Distance Measuring Equipment Accuracy Performance Today and for Future Alternative Position Navigation and Timing (APNT)

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BIOGRAPHY

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1. INTRODUCTION

Distance Measuring Equipment (DME) is seeing renewed interest for its ability to support future aviation navigation and surveillance needs. It is one of the primary technologies being examined by the Federal Aviation Administration (FAA) Alternative Positioning, Navigation and Timing (APNT) project to support needs to provide an alternative to global navigation satellite systems (GNSS) in the Next Generation Air Transport System (NextGen) airspace.

As part of the APNT study of DME, the APNT team has been examining means to improve DME beyond its specified accuracy. In fact, the fielded system may already perform much better than specifications require. Furthermore, additional improvement may be gained with little or no change to today's system. However, meeting the most stringent APNT goals would likely require changes to ground and airborne system components.

OUTLINE

This paper examines DME accuracy starting with its performance today. Accuracy values from several data collection efforts are presented. A top-level examination of range accuracy is done using FAA flight inspection data. The results show that the measured DME ranging accuracy is generally much better than that listed in the current specifications.

The potential performance of DME is studied using a bottom-up approach considering the components of range error. Breaking down the overall error into components allows for the determination of what most limits accuracy and where improvements are most easily gained. The simplest would be to take credit in the next DME specifications for current operations. This may achieve some APNT targets. Key components discussed and examined are the precision of the DME ground transponder signal in space, transponder reply delay and multipath effects. A similar examination is underway to identify the elements of airborne interrogator error. This paper discusses the APNT accuracy results for DME and is a follow on to the 2012 APNT DME white paper [1].

2. BACKGROUND

The APNT group was formed to determine and develop the promising solutions that provide FAA navigation, surveillance and other services in the event of a Global Positioning System (GPS) or GNSS degradation event. The need for APNT is particularly important as aviation use of GPS increases in coming years. Under NextGen, GPS will be the primary means of navigation and surveillance. GPS will enable the operations that are needed to handle the increased air traffic levels anticipated in the 2025 time frame. Currently, GPS is often the only system capable of supporting many envisioned operations. Current terrestrial based navigation systems either cannot provide the area navigation (RNAV) capabilities or the performance needed to sustained future operations.

Hence, the FAA is working on developing an APNT solution that can sustain operations in the event of GPS unavailability. The solution will provide RNAV capability for en route operations throughout the CONUS as well as terminal area coverage in major airspace. For terminal operations, the APNT should be able to support Required Navigation Performance (RNP) or Area Navigation (RNAV) operations down to 0.3 nautical miles (RNP/RNAV 0.3)[1]. A further goal is to provide position information for Automatic Dependent Surveillance - Broadcast (ADS-B) to support 3-mile and 5-mile aircraft separation. Currently, 3-mile separation rules require 92.6-meter position accuracy, which is a navigation accuracy category (NAC_p) of 8[3].

DISTANCE MEASURING EQUIPMENT

DME is a two-way ranging system operating in the L-band of radio frequencies between 960-1215 MHz that enables the aircraft to calculate its slant range to a DME ground station or transponder by transmitting an interrogation signal to the ground station and receiving a corresponding reply. The interrogation, like all DME transmissions, is in the form of a pulse pair. The transponder receives and verifies the interrogation as a DME transmission. Verification proceeds through identification of the second pulse, which is at a known fixed time after the first pulse. After verifying, the DME transponder, if operating on the X channel, transmits a reply pulse pair following a 50 microsecond (μs) delay (the "reply delay") measured from the time of arrival of the first pulse. Figure 1 shows this operation of the DME transponder.

In the DME interrogator, the calculation of pulse-pair Time of Arrival (TOA) is based on detection of the first pulse. The purpose of the second pulse is to distinguish the transmission from random or spurious pulses. For standard DME (DME/N - narrowband), the timing of the transmission is based on the half-amplitude point of the rising edge of the first pulse. The measurement method represents a compromise between multipath and noise performance with consideration also for radio frequency (RF) spectrum requirements..

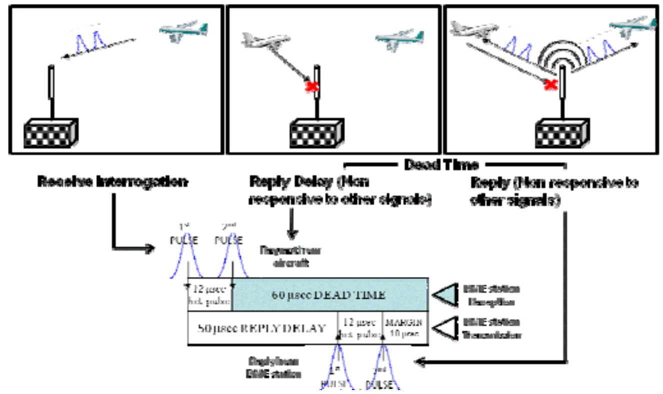

Figure 1. DME Transponder Operations (X channel)

From the interrogation and reply, the avionics then determines the round trip time and calculates the range to the DME transponder, provided it knows the interrogation time of transmission and the reception time of the corresponding reply. More details on DME are provided in [4].

DME FOR APNT

DME and its military counterpart, Tactical Air Navigation (TACAN), have many desirable features for providing APNT service. It has a long operational history around the world. Today, a scanning DME (DME/DME) can support RNAV en route operations when used with an Inertial Reference Unit (IRU). However, APNT performance targets including accuracy are not met by current DME system specifications. Fortunately, the system performs better than specifications and it is possible that DME, with minor changes, can meet some or all APNT accuracy targets.

Today's DME is specified to provide position accuracy of around 0.6 nautical miles (nm). This is seen in the DME overall range accuracy specifications presented in Table 1[5][6][7][8]. The table shows the specified standard deviation of the signal in space and airborne interrogator (σ_{sis} and σ_{air}, respectively) for various standards. The signal in space accuracy is due to errors caused by the ground transmitter and the propagation of its transmission. Likewise, the airborne interrogator accuracy represents that performance given errors caused by the avionics and the airborne transmission.

Source	σ_{sis} (nm)	σ_{air} (nm)
ICAO Annex 10 & E-2996	< 0.0524†	< 0.085 (up to 200 nm)
AC90-100A	0.05	max(0.085, .125%**d*)† †
DO-189		0.085
† From a total system range accuracy of 0.2 nm †† *d* is distance from transmitter in nm		

Table 1. DME range performance from current standards (post 1989 equipment)

While the current specifications and standards for DME accuracy only allow the system to support en route operations such as RNAV 1.0, the research by the APNT team has determined that the existing DME system performs better than those specifications. The errors may be significantly less than specified. The ground system provides an illustrative example. Several factors indicate it can perform significantly better than specifications. First, the transponder reply delay error currently is allowed to be up to ±500 nanoseconds (ns). Consulting with manufacturers and tests indicate that a limit of ±100 ns can likely be met with today's equipment. With this improvement alone, a 0.05 nm σ_{sis} would be reduced significantly given that currently the transponder is allowed to contribute a significant portion of the error. The ±500 ns error corresponds to 150 meters contribution to radio round-trip timing error. Since one-way range is determined by dividing round-trip time, this corresponds to a 75 m (0.0405 nm) range error. With ±100 ns, this contribution becomes 15 m (0.00801 nm). For the purposes of the calculations in Table 2, the not-to-exceed value is conservatively used as a 2 σ value.

Additional errors may be easily eliminated if apparent. FAA flight inspection tolerance for DME range is currently 0.2 nm accuracy (2σ) which is suitable to validate RNAV 0.6 performance as seen in last column of Table 2 for the Current DME/N row. However, this tolerance levels can mask some easily correctable errors such as survey errors in DME transponder location that may be significant for APNT. Hence, through consultation with manufacturers, it is believed that the current DME/N ground system accuracy can be significantly better than specifications.

The team is evaluating an evolutionary path for DME capable of supporting APNT goals. The path starts with: 1) the current system as specified in the standards (DME/N) and then 2) the potential system based on fielded ground equipment (Improved DME/N) and 3) a high-accuracy system, if necessary. The anticipated performance based on current APNT findings is seen in Table 2. The range error is converted to a position or navigation system error (NSE) by assuming a worst-case dilution of precision (DOP) of 2.8. As RNP and RNAV performance is specified in terms of total system error (TSE), a flight technical error (FTE) of 0.25 nm is assumed and added to the NSE in an RSS manner. The FTE value is that for a flight director in DO-208[9]. For the high-accuracy system, the changes needed to meet the accuracy target are being determined. More-optimum pulse shapes, improved receiver detection and possible carrier-phase processing are among the methods under consideration.

The Improved DME/N values reflect APNT findings and projections to date, emphasizing ground system and standards changes, with unaltered avionics. Given these results, the TSE is projected to meet the RNAV 0.3 goal with a small margin.

Propagation errors are dominated by multipath, which can affect both the downlink (interrogation) and uplink (reply). Small errors due to pulse collisions with interrogations from other aircraft and from diffuse multipath are also included. The table value is the result of analysis by the APNT team and others[1][3][12].

Case	Transponder	Propagation	Avionics	Range	NSE* nm	FTE** nm	TSE*** nm
Current DME/N flight-inspection	--	--	--	0.2 nm (370.4) FAA Flt Insp	0.56 nm (1047.6) Calc	0.25	0.64
Current DME/N standards	0.041nm (75m) E-2996	0.097† (180) Derived	0.17**** (315) DO-189	0.20 (370.4) Calc	0.565 (1047.6) Calc	0.25	.618
Improved DME/N	0.0081 (15) Industry	0.027 (50.83) Analysis	0.046 (85) Lab Tests	0.054 (100.2) Calc	0.153 (283.32) Calc	0.25	0.29
High-Accuracy for 3-nm Separation	0.0054 (10) Demo††	0.013 (24) Demo	0.008 (15) Demo††	0.016 (29.7) Calc	0.0454 (84) Calc	--	--

† From a total range accuracy of 0.2 nm
* Position from 2 DMEs. Included angle 30-150 degrees (maximum geometry factor of 2.828) [7]
** 0.25 nm (Flight Director, per DO-208[9], DO 236B[10], DO 283A[11])
*** TSE (Total System Error) value is root sum squared (RSS) of FTE (Flight Technical Error) and NSE (Navigation System Error). TSE is numerically equal to RNAV or RNP value.
****Range accuracy at 0.17 nm per DO-189[8] for post 1989 equipment
†† From Table XX of [3]

Table 2. DME 95% (2σ) range and position error, nm and (meter)

3. OVERALL ACCURACY

The overall accuracy of the system is obtained from flight measurements. Two sources of data were examined for the initial evaluation: FAA flight inspection and Boeing flight data. The data from these tests indicate that an overall 0.05 nm Path Following Error (PFE) accuracy is typical in today's system. PFE is derived from a second order low pass filter of the DME position data. Hence it averages out some of the momentary position spikes.

FAA Flight Inspection Data

Flight-inspection data library and the other FAA tools allowed for a preliminary inspection of DME range accuracy. To examine the flight inspection data, the FAA provided a Logger File Conversion Utility (LFCU) [13].

While the raw position errors can be examined, filtered results such as PFE are more relevant to the analysis. Filtering routines initially developed for the microwave landing system (MLS) program [4][14] were re-coded for DME range-accuracy determination in compliance with current FAA methodology[6]. Both PFE and Control

Motion Noise (CMN) filtering routines were coded and used to study DME. PFE data remove at least some high-frequency error, to give an approximation of the range data which will reach the aircraft's flight-management system. The CMN filter is a high-pass filter which separates the high-frequency components of position error which could cause motion of control surfaces, but no proper motion of the aircraft path guidance. This CMN factor is less of an issue in terminal operations with today's flight control systems, compared with earlier applications for MLS final-approach guidance.

An early site examined was the Olympia, WA (OLM) DME. The flight inspection data was retrieved from the FAA library and range data from orbits flown about the station were studied. Figure 2 shows the initial reformatting of raw FAA data. Figure 3 shows the PFE filtered errors as a function of bearing to the station. The range of the aircraft from OLM varied from 17.8 to 18.2 nm. In the unfiltered data, several position error spikes are seen. These are momentary and are smoothed out by the PFE filtering. This is seen in Figure 3 with the arrows indicating where the spikes occurred in the unfiltered data. Note that after PFE filtering, there is still a small bias (~ -0.02 nm) to the range error. In spite of the bias, the range errors rarely exceeded ±0.05 nm.

Figure 4 shows the Path Following Noise (PFN) of the error along with 95% error bounds. PFN is simply PFE with bias removed over the entire flight path being considered. It shows that the maximum 95% error after removing the bias is 0.048 nm. Another observation is that the error exhibits a sinusoidal pattern with respect to bearing. A possible cause is an error in station location used for the truth range calculation.

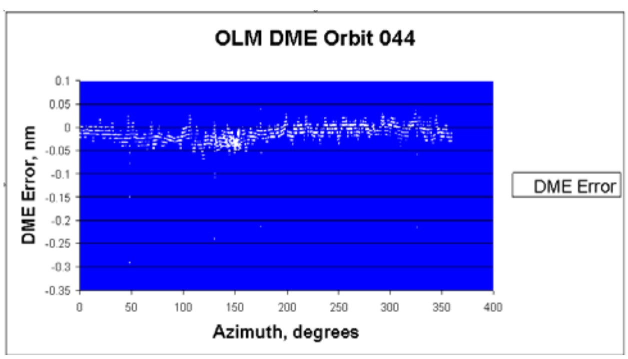

Figure 2. Unfiltered Range Errors about Olympia, WA vs. bearing to DME facility

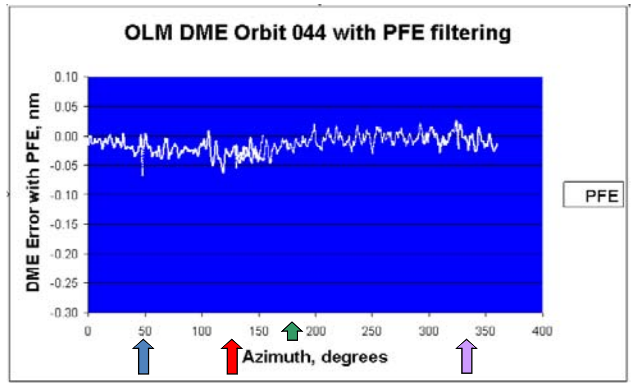

Figure 3. PFE Filtered DME Range Errors about Olympia, WA

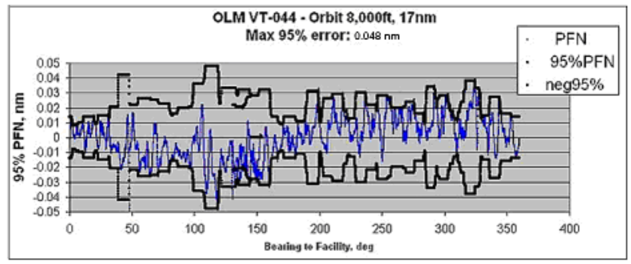

Figure 4. PFN Filtered, Bias Removed DME Range Errors about Olympia, WA with 95% Error Bound; (expanded vertical scale)

Error spikes are not uncommon and seen in several other measurements. Similar spikes are observed at other stations such as the DME at Telluride, CO (ETL) as seen in Figure 5. The cause of these spikes remains under study. Possible causes are multipath and momentary receiver range-gate dropouts.

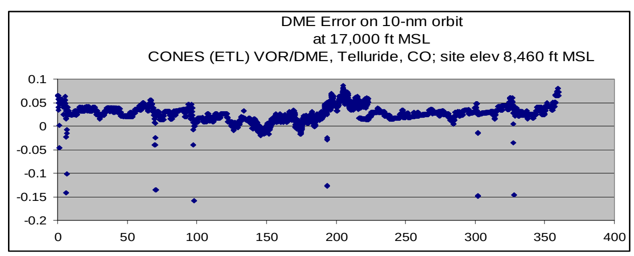

Figure 5. Unfiltered DME Range Errors about Telluride, CO

An FAA demonstration and evaluation of new tower systems at Dallas/Fort Worth (DFW) in April and May of 2011 offered a different opportunity to examine DME performance. The evaluation required a dedicated FAA Flight Inspection King Air aircraft to conduct local airport taxiing, departures, arrivals, and low altitude maneuvers within 30 nm of the airport. As the Automated Flight Inspection System (AFIS) onboard the test aircraft was not needed for the evaluation, it was made available to collect range data from navigation aids (navaids) providing DME services operating around DFW. The

AFIS was operated in the VOR/TACAN mode (VT) as if conducting an orbit. This mode allowed DME performance data to be collected regardless of actual flight profile (not orbits) but for only one selected DME at a time. The collection thus provided data close to the ground as well as data at different ranges.

DFW has three local navaids offering distance-measurement service -- Maverick VOR/DME (TTT), Ranger VORTAC (FUZ) and Cowboy VOR/DME (CVE). Figure 6 shows the range error from these navaids during the flights. As seen in the upper half of the figure, a majority of the errors are between -0.07 and +0.07 nm but several outliers exist on the "high" side of the DME error distribution, indicating late arrival of reply pulses. These outliers are likely due to multipath when the aircraft was close to or on the ground. These outliers are eliminated if the results are filtered. This is seen in Figure 6. It is even clearer in Figure 7 which only includes those measurements taken while the aircraft was at or above 400 feet above ground level (AGL) and above -90 dBm (decibel relative to 1 milliWatt). The data also indicate that accuracy performance better than 0.05 nm is prevalent.

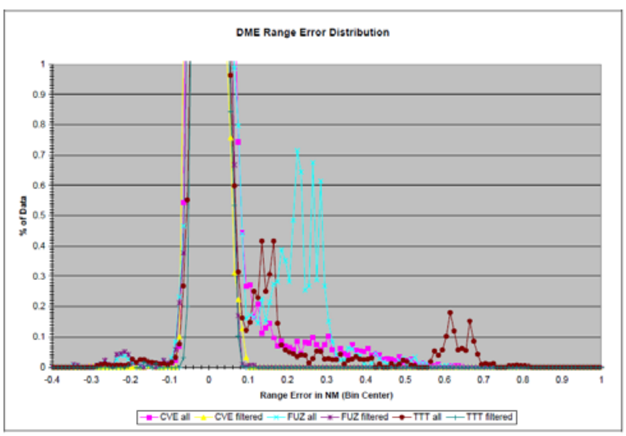

Figure 6. DME Unfiltered & Filtered Range Error Distribution for DFW DMEs (CVE, FUZ, TTT)

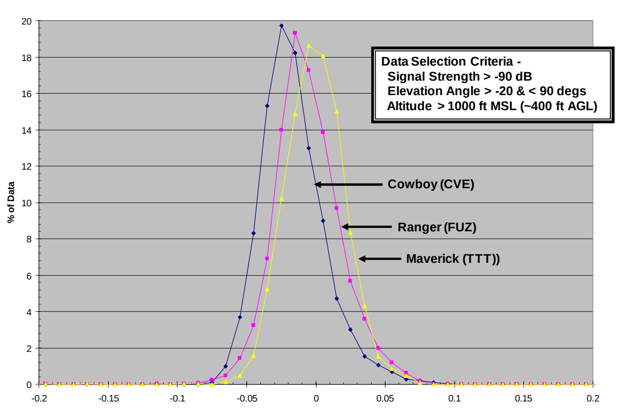

Figure 7. DME Filtered Range Error Distribution for Dallas Fort Worth DMEs (CVE, FUZ, TTT)

Boeing Flight Measurements

Boeing engineers in support of the APNT team assessed DME measurements of opportunity taken over the course of many of its test flights. The data files contained over two million DME navigation-system error data points with aircraft position truth accuracy of 1.5 m, 95%. Truth data were converted to slant range for comparison with DME range data. Data were collected from 125 DME facilities during long flights throughout the western United States. Distances from DME facilities varied from overhead to 220 nm. The results showed that 94.9% of stations had mean error less than 0.05 nm and 95.5% of stations had standard deviation of error less than 0.05 nm. However, range data from three stations were found to have standard deviations of > 0.2 nm. These results were presented in [15].

Another assessment performed was an examination of the range performance of different DME avionics. Three DME interrogators representing current fleet equipage were tested for range accuracy as a function of signal strength and other parameters. To control the environment, DME transponder simulators were used. Two simulators were used. There is variability among interrogators and also between the two test sets used for these measurements. Figure 8 shows the raw data.

In all cases the range uncertainty was within 40 meters, 95% (0.01 nautical miles, 1-sigma). At power levels greater than -80 dBm, which represents the edge of coverage, the mean range error in the raw data for all units was within 93 meters (0.05 nautical miles). The maximum variation in the bias for power levels greater than -80 dBm was approximately 43 meters (0.025 nautical 136 miles) for a single test, but as much as 56 meters (0.03 nautical miles) for the same interrogator over multiple tests. Details of these results are presented in [15].

The DME team continues its work in this avionics area. One question is: "to what extent is bias removed from the manufactured units?" Each unit clearly meets the basic 0.17 nm 95% RTCA DO-189 accuracy requirement, and also the accuracy of 0.1 nm advertised by the industry. But if the requirement were tightened, would more bias be removed on the production line? The result could be a very positive step toward APNT application of existing, unmodified avionics.

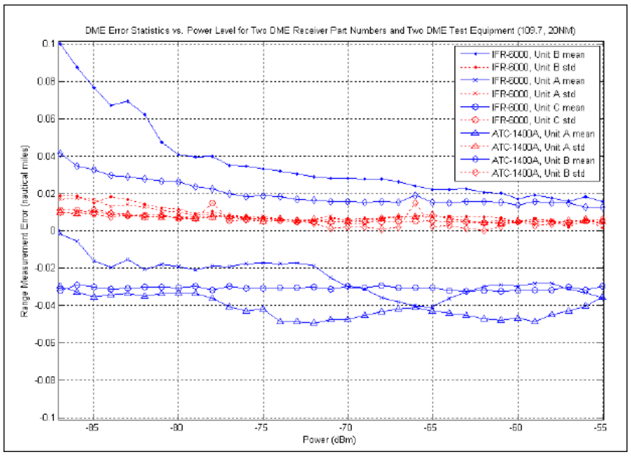

Figure 8. Bench test data for DME interrogator performance

4. COMPONENTS OF ACCURACY

Assessment of the constituent components of system accuracy is useful for understanding the potential for improvement as well as integrity concerns. It identifies the contribution of various sources of error such as signal in space, transponder reply delay, database errors, and multipath. It is also useful because the analysis aids in understanding and improving DME support for the APNT's L-band pseudolite concept[16][17]. The range error sources can be broken down into a few major categories. For assessment in this paper, the error categories are divided to align with the standards: signal in space (sis) and airborne interrogator (air). Additionally, database error affects position, but not the range calculation. Figure 9 shows these errors.

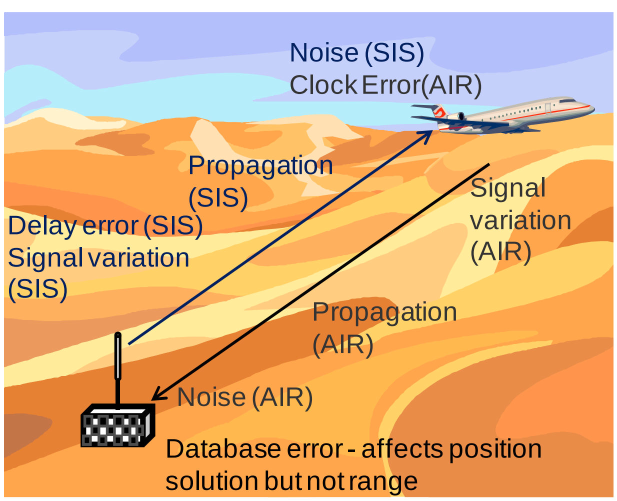

Figure 9. Error Sources for DME Ranging & Positioning

Ground System Errors

Signal in space errors, based on the definition used in the specifications, are any ranging errors contributed by the ground system. Sources include time of arrival (TOA) and propagation errors on the reply signal, as well as reply delay errors. Since DME is a two-way system, similar errors will affect the aircraft transmitted interrogation signal.

TOA Errors

The nominal reply TOA error is due to noise and signal waveform variations. Nominal TOA error was assessed both empirically and analytically. Empirical assessment utilized collected raw measurements and examined the ability to measure TOA accurately. As DME transmissions are not synchronized in time, other means must be used to make the assessment. The methodology used was to examine the TACAN burst transmissions, which are regularly spaced, and calculate the measured differential TOA (dTOA). A TACAN station, on the DME X Channel, sends a burst of 12 and 6 pulse pairs at a rate of 15 and 135 Hz, respectively. The pulse pairs in these bursts are spaced 24 microseconds apart. This method is discussed in [18]. Precision is calculated by examining the variation of dTOA.

Several DME stations were assessed using this method. Data were taken in the San Francisco Bay Area for up to a year for three stations: Woodside (OSI, from July 2011 to May 2012), Oakland (OAK, from November 2012 to February 2013) and Sausalito (SAU, from November 2012 to February 2013). These were measured from the roof (above the fourth floor) of the Department of Aeronautics & Astronautics at Stanford University. Additionally, the operational TACAN at Atlantic City airport (ACY) was measured as were two different transponders operating from the FAA Technical Center (FAATC) VORTAC Test Site also near ACY. The Atlantic City data (ACY and FAATC) were collected over the course of two days in July 2012 and used a more portable data collection hardware that had more noise than the unit used at Stanford.

Table 3 shows the resulting one-standard-deviation results of the dTOA error averaged over a 12-pulse-pair burst. This equals a two standard deviation value for TOA as dTOA takes the difference of two TOA measurements, assuming the measurements are independent. The results indicate that the transmitted signal in space can be measured quite well. One outlier is the Oakland TACAN. The signal experienced greater error levels of the signal due to greater propagation attenuation. The TACAN is nearly at sea level and has to propagate over urban and terrain features to reach the receive antenna. In contrast, both SAU and OSI are located at altitudes of over 2000 feet above sea level and have much better line of sight to the receive antenna. Comparing the FAATC results show that the modern military TACAN transmitter tested, which had a better-controlled waveform, performed better than the installed (second-generation design) transmitter.

DME (11 pulse average)	Precision (2σ)	Distance to station (nm)
Woodside, CA	1.94 m	5.6
Sausalito, CA	2.76 m	30.8
Oakland, CA	13.87 m	20.9
Atlantic City Airport, NJ	2.08 m	0.6
FAATC (Installed), NJ	3.63 m	1.2
FAATC (Modern TACAN), NJ	1.02 m	1.2

Table 3. Precision of Selected DME/TACAN Reply Signals

An analysis of two methods of determining TOA, using the leading edge of the pulse at half peak amplitude point and using the peak of the correlation of the DME pulse, was conducted to determine the theoretical performance. Figure 10 shows the TOA or pseudorange accuracy of a DME pulse as a function of signal to noise ratio (SNR) in a 1.4 MHZ noise equivalent bandwidth (NEBW).

The results can be compared with the empirical results. A Low altitude (L class) DME/TACAN like OSI and SAU typically transmits at 100 W and is required to provide coverage to a radius of 40 nm (74 km). A pulse generated by a 100 W transmitter is received with a SNR of approximately 37 decibel (dB) at 40 nm. Averaging 11 pulses gains an additional 10.4 dB. Extrapolating from the figure, the result shows between 2 and 10 ns of error, or accuracy between 1.2 to 6 m which aligns with the empirical results from Sausalito.

Another way to arrive at approximate SNR examine for the edge of coverage for Figure 10 is to note that 1.4 MHz NEBW represents about -109.5 dBm of noise. Given the edge of required DME avionics performance is around -79 dBm, the SNR at the edge of operations is 31 dB.

Another result suggested by the figure is that better accuracy can be achieved using the correlation method (comparable to 5-10 dB improvement). Hence one means of improving performance is to utilize more accurate methods for determining TOA. Indeed, the calculation of dTOA used for the empirical analysis used a curve fit utilizing a significant portion of the pulse to determine the half-amplitude point. The downside is that avionics modification is required – not a popular subject with current DME users!

Reply delay error results from inaccurate timing on the part of the ground system. Current specifications allow for variations of ±500 nsec (±150 m) before the monitor limits are exceeded, for low-level RF input signals. This is a not-to-exceed limit rather than a 95% bound. Based on discussions with industry representatives, a reply-delay monitor limit of ±100 nsec or less should be achievable. In fact, MIL-STD-291C has required a ±100 nsec monitor alarm limit since 1998[19]. The current FAA DME contractor has been asked to assess the effects of such a change to FAA E-2996, particularly on availability and continuity. Recall that the range calculated by dividing the round trip time by two and hence the ±100 nsec limit translates to a ±15 m range error.

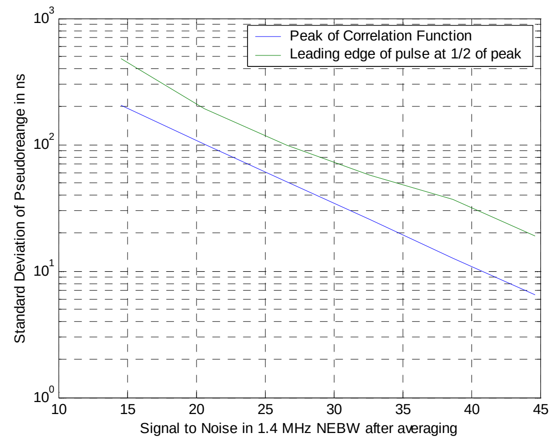

Figure 10. Theoretical Accuracy of DME Pulse

Propagation

Propagation errors affect both the ground and airborne subsystems. Sources of error include multipath, random pulse interference and troposphere delay. The latter is insignificant compared to multipath. Pulse interference may cause momentary errors but these are typically smoothed out as seen previously. This section will focus on multipath, as it is the largest potential source of propagation error. The results apply equally to reply and interrogation except when noted.

Figure 11 (left) shows multipath error when using a nominal Gaussian DME pulse, presented as a function of multipath delay given a multipath signal with half the direct signal amplitude (1/4 or -6 dB power). As can be seen, the instantaneous multipath error can be significant – around 100 m. Mitigating the error for APNT are several factors. Averaging can be useful as the aircraft is in motion, potentially causing the multipath delay to vary (or “scallop”) quickly. The variation changes the effect of multipath between the top of the envelope to the bottom resulting in significant cancellation. Averaging in the airborne interrogator effectively averages the multipath effects on both the interrogation and reply. As suggested by the DFW results, altitude could play a factor in the strength and hence the effect of multipath. The APNT coverage floor is anticipated to be 1000 to 1500 feet AGL. At this level, all the significant multipath errors seen in the DFW measurements are eliminated.

Stronger mitigations are possible. One means is to track the underlying carrier and use carrier smoothing in a manner similar to that used in GPS receivers. This technique is likely only suitable to mitigate multipath experienced by the avionics. However, this tracking can enable long-term averaging, provided the DME transponder has a stable oscillator [12]. Another mitigation method that can be used by both aircraft and ground is a faster rise time signal, though this requires changes in ground transponder and avionics, respectively. The APNT tested faster rise time signals that may still be operated within the DME standards using a modern military TACAN transponder. Figure 12 shows a nominal DME pulse with a fast rise time pulse. Figure 11 shows the multipath error curve for 6 dB multipath (power) of the two pulse types as a function of multipath delay.

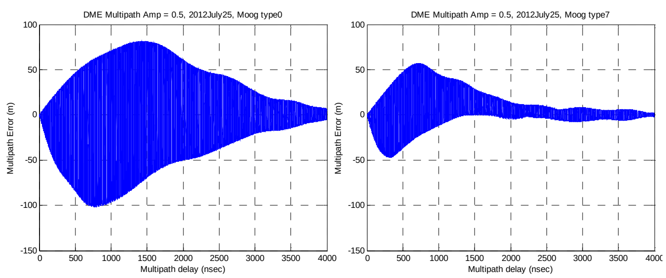

Figure 11. Multipath Error for Nominal (Left) and Fast Rise Time (Right, cos-cos^2) DME pulse assuming -6 dB Multipath

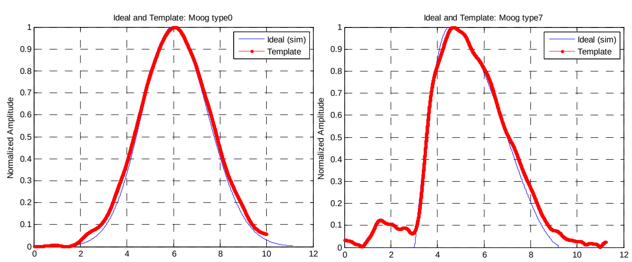

Figure 12. Nominal and Fast Rise Time (cos-cos^2) DME pulse (Moog Transmitter)

The APNT is continuing to study the capability and it is felt that multipath can be mitigated enough to meet most requirements.

Airborne Interrogator Errors

Since DME is a two way system, similar errors will affect the aircraft transmitted interrogation signal. Again, TOA, timing and propagation errors must be considered. Additionally, variation in avionics and processing is also a factor. TOA, avionics and propagation errors have already been discussed in some detail and will only be revisited briefly for the interrogator.

Interrogation TOA Errors

The results from the reply TOA precision assessment apply to the interrogation TOA, as the signals are similar. However, the airborne or interrogation signal is not as tightly specified as the ground signal, which means increased signal variation and potentially larger TOA and multipath errors. Figure 13 shows the measured pulse pair from a low-cost, single-channel DME avionics unit which deviates significantly from the ideal Gaussian pulse shape. However, the results from the prior TOA assessment provide an indication of the error level and what is achievable, especially if airborne interrogator waveform specifications are tightened.

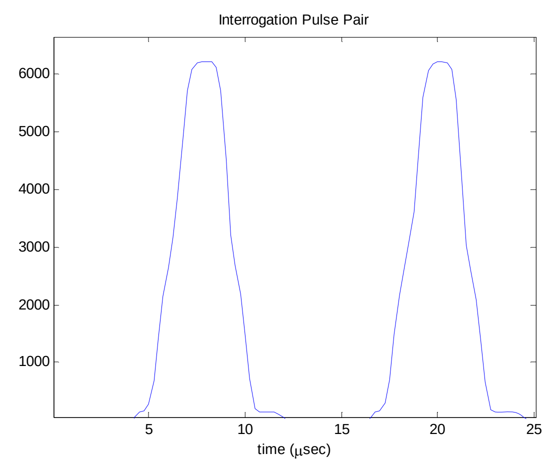

Figure 13. Measured Pulse from Low Cost Single Channel DME

Timing Errors

Both the avionics and ground transponder can introduce timing errors that result in range errors. The avionics must measure the time between the transmission of its interrogation and the receipt of the corresponding reply. Given an extreme range of 200 nm, the result is a round trip time of approximately 2.5 milliseconds (msec). Given the drift and aging of a temperature compensated crystal oscillator, this amount of time should not result in more than a few nanoseconds of error.

Avionics

As discussed earlier, variations in avionics can result in different performance and more error. The Boeing results showed that an error significant for RNAV 0.3 can exist in avionics unless bias can be removed without modification of the unit. However, a DME/DME capable of RNAV 0.3 and potential 92.6 m accuracy will require new avionics, revised standards with tightened specifications. Tests will hopefully alleviate those significant errors.

Database Error

Database error is an error in the recorded location of a DME transmitter used for DME-based position solution. It is analogous to ephemeris error for GNSS. The error manifests itself in a DME position solution and is a likely cause of the sinusoidal error behavior seen in Figure 4. A similar behavior is seen in other orbits such as OSI DME/TACAN as seen in Figure 14. Furthering the work of [15] which speculated database error was a possible cause, a precise survey of the DME antenna was conducted to examine the issue. The location of the antenna along with that of the non-collocated VOR antenna is seen in Figure 15. Also seen in the figure is the published location of the DME (source: pilotnav) which is very close to the survey result. From Figure 14, the largest deviations are about 0.04 nm at approximate bearings of 100 and 280 degrees. The distance and direction correspond with the difference in distance and direction between the DME antenna and VOR antenna.

Note errors on the order of hundredths of nm are not an issue for today's DME. However, they are significant when trying to meet 0.3 nm TSE position or 0.05 nm NSE range requirements. Facility database resolution and fidelity, and precision of DME ground system location surveys are a function of today's 0.2 nm system error limit. These errors become noticeable when viewing flight data that is processed to the tighter tolerances required by APNT. Their contribution to system error will likely require reduction.

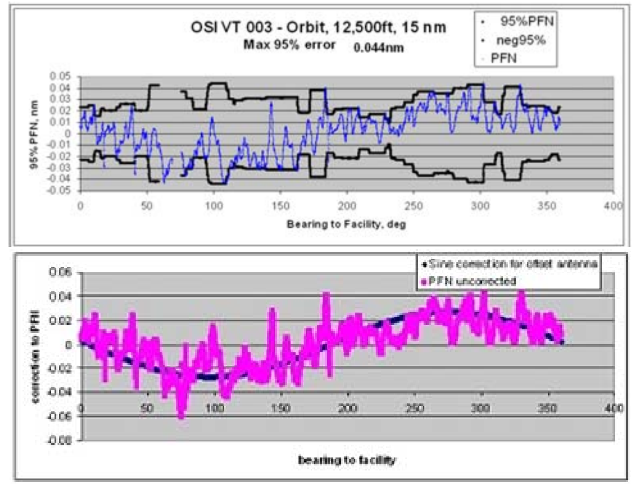

Figure 14. PFN Filtered, Bias Removed DME Range Errors about Woodside, CA with 95% Error Bound

Figure 15. Woodside VORTAC (DME/TACAN Antenna & VOR Antenna)

Overall Error Budget

From this study, an overall error budget for a potential system based on current DME and better avionics for RNAV/RNP 0.3 and 3 mile separation can be determined. The budget is presented in Table 4. From the TOA analysis, a reasonable accuracy of TOA, averaged over 10-15 pulses, is 10 and 20 m for reply and interrogation, respectively. Note that the aircraft will not be at the extremes of DME coverage (130-200 nm) when requiring these services, as line of sight will not support a large coverage radius at low altitude. The maximum reply delay of 100 ns (30 m) and 3 m for aircraft clock error is used. The remaining error is propagation. A propagation error allocation of slightly less than 40 meters for both the interrogation and reply signal, given the other assumptions, will essentially meet the 92.6 m accuracy. This seems reasonable given the earlier propagation assessment. Multipath at -6 dB caused a worst case of about 100 m though simple averaging will generally significantly reduce its value. Finally, no significant database error is assumed so that position error is just the HDOP times the range error.

Error Sources	Accuracy/Precision
Signal in Space	
Ground Reply Signal	10 m (2σ)
Ground Reply Delay	30 m (max)
Propagation to aircraft	40 m (2σ)
Air/Avionics	
Aircraft clock error	3 m (2σ)
Aircraft Interrogation Signal	20 m (2σ)
Propagation to transponder	40 m (2σ)
Total (RSS)	68 m
Range Error (divide by 2)	34 m
Position Error (HDOP = 2.8)	96 m

Table 4. Potential DME Range Error Budget

The above analysis assumes some other errors to be zero or negligible. Other errors not included are due measurement to range output latency and slant range to horizontal range correction errors. These errors depend partly on implementation and should be small with good implementation. However, the procedure to minimize these errors, like in the case database error, will need to be considered and assessed by the APNT team.

6. CONCLUSIONS

This paper presented the measured range accuracy of existing DMEs and assesses the potential of the system. Field measurements show that DME commonly achieve range accuracies better than 0.05 nm. The result shows that the accuracy of current operating DMEs significantly exceeds the standards. The range assessment provides an overall sense of current DME performance. Assessment of the components of error indicates that even 92.6 m accuracy is not beyond the capabilities of a reasonably upgraded DME system (both ground transponder and airborne interrogator). It shows that multipath errors of about 40 m (2σ) may be acceptable provided the other error levels are met.

Achieving APNT accuracy targets is just the start. Integrity is an important requirement, especially for RNP which requires conformance monitoring on board the aircraft. Meeting this may be a more significant challenge than the accuracy requirements. The APNT team is working on achieving adequate capacity, continuity, and integrity on DME to support APNT goals [20].

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DISCLAIMER

The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the Federal Aviation Administration or Department of Transportation.

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