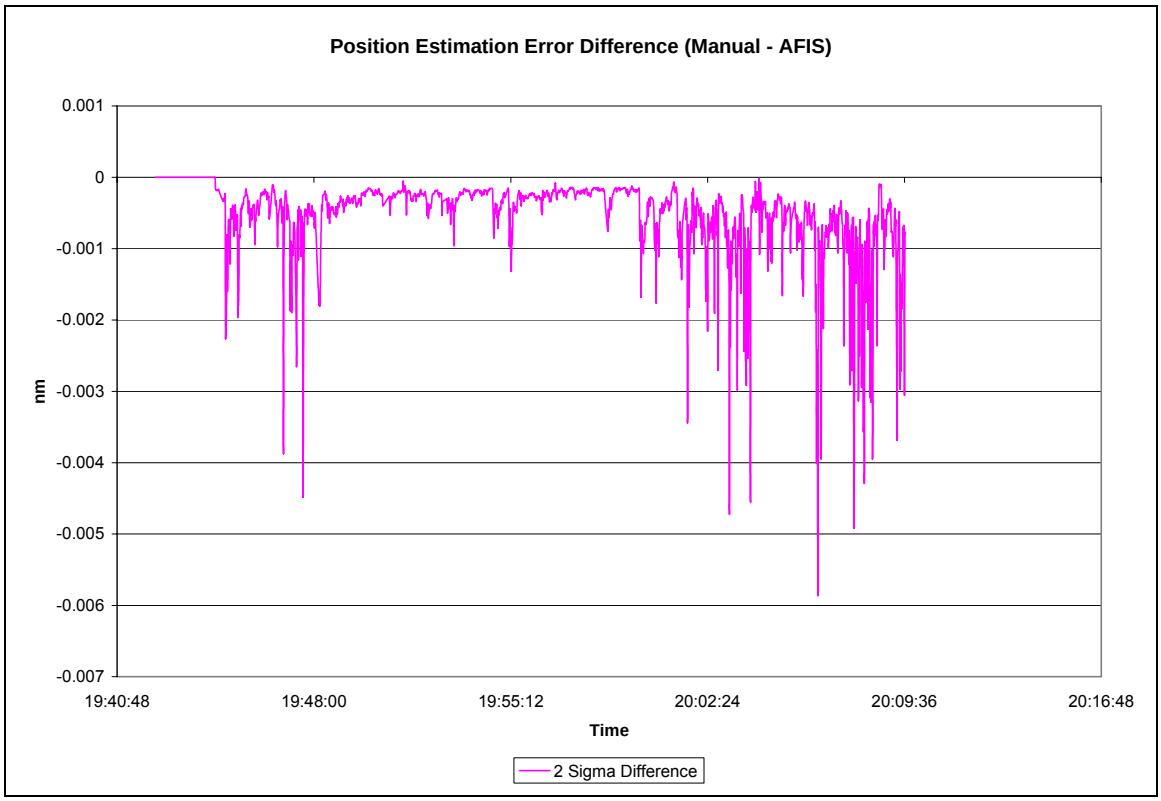

Figure 24. HOLTZ Position Estimation Error Difference (Manual - AFIS)

D. Flight Inspection Observation Activity – Charlotte, NC.

In mid-December 2006, AVN requested that AEC personnel make arrangements to meet an FAA flight inspection crew in Charlotte, North Carolina, to observe the DME RNAV flight inspection process first hand. Travel arrangements were made and AEC personnel met the flight crew at the FBO in Charlotte on the morning of December 20, 2006. The crew of N58 based in Atlantic City, New Jersey, instructed their guest on the morning's mission and prepared for departure. Once airborne the prototype AFIS software was observable for the remainder of the mission. The software was used to collect data but not to determine the success or failure of the DME RNAV route inspection. Data recorded by the prototype software was later transmitted to the RNAVPro office for DME RNAV route evaluation. Discussions, though limited, were conducted as crew workload permitted during the flight test relating to a number of items that were observed.

- Several *Leg Summary Reports* contained critical DME "failures" even though the data did not seem to support that conclusion. Some had coast events but none lasted longer than five seconds or showed an actual DME failure. The flight inspection engineer noted that there are criteria for evaluating unlocks or coasts for normal DME inspections but was unaware of any for DME RNAV inspections.

- On one run, no PEE was calculated until after the second leg was started. Despite having what appeared to be healthy DMEs the PEE was not calculated. Additionally, during this time the status indicated "P/P" (i.e., pass/pass) for PEE/TSE. The TSE did appear to be increasing at a rate in line with what is expected (given no FTE contribution) from IRU drift.
- A VOR/DME solution was indicated for a portion of the last run of the morning indicating that VOR use is included in the inspection software if insufficient DME coverage is available. The output was noted as "*V" next to the PEE/TSE values when the VOR was being used.
- It appears that when re-tuning the DME to a different set of DME facilities all five channels are disabled or re-tuned even if some are to be tuned to the same facility. The reasons for this could be due to software implementation but are unknown. While these outages can be accommodated procedurally an explanation of the re-tuning process and reason for dropping all channels would help ensure proper traceability.
- When PEE is not calculated due to lack of DME facilities the PEE indication should not show as passing or "P". This also happens at the beginning of a flight inspection run. It is suggested that all flight inspection runs begin prior to the starting waypoint of the segment to be inspected and continue beyond the ending waypoint. This will ensure that data exists, at either end, to support the inspection decisions made at the starting and ending waypoints. This would also serve to help alleviate some of the issues noted in the previous comment.

E. Summary of Observations

Once corrected to reflect two-sigma values, the AFIS data sets analyzed during this study showed good agreement with the basic PEE manual calculations. It is important to note that while the data sets do contain short duration (less than five seconds) spikes in range data, these should have little impact on DME/DME procedures and no impact on DME/DME/IRU procedures that use TSE as the metric for navigation performance. In these cases, a sufficient TSE value indicates that the IRU was capable of providing guidance caused by gaps due to holes in the DME coverage or region of poor geometry.

Based upon the examined flight inspection data the AFIS software appears to latch or "hold" the maximum PEE value in the "Worst PEE" data field within the DME-DME data package regardless of duration. The Worst PEE data field appears to be updated with new data one second after the "max" PEE event occurs. Upon further examination it also appears that, in the data sets provided to AEC, the "Worst PEE" values are based on two-sigma values while the "Present PEE" and "Average PEE" values are based on one-sigma values. Resolution of these differences may already be addressed by FAA actions taken to ensure usage of two-sigma values for the PEE. If the AFIS software uses the Worst PEE value to determine if a procedure passes or fails it could result in an unnecessary denial. However, although the AFIS manual does not mention use of this "Worst PEE" in the leg summary reports it does appear to be included in the report (see bottom of Figure 18). It is thus unclear if this value is used to determine the status of the

flight inspection. The exact criteria for determining procedure "pass" or "fail" as related to the "Worst PEE" value should be investigated and characterized.

The excessive ramping of the DME transceiver in the ALPHE flight check data is an issue that should be addressed by the FAA. A ramp rate based on the previous aircraft rate of change would be expected. However, in this case the ramp rate appears to have exceeded the abilities of the DME transceiver which gives rise to the question "What happened?" The available electronically recorded data doesn't provide much insight in this case. An investigation into the behavior of the DME transceiver used for the flight test in ALPHE and possibly other missions needs to be performed to ensure that procedures are not unnecessarily denied.

During the flight check activities in Charlotte, NC, the presence of VOR derived position information in the DME/DME/IRU data was observed. This information was provided to the FAA in an informal email concerning trip results and observations. Active discussions concerning the use of VOR/DME providing RNAV solutions during flight inspection of DME/DME RNAV procedures followed distribution of the email. There are two statements in FAA Advisory Circular 90-100A that provide the following guidance: "There is no requirement to use VOR … during normal operation of the …" for the DME/DME (Appendix 1, Section 2, paragraph e) or DME/DME/IRU RNAV System (Appendix 2, Section 2, paragraph b). Additionally, Appendix 1, Section 2, paragraph h states "The RNAV system must ensure that an erroneous VOR signal-in-space does not cause the position accuracy to exceed 1.75 nmi for RNAV 2 and 0.87 nmi for RNAV 1."

The AFIS manual states that the VOR/DME mode can be enabled manually or automatically if there are less than two DME facilities or the include angle is beyond the acceptable range for the best DME pair [29]. When encountering a DME RNAV coverage gap, it would be better for the procedure assessment to be based on the IRU drift rate. For example, the AFIS software could start a timer upon lost of requisite DME RNAV coverage and this timer can be used to calculate the accumulated IRU drift and thus the NSE_T. VORs should not be used by the AFIS to augment the PEE calculations during a coverage gap since this approach is not representative of the required minimum equipage (i.e., DME/DME/IRU).

V. CONCLUSIONS AND RECOMMENDATIONS

Flight inspection of new DME RNAV procedures is an essential element in ensuring that aircraft containment levels (e.g., RNAV 1) required for the procedure are achieved while using the DME infrastructure in the NAS. The assessment of non-sensor dependent items such as obstacle clearance and flyability for the new procedure also necessitates flight inspection. Additionally, new sources of interference, blockage, and multipath can not be sufficiently modeled to protect the procedure while optimizing airspace utilization.

Based upon the data sets reviewed by AEC, initial RNAVPro results tend to create an overly restrictive DME RNAV procedure presuming that the DME equipment is operating at the full system tolerances for accuracy and efficiency. That is, if the equipment is operating well within these full system tolerances the RNAV Pro results can be pessimistic. However, the more critical case in terms of ensuring containment is if the equipment is not operating within system tolerances, then the results could be overly optimistic. Thus, the results may not be representative of the available service and can not be used as justification for authorizing the procedure without flight inspection data.

The following conclusions and recommendations apply to the modification of the Next Generation AFIS software and not the current DME RNAV inspection process. The FAA flight inspection office is conducting inspections of DME RNAV procedures using the FAA prototype Next Generation AFIS software to collect data that is transmitted to the FAA office responsible for RNAVPro for post-flight processing. This post-flight processing determines the pass/fail status of the procedure provided the flight inspection mission was successful in terms of obstacle clearance, flyability, etc.

The FAA needs the ability to make an in-flight assessment (pass/fail) of the DME RNAV procedure and is moving to acquire this capability with the Next Generation AFIS software. The FAA Next Generation AFIS will be capable of providing PEE/TSE data to support and provide this airborne determination of DME RNAV procedure success or failure when the recommendations made herein are appropriately addressed and the resulting software validated. The algorithm used to calculate the PEE will, when updated, provide the inspector with an accurate two-sigma PEE value. The algorithm used to calculate the AFIS TSE requires additional definition, investigation, and validation as does the application of the 95% criteria to the AFIS TSE value. Recommendations to address these items are included in the list below.

Recommendations one and two are made with respect to *General Guidance Information* reviewed and utilized throughout this assessment. These findings were identified during the review and assessment of the prototype AFIS software and flight inspection procedures.

1. The FAA must complete resolution of the correction of the PEE equation as currently presented in RTCA publications concerning DME/DME RNAV. The FAA has issued several documents (including an advisory circular) with a corrected version of the equation (equation 1) and is using it in flight inspection services (equation 4);
2. The name for AFIS "TSE" should be changed as it is not intended to be a measurement of the value generally accepted as "TSE" as defined in RTCA and ICAO documents;

The following recommendations (three through eight) identify findings that are necessary to strengthen and complete the prototype *AFIS DME-RNAV software*. Findings five and six are a result of the prototype AFIS software assessment and review of flight inspection requirements and procedures. Findings six through eight were identified during an

observation mission with a flight inspection crew and subsequent review of the mission data.

3. The PEE values calculated by the prototype AFIS software were not initially correct. One-sigma values were calculated instead of the two-sigma values needed for the 95% containment and comparison with RNAVPro. AVN worked with the AFIS support contractor to identify the requirements and has initiated corrective action to update the software with two-sigma PEE calculations. Upon completion of the evaluation of AFIS TSE calculations and any necessary corrections and validation, that value be used to directly determine the status of the flight inspection mission for the RNAV 1 (DME/DME/IRU) procedure;
4. Upon completion of upgrades to the AFIS software to enable direct computation of the two-sigma PEE, that value be used to directly determine the status of the flight inspection for the RNAV 2 (DME/DME RNAV) procedure (all routes in the U.S. presently require DME/DME/IRU even though there may not be a gap in coverage requiring inertial so TSE is required);
5. An interval or windowed definition for applying the 95% criteria, similar to those defined for existing navigation and landing systems, should be developed for the RNAV 1 and RNAV 2 requirements;
6. Disable VOR/DME RNAV position generation during procedure flight checks;
7. To eliminate potential confusion between RNAV procedure tolerances and provide a permanent record of the RNAV procedure performance it would be prudent to modify the AFIS software such that at the completion of a procedure segment a statement such as "DME performance supports RNAV level 2.0", "DME performance supports RNAV level 1.0", etc. be provided in hardcopy in addition to the provision of PEE/TSE pass or fail indications;
8. Some non-zero and non-legitimate value should be used to fill PEE/TSE data fields when the results are not valid. The results displayed and recorded should be easily recognized as invalid;

Recommendations nine through twelve address *flight inspection procedure* findings. Items nine and ten were identified during post-flight assessment of a flight inspection observation mission. Item 11 was identified during assessment of the ALPHE-RDVA mission and item 12 addresses guidance to the FAA, industry and general public with respect to the "DME Include Angle".

9. Start data capture during DME RNAV segment inspections at least 30 seconds prior to crossing the beginning waypoint and 10 seconds after crossing the end or last waypoint (this data should not count toward PEE/TSE measurements of the segment);
10. If it should become necessary in the future to use the VOR/DME mode of the AFIS as a fallback during flight inspection of DME RNAV procedures, the methods of computing PEE and TSE while using this mode will need to be defined, reviewed, implemented, and validated;

11. Determine the source of range excessive ramp rate for the DME transceiver used during the ALPHE testing to ascertain if it could result in the unnecessary denial of DME facility and RNAV procedure flight check approvals;and,
12. Information searches have not yielded a definition for "DME include angle" that includes supporting descriptive text and graphics. To assist the FAA, industry, and general public, provision of an official "DME include angle" definition would be beneficial.

VI. REFERENCES

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8. Electronic correspondence (RNAVPro Use Explanation), Mr. Don McGough, Federal Aviation Administration AVN, Airspace System Inspection Pilot, Aviation System Standards Flight Inspection Policy, December 7, 2006.

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12. Electronic correspondence (FAA FI Fleet RNAV Capability), Mr. Don McGough, Federal Aviation Administration AVN, Airspace System Inspection Pilot, Aviation System Standards Flight Inspection Policy, December 5, 2006.

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14. United States Standard Flight Inspection Manual, Federal Aviation Administration Order 8200.1C, Section 11.21:f:4.a, October 15, 2005.

15. United States Standard Flight Inspection Manual, Federal Aviation Administration Order 8200.1C, Chapter 22, Figure 22-2, October 15, 2005.

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17. "U.S. Terminal and En Route Area Navigation (RNAV) Operations," Advisory Circular AC 90-100A, Federal Aviation Administration, Appendix 1, Section 2.f, March 01, 2007.

18. "*Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation*," RTCA Document, DO-236B, Appendix C.3.2, October 28, 2003.

19. FAA "Request for Clarification" memo, W. Scales, C. Hegarty, no date.

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21. "U.S. Terminal and En Route Area Navigation (RNAV) Operations," Advisory Circular AC 90-100A, Federal Aviation Administration, Section 4.n, March 01, 2007.

22. "*Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation*," RTCA Document, DO-236B, Appendix C.3.1, October 28, 2003.

23. "System Description FAA Automated Flight Inspection System," NXT TM3500-071 Rev J, NXT Inc, Ronkonkoma, New York, March 2006.

24. Electronic correspondence (AFIS TSE algorithm implementation), Mr. Don McGough, Federal Aviation Administration AVN, Airspace System Inspection Pilot, Aviation System Standards Flight Inspection Policy, December 8, 2006.

25. Electronic correspondence and files, Mr. Lou Volchansky, AIR-130, Federal Aviation Administration, Aerospace Engineer, January 31, 2007.

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APPENDIX A

RTCA REQUEST FOR CLARIFICATION MEMO

W. Scales
C. Hegarty

Request for Clarification

Subject: Expression for $\sigma_{DME/DME}$ in RTCA DO-283 Appendix C, similar expression in DO-236A Appendix C

References:

1. "The Comparative Accuracy of Various Existing And Proposed Radio Navigation Systems," W. Q. Crichlow, National Bureau of Standards Report CRPL-4-1, December 30, 1946.
2. Minimum Operational Performance Standards for Required Navigation Performance for Area Navigation, RTCA DO-283, October 10, 2002.
3. Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation, RTCA DO-236A, September 13, 2000.

Summary of the Issue: Section C.3.1.2 of DO-283 contains the following expression for $\sigma_{DME/DME}$:

$$\sigma_{DME/DME} \leq \sqrt{\frac{0.02}{\sin(\alpha)}}$$

Where α is "the inclusion angle of the two DMEs". Reference 1 and other sources derive $\sigma_{DME/DME}$ as a quantity that is inversely proportional to $\sin(\alpha)$ rather than $\sqrt{\sin(\alpha)}$. For $0 < \alpha < \pi$, $\sqrt{\sin(\alpha)}$ is always greater than or equal to $\sin(\alpha)$; therefore $1/\sqrt{\sin(\alpha)}$ is always less than or equal to $1/\sin(\alpha)$. So it would appear that the right side of the inequality in C.3.1.2 is smaller than it would be under the derivation given in Reference 1 and other sources, i.e., it is generally an underestimate of the DME-DME error rather than an overestimate. Section C.3.2 of DO-236A contains a similar issue, since σ^2 is taken to be inversely proportional to $\sin(\alpha)$ rather than $\sin^2(\alpha)$.

Recommended Action: The authors of this note believe that it would be useful to review and revalidate the derivations of the expressions for DME/DME RNAV error in DO-283 and DO-236A.