Containing a Difficult Target: Techniques for Mitigating DME Multipath to Alternative Position Navigation and Timing (APNT)

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BIOGRAPHY

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1. INTRODUCTION

Distance measuring equipment (DME)/Tactical Air Navigation (TACAN) has been serving aviation for approximately 60 years. It has been a primary navigation aid in the national airspace (NAS) for much of that time with its basic operations little changed since its inception. However, future airspace will demand greater navigation performance to support higher traffic levels and more efficient operations. While Global Navigation Satellite Systems (GNSS) will be the primary source of this capability, DME can have a vital role in the future navigation infrastructure. The Federal Aviation Administration (FAA) Alternative Position Navigation and Timing (APNT) program is examining the use of DME to provide accurate two-way and passive ranging. APNT is examining whether DME has the capability to allow for continued operations of the NAS with minimal economic impact. For DME to support this capability, it must have better performance in several areas: accuracy, integrity, capacity and coverage.

Multipath limits DME performance in two key areas: accuracy and integrity. The challenge with the DME/TACAN is that its signal was not designed to mitigate multipath to the levels required by APNT. This paper examines DME multipath and different techniques to mitigate it. The first part examines the effects of DME multipath and the challenge it poses for APNT. The second part describes several mitigations being developed and examined by the APNT team

2. BACKGROUND

The FAA APNT group was formed to determine and develop the promising solutions that provide navigation, surveillance and other services for the national airspace in the event of a loss or degradation of GNSS. The need for APNT is particularly important as aviation use of and dependency on GNSS is forecasted to increase significantly in coming years. Under the Next Generation Air Transportation System (NextGen), GNSS/Global Positioning System (GPS) is the primary means of navigation and surveillance. GNSS enables the operations that are needed to handle the increased air traffic levels anticipated in the 2025 time frame. It also enables more efficient operations. Currently, GNSS/GPS is often the only system capable of supporting many of these envisioned operations. While current terrestrial-based navigation systems can provide a roust navigation alternative to GNSS, they either cannot provide area navigation (RNAV) capabilities or the performance needed for sustained future operations. APNT is chartered with developing these terrestrial navigation systems with the capability to support necessary future operations.

Given this need, APNT has targeted several capabilities. Amongst these are support of RNAV 1.0 nautical mile (nm) for en route as well as RNAV and Required Navigation Performance (RNP) 0.3 nm for terminal area [1][2]. The terminal area goals represent a major improvement on the current DME capability of RNAV 1.0. RNP is a further challenge as it requires additional safety monitoring in addition to meeting RNAV requirements. Another 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]. This is a tenfold improvement on current DME accuracy. Hence both significant improvements in accuracy and integrity are needed with the major determinant of accuracy and integrity being multipath.

DISTANCE MEASURING EQUIPMENT

DME is a two-way ranging system operating in the L-band of radio frequencies between 960-1215 MHz. It enables aircraft to calculate slant range to a DME ground station or transponder by transmitting an interrogation signal to the ground station and receiving a corresponding reply. This is shown in Figure 1 where the ground station (sometimes termed transponder or beacon) imparts the 50 microsecond (µs) reply delay used in a DME X channel.

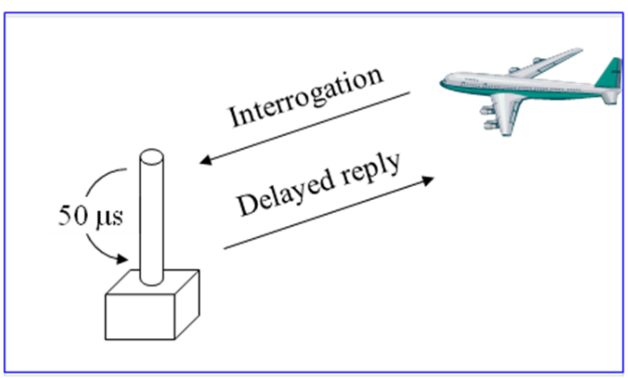

Figure 1. DME Transponder Operations (X channel)

The interrogation and reply, like all DME transmissions, are in the form of a pulse pair. The purpose of the second pulse is to distinguish the reply from random or spurious pulses. An X channel pulse pair is seen in Figure 2 where the pulses are spaced 12 µs apart. While the figure uses an ideal Gaussian pulse shape, the specifications allows for some variation in the pulse shape. Figure 3 shows the transmitted pulses measured at two DME/TACANs – FAA Technical Center (FAATC) and Woodside, California (CA). In the figure, the blue pulse is shown to indicate an "ideal" pulse. As seen these pulses differ from each other and the ideal. Range is calculated by the aircraft which measures the time of transmission (TOT) of the first pulse of the interrogation pulse pair and the time of arrival (TOA) of the first pulse of the reply pulse pair. This is used to calculate the round trip time/distance and the range is calculated by dividing the round trip distance in half. The FAATC transmitter is shown in Figure 4.

In addition to DME pulse shape variations, there are two major international standards for DME: standard DME (DME/N or DME Normal) and Precision DME (DME/P). DME/P was developed to provide a higher accuracy DME to support the microwave landing system (MLS). It has a faster rise time pulse than those seen in Figure 3. As there are few MLS installations, it is little used worldwide. More details on DME are provided in [4].

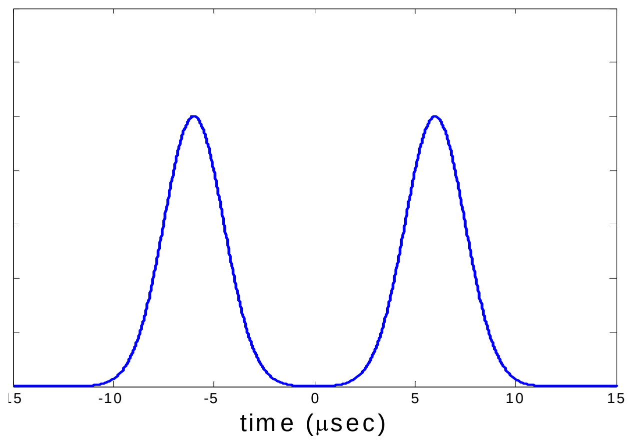

Figure 2. DME Pulse Pair (X Channel)

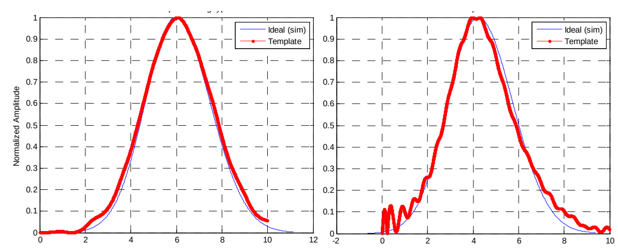

Figure 3. Transmitted Pulse Measured from FAA Technical Center (Moog TACAN, Left) and Woodside, CA TACAN (Right)

DME FOR APNT

DME has many favorable properties for APNT. There is decades of operational experience with DME/TACAN. Its two-way interaction provides true ranges. This provides better coverage than passive range as two-way systems do not require the additional station needed by passive range systems to solve for system time. It is transmitted and received using a relatively simple antenna that can be used to support other L-band terrestrial signal such as those used for ADS-B. DME transmissions are high powered with DME and TACAN ground stations transmitting at 1 and 3.5 kiloWatt (kW), respectively.

Additionally, it is: 1) fielded with over 1100 stations in the conterminous United States (CONUS), 2) has a large existing user base, and 3) likely performs much better than its specified 0.6 nm position accuracy.

DME for APNT will require improvements on today's DME. The team is determining the performance of today's equipment and modest modifications to improve its accuracy/integrity. Mitigating multipath is major part of the effort. Other improvements are also needed.

Supporting RNAV with DME only means that scanning DME (DME/DME) avionics, which takes measurements from multiple DME near simultaneously, is needed. While lower cost, single channel DME can be used for point to point operations, this is not suitable for RNAV/RNP as the user calculates range to a single DME, rather than position. The FAA currently allows DME/DME to support RNAV 1.0 operation only if it has an inertial reference unit (IRU), i.e., DME/DME/IRU. The IRU is needed to bridge current coverage gaps. Current work is being conducted to fill in these gaps so that an IRU will not be required.

DME for APNT will also be improved in other ways operationally. APNT has developed an appliqué DME design to provide passive or pseudo ranging capability compatible and transparent to today's DME users [5]. This is termed DME pseudolite (PL) or passive ranging. DME pseudolite allows for pure passive operations as well as combined DME and pseudolite operations [6]. These operations are beneficial for improving DME capacity and supporting small unmanned aerial systems (UAS) that may be too power-constrained to use an active DME. The DME/DME PL combination enables time synchronization with the ground with a single DME station (hence, single channel DME) as well as positioning with only one other passive ranging source. DME PL will also benefit greatly from multipath mitigation.

Figure 4. FAA Technical Center Test VOR TACAN (VORTAC) Station with DME monitor antenna highlighted

3. DME MULTIPATH

For DME to support APNT, it must be more accurate than it is currently specified today. Table 1 shows the accuracy budget for DME. Today's DME specifications divide the error sources into two major categories [7][8][9][10]. These are the signal in space (SIS) and airborne interrogator (AIR) accuracy levels. The current specified accuracy based on ICAO Annex 10 [7] and FAA E-2996 [8] is shown in column two. Column two shows today's DME is specified to provide position accuracy of around 0.6 nm. This is derived from 0.2 nm range accuracy times a horizontal dilution of precision (HDOP) of approximately 2.8 based on a specified maximum of 30 or 150 degree angle between two stations. This supports RNAV 1.0 accuracy requirements.

To determine actual or projected performance, the APNT team further examined and subdivided the error sources in each category [11]. This is shown in column three which presents the estimated accuracy (2 standard deviations) for each category based on measurements, analysis and/or estimates. This work indicates that these errors can be at these levels with some reasonable changes in ground stations and perhaps new avionics. Note that the contribution of the errors in each category is generally root sum squared (RSS), unless it is a bias, and divided by half, due to DME range calculation. The biggest error source presented in the table is multipath with the airborne component worse than ground. The airborne transmission is worse as it does not need to be as well controlled as the ground. An example of a measured airborne pulse pair from a low cost DME interrogator is shown in Figure 5. Compare the pulses with those in Figure 2 and Figure 3.

Error Sources	Current Specifications	Projected Current DME w. modest changes
Signal in Space (RSS/2)	**390 m**	**26 – 53 m**
Ground Reply Signal		10-20 m
Ground Reply Delay	150 m (max)	30 m (max)
Propagation to transponder		40-100 m
Air/Avionics (RSS/2)	**630 m**	**22-79 m**
Aircraft clock error		3 m
Aircraft Interrogation Signal		20-50 m
Propagation to transponder		40-150 m
A/C Cable Delay (bias)		0 – 80 m
Total (RSS + bias)		68-271 m
Slant Range		6 m
Survey Error (bias)		1-5 m
Range Error (divide by 2)	370.4 m	39-136 m
Position Error (HDOP=2.8)	1047.7 m	110-380 m

Table 1. Accuracy Budget for DME: Current Specifications & Projected with Modest Changes [11]

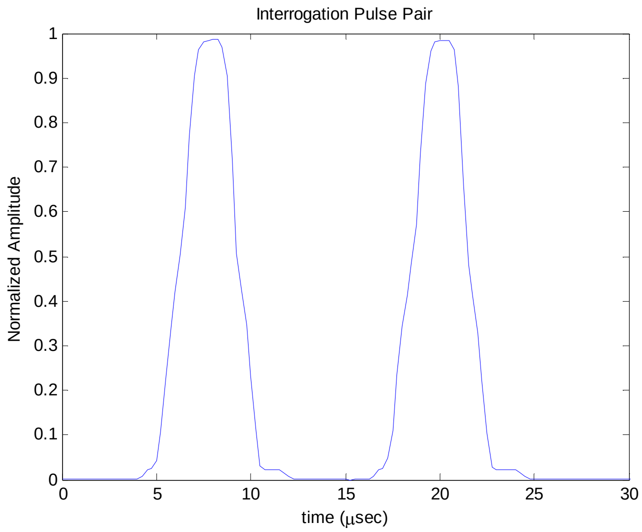

Figure 5. Measured Pulse Pair from Low Cost Single Channel DME Avionics

The multipath error values in the table are arrived at by examining the multipath error curve for a nominal DME signal. Figure 6 shows the multipath induced errors as a function of multipath delay for a direct-to-multipath signal power ratio of 6 decibel (dB) (3 dB amplitude). The figure is generated using samples of a clean signal measured from a modern TACAN at the FAATC. It shows multipath errors over 330 ns or 100 m. While the error level is significant, the relevant question to answer is "what is a worst case level of multipath?"

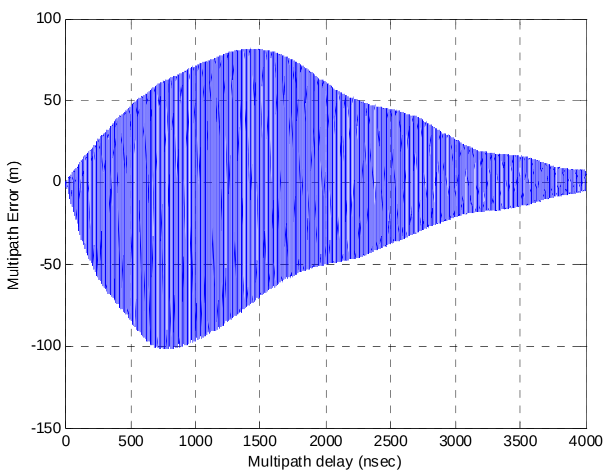

Figure 6. Multipath Error Curve Generated from On-Air DME Signal (6 dB Direct-to-Multipath Ratio)

To determine the DME multipath power level to use, measured data from our data collection campaigns were examined. Our effort found that data captured at Rhode Island (RI) T. F. Green airport (Providence, RI) showed significant DME multipath. The data collection site was located on the ground right off of airport property, 832 m from the airport TACAN and is shown in Figure 7. Figure 8 shows the first pulse of a regular TACAN transmission - the first North burst pulse. The blue line shows the measured data while the dashed red line shows a model estimate of the based estimating multipath delay and amplitude. In this case, the delay and direct-to-multipath power ratio were estimated to be 3.2 μsec and 14 dB, respectively.

Figure 7. DME/TACAN Data Collection at Providence Airport (T. F. Green), Rhode Island

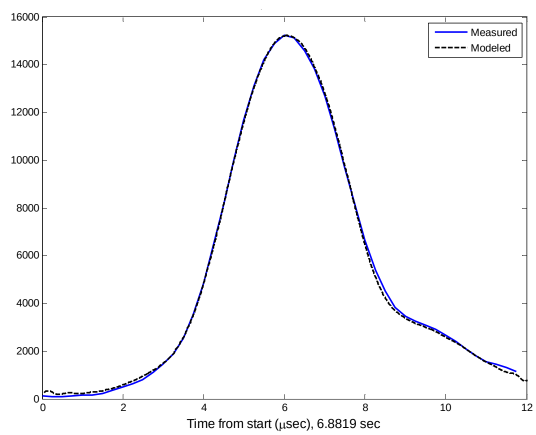

Figure 8. Measured and Model Estimate of North Burts Pulse (6.9 sec from Start of Data Collection)

Modeling and analysis were conducted to estimate the multipath delay and direct-to-multipath signal ratio over each data set. Figure 9 shows an example result. The analysis estimated the direct signal power to be typically 8 to 10 dB higher than the multipath power. However, there were times where the direct-to-multipath signal power ratio was much smaller. At around 8 seconds, the ratio drops to nearly zero. Figure 10 and Figure 11 show the corresponding change of the North pulse at various times during that data set. As seen from Figure 11, the lower power ratios were due to direct signal attenuation, likely from an aircraft passing between the TACAN and the data collection site.

For the T.F. Green site, a direct-to-multipath power ratio of 6 dB power seems like a conservative upper bound. Hence, the 6 dB value is used as starting point – in that the final mitigation(s) should handle this level. Further study as needed to determine reasonable bound for all anticipated environments.

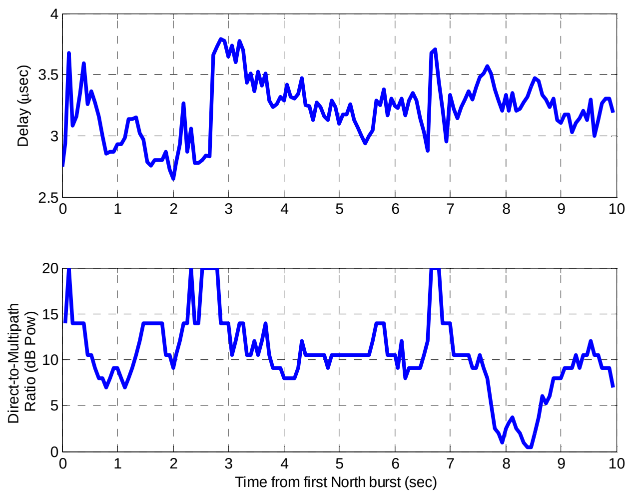

Figure 9. Estimated Delay in μsec (top) and Direct-to-Multipath Signal Power Ratio (bottom)

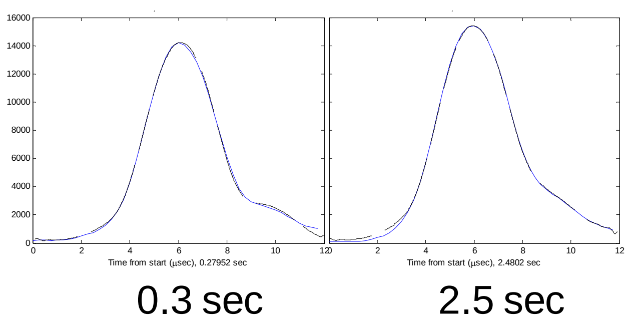

Figure 10. Measured and Model Estimate of Pulses (Time from Start of Data Collection)

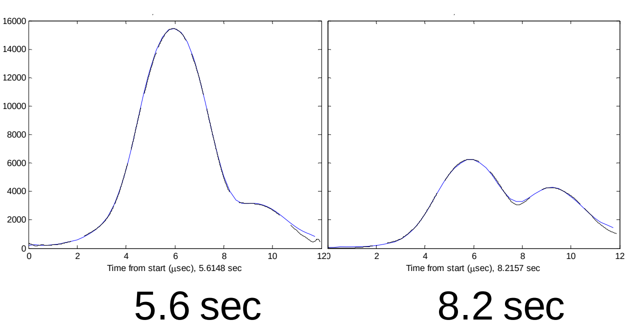

Figure 11. Measured and Model Estimate of Pulses (Time from Start of Data Collection)

The modeling indicates reasonably constant delay but some variations in direct-to-multipath signal power ratio. This supports the thesis that multipath effects should be static, at least over the short term. However, changes in environment due to weather (e.g., snowfall), new buildings, etc. may result in changes in multipath effect and/or location.

From the analysis and data collection, it is evident that multipath is a significant problem that requires mitigation in order for DME to serve APNT.

4. MITIGATIONS

Mitigating multipath to the level needed by APNT is not a trivial task for several reasons and a range of mitigations is needed. One reason is that DME based APNT must operate using today's infrastructure before transitioning to newer DMEs. Hence techniques are needed to support near term use to get partial benefit while other, more powerful techniques will have to wait until the ground infrastructure is more fully upgraded. In other words, different mitigations are needed for difference classes of users and installed equipment. Furthermore, the overall DME multipath mitigation employed is likely a combination of some or all of these techniques.

This section covers five different mitigation techniques. A basic mitigation is operational design whereby areas of high multipath may be indicated and operations there limited. Another basic mitigation is averaging (termed simple averaging to distinguish it from extended averaging). The attractiveness of these basic mitigations is that they require at most changes to avionics and can be implemented immediately. More powerful mitigations are possible but require more changes, particularly at the ground transmitter. One change is a faster rise time signal similar to the one used for DME/P. More powerful techniques such as carrier smoothing and extended averaging are the last two techniques covered. These last two techniques require a stable carrier from the ground station. The mitigations are roughly ordered from simplest to hardest to implement in terms of new hardware and changes in the ground system.

Operational Changes

A simple mitigation, in terms of changes to equipment, is to change behavior. One means is to modify flight operations and procedures mitigate the effects of multipath. This means surveying the airspace to determine areas of severe multipath and changing procedures accordingly.

Operational changes based on survey location is useful as multipath is a reasonably static phenomenon. Multipath is caused by reflections off of the ground or buildings and the DME ground stations are not moving. The difficulty with this mitigation is that surveying can be time consuming (need to cover a large area), challenging, and subject to change with environment changes. However, this survey can be arrived at through many sources such as regular FAA flight inspection. Even better would be to have aircraft equipped with both GNSS and DME report potential areas of DME multipath (where DME and GNSS estimated ranges disagree) when GNSS is operating normally. Flight inspection can then verify and precisely determine the region and level of multipath. With the determination, the source of the DME multipath may also be discovered by estimating the delay.

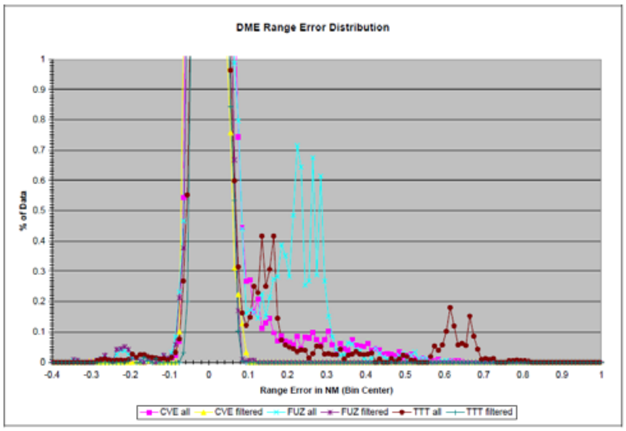

Figure 12. DME Raw & Screened Range Error Distribution for DFW DMEs (CVE, FUZ, TTT) [11]

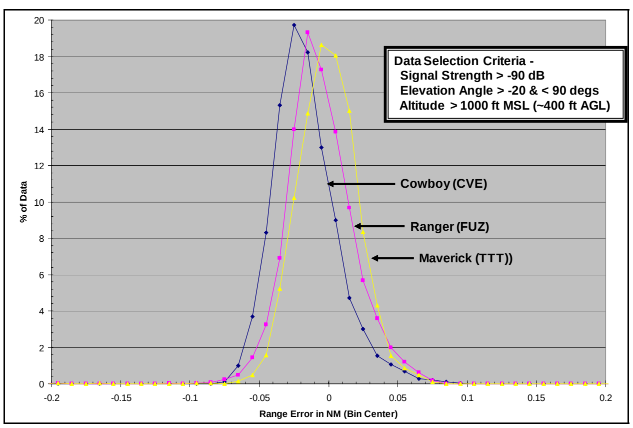

Figure 13. DME Screened Range Error Distribution for Dallas Fort Worth DMEs (CVE, FUZ, TTT) [11]

Once areas of high multipath are identified, the mitigation would alter DME use in these areas. Several changes are possible – inflate integrity bounds to account for increase in error, provide a location dependent multipath correction or restrict use of DME at those locations.

An example of an operational mitigation is altitude limits. From data collected by FAA flight inspection, multipath effects seem to decrease with increasing altitude above ground level (AGL). Figure 12 shows the distribution of range errors of flight inspection around Dallas Fort Worth (DFW) in April and May of 2011. DFW has three local navaids offering distance-measurement service -- Maverick VOR/DME (TTT), Ranger VORTAC (FUZ) and Cowboy VOR/DME (CVE). In addition to the roughly Gaussian central distribution between -0.07 and +0.07 nm, there are outliers that exceed 0.1 nm for each station. The theory is that these outliers are caused by ground multipath as they exist on the "high" side of the DME error distribution, indicating delayed arrival of reply pulses (multipath is always delayed relative to the direct signal).

Figure 13 shows that same data except it has been screened to eliminate that below 400 ft AGL and weaker than -90 dBm (decibel relative to 1 milliWatt). The result bodes well for APNT operations as there is no plan for APNT to provide radio navigation coverage below 500 ft AGL. Essentially, APNT will leverage reduced multipath at higher altitudes. The limit emanates from line-of-sight (LOS) limitations rather than multipath concerns.

Based on the DFW results, the APNT altitude limitation would significantly reduce multipath induced errors. However, these results are only from one test and one location and need to be further validated.

Simple Averaging

Simple averaging is a traditional means of mitigating multipath and other fluctuating errors. Simple averaging works on multipath because multipath effects vary with the multipath delay. As the aircraft is moving, usually very fast, the multipath delay can change very rapidly. Given the motion, averaging can be used to cancel out much of the multipath induced error. Simple averaging is also good because it affects multipath on both the interrogation and reply signal. Current flight management systems (FMS) conduct some filtering of the DME ranges to update the inertial system. A complimentary and Kalman filters are common used filters. Hence, it may be that current FMS filtering already provide some averaging of multipath.

Figure 14 shows an example scenario to illustrate the effect of averaging. The multipath error curve from Figure 6 is used as the underlying model for multipath error. In this scenario, the aircraft flies in a direction where it is constantly exposed to multipath with a constant 6 dB direct-to-multipath signal power level assumed. The aircraft flies in this direction at 100 m/s or 224 miles per hour (mph). Given the initial position shown in the figure, the multipath delay is initially 465 m (or 1.55 μsec) with a rate of change approximately 35 m/s. Figure 15 shows the multipath error for the next 20 second of flight with the blue, red, and black curves indicating instantaneous, 2 second averaged, and 10 second averaged multipath error, respectively. With averaging given this motion, the multipath induced error is reduced from about 70 m (instantaneous) to about 10 m (2 second) or less (10 second). Ten second averaging would require clock stability of roughly 10^{-8} seconds/second. The avionics would require a better oscillator than a crystal oscillator (XO). A good and recently calibrated temperature compensated XO (TCXO) is likely the minimum required.

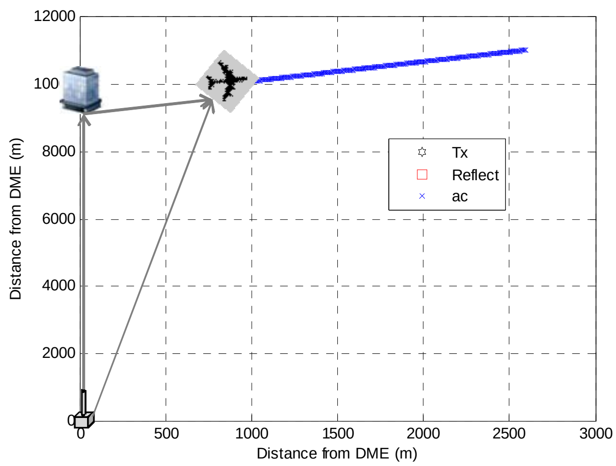

Figure 14. Scenario 1: Signal & Multipath Geometry (Aircraft Movement over 20 Seconds Shown)

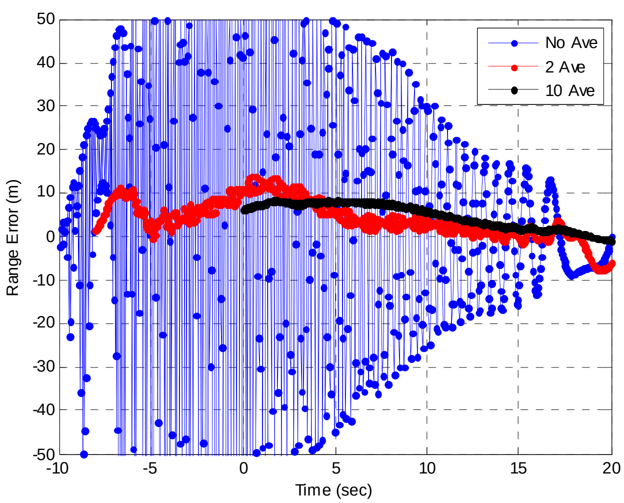

Figure 15. Multipath Induced Error Over 20 Seconds (Scenario 1) with Averaging (none, 2 & 10 sec)

The important effect that averaging is leveraging – averaging over several peak to trough cycles of multipath is an assumption. This does not happen for all cases and depends on geometry.

Figure 16 shows scenario where the geometry results in a slow rate of change in multipath delay. This is the case with a shallow multipath reflection. This scenario uses an aircraft traveling at same 100 m/s speed. In this scenario, the aircraft at its initial position experiences multipath with a delay of 79 m (or .263 µsec) and a delay rate of change of less than 0.1 m/s. Figure 17 shows the resulting multipath error experienced. In this case, 2 second averaging does very little with maxi mum error still over 50 m. Ten second averaging does decrease the maximum error to slightly over 20 m. Furthermore, one can imagine geometries that are worse where the multipath varies even more slowly. However, these situations typically exist at long ranges and because of line-of-sight (LOS), this will occur at higher altitudes. Fortunately, at higher altitudes, APNT has more margin as the target is RNAV 1.0 instead of RNP/RNAV 0.3.

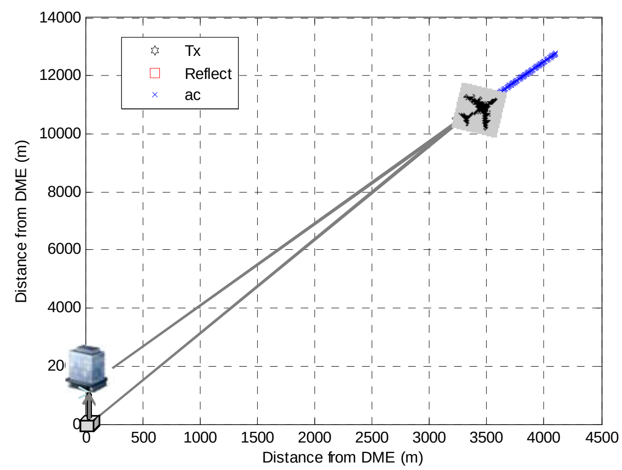

Figure 16. Scenario 2: Signal & Multipath Geometry (Aircraft Movement over 20 Seconds Shown)

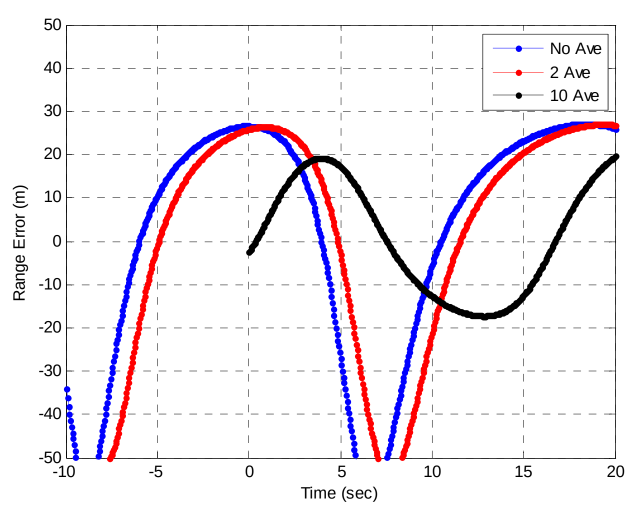

Figure 17. Multipath Induced Error Over 20 Seconds (Scenario 2) with Averaging (none, 2 & 10 sec)

Fast Rise Time Pulse

Another possibility is to have a sharper signal – that is, a fast rise time pulse. This may be implemented on the aircraft transponder, ground station or both which is needed to achieve the maximum benefit. As such, this would require changes on both the avionics and ground equipment.

To quantify the benefit of a faster rise time pulse, several fast rise time pulses were implemented and tested on a prototype DME/TACAN at the FAA Technical Center. The pulse shapes implemented complied with international standards [7]. Some were consistent with DME/N standards while others did not comply with DME/N standards but were acceptable under DME/P standards.

Figure 18 shows the measured on-air signal for fastest rise time pulse tested. It is compatible with DME/P standards. Figure 19 shows multipath error for 6 dB direct-to-multipath signal power ratio when using this pulse. Relative the normal DME pulse whose multipath error curve is seen in Figure 6, the fast rise time pulse significantly reduces the overall error with maximum error reduced by over half. The maximum error is about 50 m. This is still too large for APNT and it is not enough to solely use this fast rise pulse compatible with nominal processing – measuring the half amplitude point. Simple averaging can provide further reductions. But geometry can still pose a problem. Using the previous shallow multipath geometry scenario of Figure 16, the performance of the fast rise time pulse with simple averaging is shown in Figure 20. For this scenario, multipath errors are only reduced slightly with 10 second averaging resulting in almost no difference in maximum error relative to a normal DME pulse.

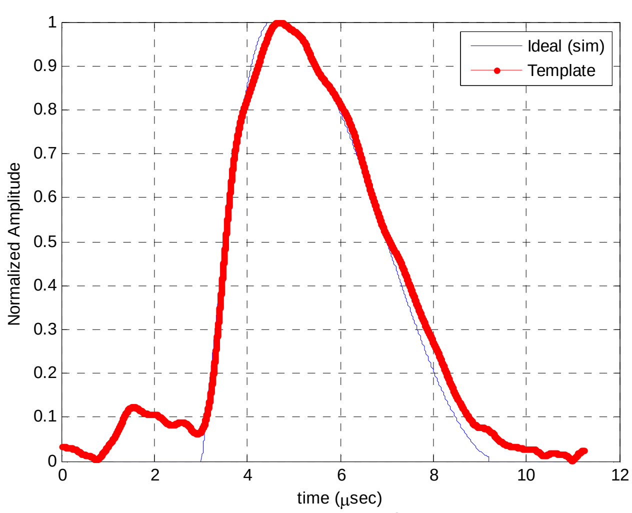

Figure 18. Fast Rise Time (cos-cos^2) DME pulse

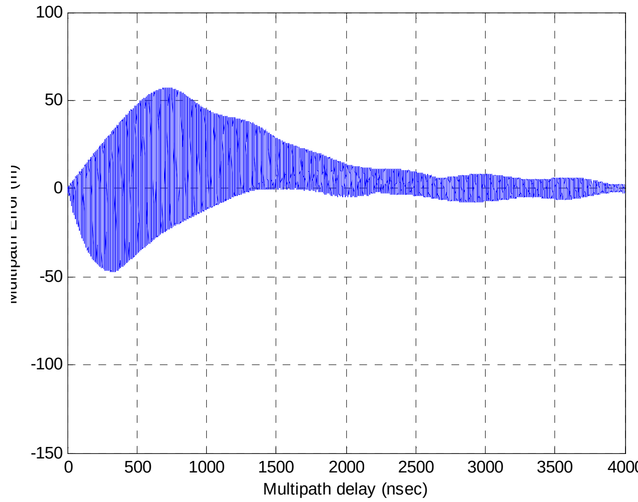

Figure 19. Multipath Curve Error for Fast Rise Time (cos-cos^2) DME pulse (6 dB Direct-to-Multipath Ratio)

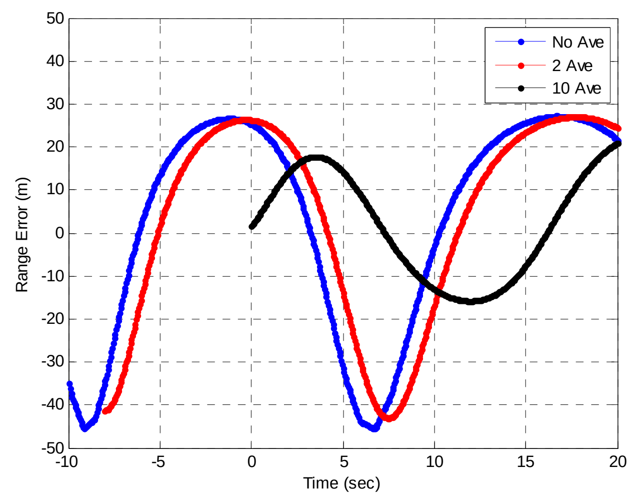

Figure 20. Multipath Induced Error Over 20 Seconds (Scenario 2) for Fast Rise Time Pulse with Averaging (none, 2 & 10 sec)

This leads the APNT team to consider stronger mitigations. Carrier processing is discussed next. Another possibility is improved processing or processing earlier on the leading edge (akin to narrower correlator in GNSS). The latter takes more advantage of a fast rise time pulse.

Carrier Smoothing & Extended Averaging

Processing of the DME carrier presents several multipath mitigation possibilities. The idea of DME carrier processing is based on the observation that if the underlying DME signal is generated by a continuous carrier and if that carrier is stable enough, then one can implement on DME many of the carrier phase processing techniques used in GNSS [12]. Figure 21 illustrate the basic assumption. With about 3000 pulse pairs per second (ppps), there is a signal approximately every 330 μsec for tracking.

In terms of multipath, carrier smoothed code (CSC) and extended averaging (with a stable clock) could result in significant multipath reduction. CSC, much like in GNSS, is useful as multipath effects on carrier is significantly lower than on the pulse provide there is no cycle slip. However, it is only useful on ground-to-air (reply) signals and does not mitigate multipath on air-to-ground (interrogation) signals. The ground receives transmissions from various aircraft which all look similar and do not have a stable or common carrier. Hence, the ground station cannot track and smooth the carrier from each individual aircraft using the station. Extended averaging is based on tracking the carrier signal assuming there is stable ground clock/oscillator underlying that signal. This essentially transfers the stability of the ground clock to the aircraft. Like simple averaging, it is effective on multipath on both the interrogation and reply signals. These techniques are discussed in detail in [12]. Both these techniques require a stable oscillator on the ground. Extended averaging would also need an accurate clock as the aircraft ranges need to be propagated in time.

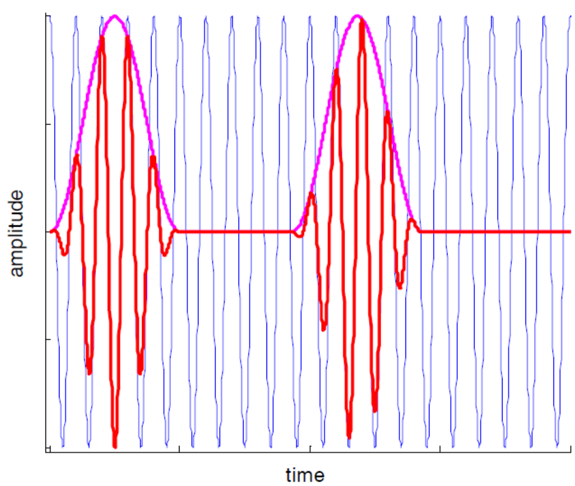

Figure 21. DME Pulse Pair & Underlying Carrier [12]

The APNT team examined if it is possible to process carrier effectively for these techniques without modifying the existing DME transmitter. This investigation examines how stable the transmitted signal is at existing stations as well as the specified oscillator stability. [12] found is that the current DME they used did not have the stability to support these techniques.

Measurements were made to determine if other DME/TACANs could have adequate clock stability. DME data from Woodside DME (VORTAC), which transmits of 1173 MHz, was collected from the roof of the Stanford GPS laboratory and right outside the transmitter. The two data collection sites were 5.6 nautical miles and 5 meters away from the transmitter, respectively. The data was collected an intermediate frequency (IF) slightly offset from the center frequency (400 or 600 kHz offset).

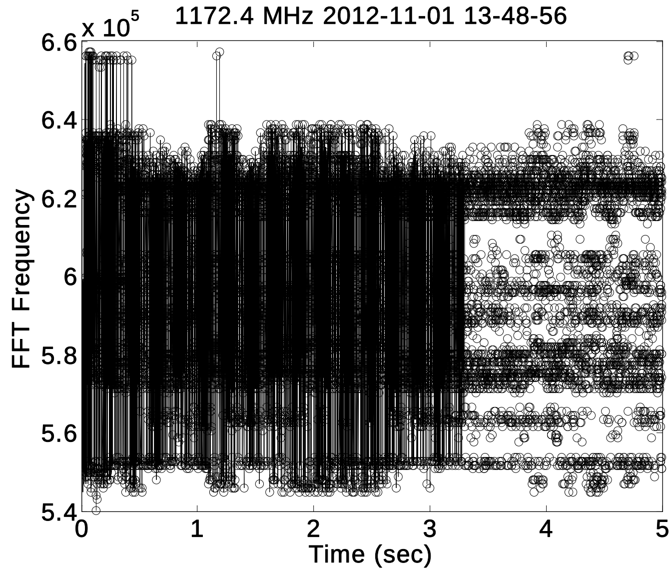

Figure 22. FFT Estimate of Intermediate Frequency of Each Pulse Pair

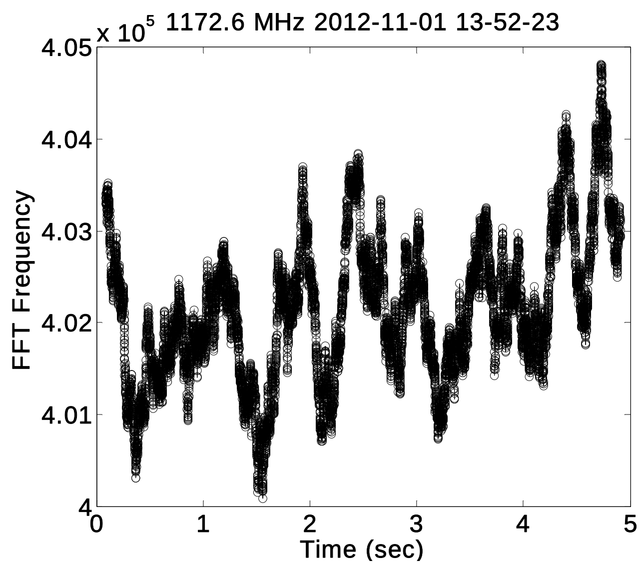

Figure 23. FFT Estimate of Intermediate Frequency of Smoothed over 501 Pulse Pairs

Analysis of the frequency of the signal on several data sets show the frequency to be noisy and not stable enough to fit any constant carrier without large errors between adjacent transmitted pulse pairs. The error would result in multiple cycle slips between pulse pairs. A fast Fourier transform (FFT) technique was developed to estimate the carrier frequency for each pulse. Figure 22 shows the raw estimated frequency for each pulse pair. As seen, it is rather noisy. Figure 23 shows the results with a 501 point (pulse pair) moving average based on that same data. Figure 24 shows similar results from a different data set.

The results indicate that the stability is not quite good enough for carrier processing. Despite having about 3000 ppps to use, there can easily be multiple cycle slips between pulses. At the same time, the results are good in that they are better than the specifications which allow for 0.001% frequency variations - about 10-12 kHz (FAA E-2996 [7]). In this case, that would be 11.73 kHz whereas less than 10 kHz variation was found. The result is encouraging and consistent with one of the findings in APNT investigation of today's DME; today's DME performance is better, often much better, than specifications.

The averaged results also show an offset with stability less than 5 kHz. This offset could be due to data collection clock, which as a Rubidium oven controlled XO (RbOCXO), or DME ground station oscillator error. While the results indicate some fielded stations do not have an adequately stable carrier without modifications, the APNT effort is modifying DME/TACAN transmitter provide an adequately stable carrier.

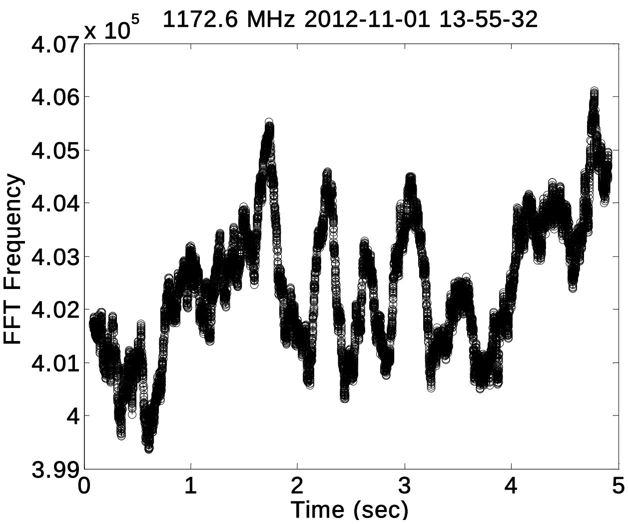

Figure 24. FFT Estimate of Interme0diate Frequency of Smoothed over 501 Pulse Pairs

6. CONCLUSIONS

Multipath is the biggest technical challenge for use of DME in APNT. The paper demonstrates the effects of DME multipath with captured on-air signals from experimental and operational DME stations. The body of this paper outlines the major techniques being contemplated by APNT.

The APNT team has analyzed several DME multipath mitigation techniques. These techniques range in terms of complexity and equipment changes necessary. The mitigations, the changes needed and benefits are summarized in Table 2. Avionics only based improvements are more easily adopted as adoption depends on solely on that aircraft having the required equipment. Ground changes are more difficult as a critical mass of upgraded stations is needed. This is likely a gradual process as the current ground system employ DMEs deployed over the last 30 years.

No single mitigation completely solves the challenge for all user classes. Some users will have to operate with currently installed equipment while others may be able to adopt more advanced avionics. The more complex mitigations will take a decade or more to fully implement as they require significant changes to the ground station. Hence, there may not be one but multiple solutions. Additionally, the solutions may be a combination of mitigation techniques. In addition to the described techniques, there are other possibilities that have not been explored extensively. For example, multipath limiting ground antenna, spectrum processing techniques to separate multipath, and improved envelope and carrier processing techniques are all possibilities that can further mitigate multipath.

Mitigation	Avionics Changes	Ground Changes	Effectiveness
Operational Changes	None	None	Varies
Averaging (Simple)	Maybe none	None	Depends on geometry but effective for "good" multipath geometries
Fast Rise Time (& improved signal proc)	Yes (if on interrogation)	Yes/Maybe (if on reply)	Reduce multipath by ½ (if within specs)
Carrier processing	No	Yes	Affects only reply, not interrogation
Extended Averaging	No	Yes	Allow for significantly longer averaging times

Table 2. Potential High Accuracy DME Range Error Budget

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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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