DME/DME for Alternate Position, Navigation, and Timing (APNT)

Robert W. Lilley, Ph. D., *Aviation Management Associates, Inc.*
Robert Erikson, *US Federal Aviation Administration*

"It should be noted that the views expressed herein reflect the personal views of the authors and do not reflect the views or positions of the Federal Aviation Administration or their respective organizations."

ABSTRACT

The Federal Aviation Administration (FAA), has established a program to define alternative means for providing positioning, navigation, and timing (Alternative PNT, or APNT) services to the National Airspace System (NAS) when Global Navigation Satellite System PNT services (GNSS), and more specifically Global Positioning System (GPS) services, are unavailable. In the Next-Generation Air Transportation System (NextGen) era, PNT services will likely be provided by a combination of GPS, Automatic Dependent Surveillance – Broadcast (ADS-B) systems and a reduced network of legacy navigational aids. These include Very-High Frequency OmniRange (VOR), Distance Measuring Equipment (DME), and DoD TACtical Air Navigation facilities (TACAN), plus surveillance radar where available.

NextGen will rely heavily on area navigation (RNAV) operations and much less on point-to-point operations defined by airways and jet routes. This paper discusses the opportunities and challenges related to use of DME as an alternate source of positioning, navigation and timing, usable in the absence of GPS services. DME enjoys support among airlines regional carriers and high-end business operators who are equipped with advanced DME avionics and who are the principal beneficiaries of RNAV and RNAV/RNP.

INTRODUCTION-THE APNT ENVIRONMENT

Upon loss or denial of GPS signals, satellite navigation and satellite-based surveillance will not be available. ADS-B will no longer report position to the Air Navigation Service Provider (ANSP) and any ADS-B-In applications will not receive position data from other aircraft within the outage area unless an alternate source of position information is available. The remaining legacy navigational aids will provide only a reduced level of service, which does not include terminal-airspace RNAV. The resulting reduction in PNT capability may cause an extremely heavy Air Traffic Control (ATC) workload, especially in the period immediately following a relatively wide-area loss of GPS services. Controllers will need to issue radar vectors to many aircraft in a navigational environment where aircraft spacing must be adjusted to regulate demand and maintain safety. In addition, in those cases where ADS-B is the only source of surveillance, radar vectors will not be possible, causing reversion to position reporting based on uncertain dead reckoning due to the GPS outage.

At major airports (designated the "Core-30") [1] and at the top 100 airports, the majority of traffic is airline, regional or well-equipped business-aviation flights. Many aircraft in this fleet may not be equipped with Inertial Reference Units (IRUs). In NextGen airspace, these flights will be conducted using Area Navigation or RNAV (using latitude and longitude references). Positioning quality will be monitored using Required Navigation Performance (RNP) criteria to achieve close spacing for airspace efficiency. If those flights can be served seamlessly by APNT during GPS outages, the added controller workload at outage onset is reduced to the point where lesser-equipped general aviation traffic in the airspace can be issued appropriate vectors, and separation can be maintained without significant workload increases. The resulting requirement upon APNT is to serve this dense-traffic airspace by preserving RNAV and RNAV/RNP so as to minimize outage effects both on pilots and controllers.

Distance Measuring Equipment is one option for providing continued service during a GPS outage. Extensive fleet equipage, existing wide deployment of DME ground facilities and a long history of successful service in the NAS all point to benefits of

DME State	Description	Costs	Projected Benefits
Documentation and projected improvements	Identify standards and equipment functions for improvement	Research and technical personnel, test equipment and flights.	Stakeholders become aware of projected benefits.
Improved DME: Ground System 0.3 Upgrades	Tighter monitoring, bias and noise reduction, better knowledge of multipath in APNT ops area, enhanced coverage.	Modify E-2996[2]; upgrade, add or replace DME facilities at APNT airports.	Increased DME accuracy. Better avionics performance without significant mods. RNAV 0.3 SIS* to support ops during GPS outage.
Standards Follow-up	Modify FAA, RTCA, ICAO documentation to enable RNAV 0.3. Modify FAA DME flight-inspection tolerance and procedures.	Possible re-approval of existing DME avionics to revised TSO c66, FMS** mods for RNP 0.3	Operators can apply for RNAV 0.3; standards in place for RNP 0.3, goal is with or without IRU.
High-Accuracy DME: Surveillance Upgrades	Apply previously-demonstrated DME/P*** techniques to extent needed to meet APNT requirements.	New interrogator functions and DME position downlink as part of ADS-B-In mod. New pulse shape in transponders.	Higher navigational accuracy; DME/DME position on ADS-B-Out benefits controller, automation and other- aircraft situational awareness

*SIS – Signal in Space – quality of position fixes to support a designated RNAV performance and, with airborne monitoring, to support RNP operations.
**FMS – Flight Management System – accepts multiple DME ranges and computes position.
*** DME/P – DME – precision, a system developed and demonstrated during the FAA Microwave Landing System program in the 1980s. DME/P elements of interest to APNT are discussed later in this paper.

Table 1: APNT DME Evolution

DME improvement and continued use, sustaining RNAV and RNP where beneficial

Table 1 illustrates a DME evolution leading to support of Next Gen APNT objectives. DME performance improvements are projected to occur in the near term with minimal ground-system changes and unchanged avionics. Operator approval for RNAV or RNP operations can follow once standards are updated. Later, coordinated with other necessary avionics modifications, high-accuracy DME may be included, with added benefits.

APNT REQUIREMENTS

Operationally, an APNT system is expected to enable an aircraft to navigate using RNAV or RNP procedures to a point within the service volume of the airport's Instrument Landing System (ILS) from which a normal ILS approach may be initiated.

The APNT DME goal for navigation is to provide APNT Zone 3[1] service equal at least RNAV / RNP 0.3[2], either with or without the IRU and without change to the scanning-DME avionics. For RNP use, changes to Flight Management System (FMS) error modeling, filtering and containment software for DME may be required.

The APNT DME goal for surveillance is to meet or exceed the position precision requirement (either 92.6 m or 128 m are under discussion), to maintain controller and other-ship awareness during GPS outages and ultimately to reduce dependence on surveillance radar. Meeting this requirement will likely require changes to DME avionics and possibly a further change in ground systems – moving to a DME/P-style pulse shape, or other technique.

APNT requirements emphasize the need for reliable terminal-area operations – specifically those that require RNAV or RNP 0.3 for Standard Terminal Arrival Routes (STARs), Standard Instrument Departures (SID) and missed approach procedures. Despite the fact that today's DME operates much better than specified, simply reducing FAA flight-

[1] APNT Zone 3 contains Terminal operations and requires RNAV 0.3 or RNP 0.3 guidance for arrival paths leading to an ILS final approach. A cone with 2-degree slope starting at 500 feet AGL 5 SM from the airport supports departures and arrival paths at airports listed in CFR Part 91 Appendix D section 1.

[2] RNAV 0.3 requires total system positioning error (navigation system and flight technical error) less than or equal to ±0.3 nm (95%). RNP 0.3 designates navigation performance which does not exceed ±0.3 nm, (95%) and a monitored 10^{-5} containment requirement of ±0.6 nm.

inspection tolerance is not sufficient to satisfy RNAV or RNP 0.3. It is expected that Improved DME can provide suitable navigation services to sustain RNAV and RNAV/RNP operations in terminal airspace.

DME OVERVIEW

Distance Measuring Equipment determines slant range between the aircraft and the ground facility. Slant range is determined by measuring the total time from aircraft radio interrogation to receipt of ground-system reply, adjusting for known reply delay, and converting time to distance. The process includes: 1) the avionics in the aircraft to "interrogate" the ground transponder, 2) the transponder to decode valid interrogations and reply after a fixed delay, and 3) the avionics to receive and decode the reply, and calculate the slant-range distance. The DME air-ground-air round trip measurement is achieved using pairs of pulses radiated in the L-band (962-1213MHz). The carrier frequency and the timed spacing of the pulses uniquely identify the radio channel on which the desired DME operates. DME is currently implemented as DME narrowband (DME/N) and DME precision (DME/P). DME/N is in general use today while DME/P was developed for the Microwave Landing System (MLS) with only limited implementation.

Slant-range information from a single ground facility defines the aircraft line of position as a circle around the facility. Aircraft two-dimensional position can be determined when slant range is combined with azimuth information (i.e. VOR) or with slant range from at least one additional DME/N facility. Combining measurements from multiple DME transponders at known geodetic locations into a position fix (DME/DME or DD fix) is often accomplished within a Flight Management System (FMS).

Terrain, geometry, aircraft height, and signal strength affect DME performance. These factors dictate the number and location of transponders required to cover a given area. Increasing the number of transponders is a cost-benefit issue and not a technical one, except that frequency management and re-use need to be taken into account.

Since DME is an active system (i.e. requires interrogation) it is capacity-limited. As the number of interrogations received by the transponder approaches overload, the transponder decreases receiver sensitivity. The effect is to reply only to stronger interrogations. Aircraft close to the transponder will be serviced preferentially (but nearby aircraft with weaker interrogators might be excluded).

Currently an IRU is required for DME/DME RNAV (DDI) operations. It is assumed that this requirement was included to allow "coasting" through a short dropout in DME coverage (or blockage due to a turn) without significant loss of positioning accuracy. Additional transponders or advanced signal processing may resolve this issue by preserving coverage throughout the APNT airspace.

DME ground transponders are monitored locally to maintain high-integrity timing. If an out-of-tolerance condition is detected, the facility will switch to an alternate transponder and/or monitor if so equipped. If the DME station is still out of tolerance it will stop operating.

DME PERFORMANCE

Two or more DME range measurements from geographically-appropriate ground locations relative to an aircraft can provide a position fix. Successive position fixes can provide continuous position relative to a desired flight path (navigation). When the aircraft periodically broadcasts this position to the ground controller and other aircraft nearby, it can be used to facilitate traffic management and aircraft separation.

APNT seeks to extract a higher level of performance from DME than is currently required to support basic RNAV functionality. DME has a successful half-century history supporting air navigation. During that time, improvements in DME ground system and avionics technologies have far outstripped the evolution of requirements and standards. However, the modest <u>minimum</u> performance required of DME avionics is a significant barrier to higher-precision performance in support of NextGen. The APNT team will propose upgrades to standards and specifications as required, to alleviate this problem for navigation.

Case	Transponder	Propagation	Avionics	Range	NSE Position* nm	FTE** nm	TSE*** nm
Current DME/N flight-inspection	--	--	--	0.2 nm (370.4m) FAA Flt Insp	0.56 nm (1047.6m) Calc	0.25nm	0.64nm
Current DME/N standards	0.041nm (75m) E-2996	0.03nm (57m) DO-189	0.5nm**** (926m) DO 189	0.50nm (930.8m) Calc	1.42nm (2632.7m) Calc	0.25nm	1.44nm
Improved DME/N RNAV/RNP 0.3	0.0081nm (15m) Industry	0.027nm (50.83) Analysis	0.046nm (85m) Lab Tests	0.054nm (100.2m) Calc	0.153nm (283.32m) Calc	0.25nm	0.29nm
High-Accuracy DME for 3-nm Separation	0.0054nm (10m) MLS Demo	0.013nm (24m) MLS Demo	0.008nm (15m) MLS Demo	0.016nm (29.7m) Calc	0.0454nm (84m) Calc	--	--

* Position from two DMEs. Included angle 30-150 degrees (maximum geometry factor of 2.828) [6]
**FTE value 0.25 nm (Flight Director, per DO-208[7], DO 236B[8], DO 283A[9])[4] [10]
*** TSE value is RSS of FTE and NSE. TSE is numerically equal to RNAV or RNP value.
**** Required APNT coverage assumed 200 nm; range error 0.25% of distance per DO 189

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

Avionics modifications will likely be necessary to fulfill surveillance requirements.

Accuracy: The APNT DME investigation began with the hypothesis that the system as deployed and used today far exceeds the performance requirements set forth in FAA and RTCA standards and ICAO recommended practices. Equipment both on the ground and in aircraft is acquired using specifications that have evolved more slowly than the technology. Ground system specifications are dated 2008 [2], while DME avionics minimum performance standards are more than 25 years old.[3] It appears that both documents will be the subject of APNT recommendations for change.[3]

The higher accuracy being sought for DME will likely also require accommodation of the vertical error – that is, the difference between slant range to the facility and the distance along-track at the aircraft altitude. Either computation of this difference, or restriction of DME use at short ranges may be required.

At least some of the improved system accuracy that is needed for APNT has already been fielded. Review of available FAA flight inspection data suggested that many facilities are operating at or near the ±0.05 nm range error that the team established as an "entry gate" for further investigation and use of DME as an element of APNT.[4] Data reported by Boeing covering over 200 DME facilities confirmed that observation.[5]

Earlier work raised concerns about ground facility location data-base entries. Today's modest requirements on DME accuracy accommodate survey error and relaxed facility location-fixing. These position data will require improvement to support higher-accuracy DME –based services. As the need for tighter tolerances on facility location is quantified, the APNT team will make appropriate recommendations.

Table 2 provides a digest of DME performance based on analysis of flight observations, laboratory tests on present-day transponder and avionics equipment, and literature research. All values are 95%. Table 2 values for Transponder, Propagation and Avionics error allowances are combined using the root-sum-square (RSS) method. The result is Range error <u>for a single DME.</u>

[3] See Kelly and Cusick [11] p. 124 ff. for a history of DME standards through 1985.

[4] Flight Director FTE is used to avoid autopilot requirement for terminal operations, and to reflect current FAA autopilot studies. It is possible that some autopilots designed for use with navaids providing angular guidance (varying linear accuracy) can require more airspace than is allowed for today's RNAV-based terminal operations.

Following FAA AC 90-100A [6], Position error is computed using two DME range measurements combined using RSS. Then, the positions of the two DMEs relative to the aircraft are taken into account by dividing the combined ranges by the trigonometric sine of the included angle between DMEs viewed from the aircraft. This Navigation System Error (NSE) is combined with Flight Technical Error (FTE) specified in RTCA DO-208 [7] by RSS and the result is Total System Error or TSE. This value in nautical miles is numerically the same as the RNAV or RNP designation.

The table gives insight into the changes which may be required to prepare the DME system for APNT service in support of RNP 0.3 and later for the more stringent surveillance requirement. DME airborne and ground subsystems will require changes for best performance; changes to pertinent standards and specifications are also certain. Legacy DME operation will remain unchanged.

Current DME/N performance level is driven by the FAA flight-inspection (FI) tolerance of 0.2 nm throughout coverage. The RNAV 0.6 level is approached using this tolerance, as shown in the last column of Table 2. Boeing reported [12] this same result, based on current standards, not on achieved DME performance.

Current DME/N standards on limits for Transponder, Propagation and Avionics error are drawn from the references noted, and their RSS combination results in a large TSE or RNAV/RNP value. This arises from the RTCA DO-189[3] avionics standard which specifies a range error limit which increases with increasing distance from the transponder. Boeing flight observations and FAA flight-inspection data do not show such error growth, and modern avionics specifications state a range accuracy throughout coverage (without a distance factor).[13, 14] An APNT recommendation is likely in this area.

Improved DME/N RNAV/RNP 0.3 table values reflect APNT findings and projections to date, emphasizing ground system and standards changes, with unaltered avionics. Note that TSE meets the RNAV 0.3 goal, with a small margin. Continuing tests and analysis on each of the error components will allow refinement of the TSE value.

Ground system error contribution is reduced to 15m by changing reply-delay monitor limits to ±0.100 usec or less.[5] Industry representatives indicated the ability to achieve this at an earlier APNT Industry Day session. FAA's current DME provider has been contracted to test a current-day transponder to reveal actual performance compared to FAA E-2996, the FAA DME ground system performance specification.[2]

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.[11, 15] Work continues in this area, on additional literature references not yet fully analyzed, which report on past DME flight tests.[16] Multipath effects in DME range data collected for APNT during flights at Dallas-Fort Worth International Airport are currently under study,[17] as are flight results from others.

Avionics error was measured by Boeing engineers [18] in bench tests on DME/N avionics currently in the fleet. Three DME interrogators representing current fleet equipage were tested for range accuracy vs. signal strength and other parameters. Agreement is observed among these tests, measurements made on a military TACAN transponder receiver, and with informal industry input quoting achievable avionics accuracy at ~0.05 nm.[19]

Tests will continue on representative avionics units including such factors as reply efficiency, temperature, frequency, aircraft dynamics and others, to characterize the interrogators and refine the DME error budgets. One specific opportunity to improve DME/N accuracy further is to examine positive effects of reply pulses with faster rise times on the accuracy of unaltered DME/N avionics. Changes to pulse shape on the ground are not complex with current software and firmware technologies. Pending successful tests, the team may recommend a new ground-system pulse shape which meets current L-band spectrum requirements.

[5] Note: 100 nsec uncertainty corresponds to 30 meters contribution to radio round-trip timing error. Range uncertainty is 15 meters (95%) due to avionics divide-by two to obtain one-way range.

High-Accuracy DME for 3-nm Separation: APNT DME activity described earlier in this paper highlighted unused capabilities in the existing system and recommended specification updates to push the system in the near term to deliver RNAV 0.3 with existing or slightly modified avionics. Moving to NextGen APNT services means going beyond the navigation alternative and seeking a backup for ADS-B surveillance services that disappear when there is a GPS outage.

Two APNT surveillance position error requirements, ±92.6m (from ADS-B) and ±128m from Wide-Area-Multilateration work (WAM), are in active discussion at this writing, and meeting either criterion requires performance well beyond the RNAV 0.3 accuracy projection that was achieved mostly by cutting “white space” out of the existing system standards and specifications. One option for greater accuracy is DME/P (for Precision DME). This system was designed, built, standardized and operated as part of the FAA Microwave Landing System. DME/P was meticulously documented. [10, 20, 21, 22, 23]

The DME/P system associated with the MLS work in the 1980’s is capable of ±84m positioning accuracy given the same geometry restrictions as for Current DME/N and Improved DME/N from Table 2, above. This impressive performance results in large part from more accurate timing of incoming pulse time-of-arrival and significant multipath error reduction. These improvements are clearly seen in Table 2, and it is also clear from the Transponder and Avionics columns that changes are required both in the Current and Improved DME ground transponder and in today’s avionics. Despite these modifications, the system remains fully compatible with legacy DME.

The downside of the improved performance with DME/P is a 22-nm coverage limitation imposed by the faster pulse rise time. Faster pulses increase adjacent radio channel interference and therefore could require lower transmitter power, which would reduce coverage and require more ground installations for a given terminal area.

The High-Accuracy DME for APNT surveillance likely does not need a fully-compliant DME/P design. The APNT application does not require coverage during final approach, which significantly reduces the multipath threat. This in turn relaxes the requirement on pulse rise time and leading-edge linearity. Therefore, APNT may not need full-DME/P capability, and this may offer trade-study flexibility. Some accuracy may be traded off for slightly slower pulses, giving a narrower RF spectrum, greater power allocation and more range.

Work remains to determine just what elements of the DME/P specifications are needed for the High-Accuracy DME application. Meanwhile, two recent activities have offered valuable encouragement.
The team participated in tests of a military TACAN transponder as fast rise-time pulses were demonstrated. Full-system tests were not possible, as representative avionics were not available during the test. However, it is evident that pulse-shape flexibility and consequent improvements in pulse time-of-arrival detection are real.

In recent discussions with a DME manufacturer, the DME team viewed summary data from a commissioning flight-inspection orbit that, on its face, would indicate that at least one specific DME ground system can support the ±92.6-m requirement today. The team immediately asked for more information (what interrogator was used, what pulse shape used, can we independently analyze raw data, etc.). The team will analyze additional data so that independent analysis may confirm or challenge the ±92.6-m statement.

In a further development related to high-accuracy DME, a GPS-like processing technique for use of both the DME pulse envelope and the DME carrier has been proposed, and the APNT DME team regards this method with great interest.

Integrity: Table 3. gives representative faults and mitigation strategies for APNT DME. The ground installations are monitored and signals are removed or replaced within seconds if they exceed tolerances. In-band identification of each facility prevents tuning blunders. APNT changes to DME facilities are not expected to affect integrity directly, but the expectation of considerably improved accuracy may require better knowledge of error sources so that integrity may be ensured.

DME avionics using Built-In Test Equipment (BITE) perform periodic end-to-end tests, assuring that faults will be flagged. The value for containment in APNT airspace is under study. If the final value reflects current practice, then DME systems should qualify for approval. Addition of a second independent monitor to DME ground systems for integrity upgrade is not difficult, although a small capacity reduction results.

Potential Faults	Description	Mitigation
DME range error "spikes"	Occasional range jumps appear in flight inspection data and ground tests [24]	Receiver, FMS filtering reduce high-frequency outliers to within 95% accuracy specification.
DME ground system timing error	Ground system fault causes erroneous range	DME ground system monitor causes reversion to second transponder or shuts down.
DME ground system low transmit power	Ground system fault causes low power output, reducing avionics SNR and reducing coverage.	DME ground system monitor causes reversion to second transponder or shuts down.
Multipath	Changes in transponder environment cause multipath-related errors in flight path.	Periodic flight inspection and FAA multipath tools [25] identify effect; multipath-limiting, directional antenna mitigates. Carrier-envelope processing identifies, mitigates.

Table 3: APNT DME Potential Faults and Mitigation

Continuity: DME continuity is not expected to decrease due to APNT modifications. The newer ground system hardware should result in improved continuity. An impact might be expected due to the more stringent timing requirements, but the APNT team is confident that ground systems can accommodate the requested changes in monitor limits.

Availability: Requests to industry for information regarding anticipated changes to traditional DME/N ground systems for APNT performance have emphasized that traditional DME services, including availability, are to be met or exceeded. Work continues, but to date, no availability concerns have been raised in response. DME ground systems using today's best design and manufacturing practices may achieve greater availability and reliability through monitoring for incipient faults plus minimization of mean time to repair through remote control and adjustment.

Coverage: Signal coverage for Improved DME/N is unchanged from the familiar DME Standard Service Volumes (SSVs) for the Terminal, Low- and High-Altitude DME facilities [26], for a given effective radiated power. The FAA's move toward a Hybrid Service Volume (HSV) [27] recognizes actual signal presence, and offers more flexibility in managing APNT DME airspace design (Figure 1). Additionally, user avionics have better receiver sensitivity and pulse-detection algorithms.

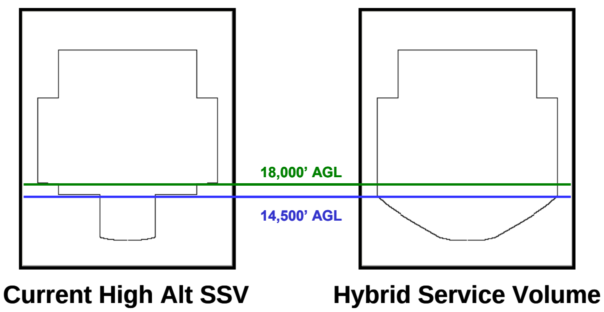

Figure 1: Hybrid Service Volume and low-altitude signal availability. [FAA graphic]

Note that reductions in coverage are a concern if High-Accuracy DME installations are required to operate with reduced power in order to use wider-band pulse shapes to achieve needed accuracy without interference to adjacent channels. Recent tests on a modern DME ground station indicate that the pulse leading edge can be made somewhat faster without radiated power reductions. Work is underway to determine the needed rise time for APNT-required system accuracy. Modern GPS-like processing techniques may also enhance coverage by reducing the effects of blockage during aircraft maneuvers

DME Capacity: Historically, Distance Measuring Equipment provides time-divided access to the ground transponder by multiple users, one interrogation at a time. Each user interrogation requires a specific amount of transponder time for processing and reply. When they are active, facility identification (ident) and monitoring functions generate reply-like pulse pairs that displace or suppress user replies.

DME Capacity Limitation	Description of Limitation	Mitigation	Potential improvement*
Maximum Ground System Transmission Rate	Current transponders are limited to a maximum transmission rate. Increasing the reply rate may cause transmitter duty-cycle to reach undesirable levels, shortening transmitter component life through excessive heating.	Industry provides designs to accommodate the DME ranging load plus data broadcast and time transmission. Manufacturers advertise various rates at present.	Increase number of DME users and/or enable support of partner APNT services without reducing traditional DME capabilities.
Ground System Reply Efficiency	Current ground-system standards require a 70% response rate to incoming interrogations. Avionics MOPS** assume 70% reply efficiency.	Modern avionics units operate normally as low as 30% reply efficiency [28]. Change avionics MOPS to 50%.	~ +40 users
Ground System Dead Time	Ground systems are constrained to produce no more than one pulse-pair reply every 60 microseconds. Blanking prevents self-interrogation and possible transmitter overload.	Reduce dead time or replace with echo-suppression. Pipeline multiple interrogations through the ground system.	Potential significant capacity increase if transmitter duty cycle allows. Reduced dead time increases reply efficiency.
DME Monitor	Current standards allow up to 120 interrogations per second. Two monitors may be required to meet integrity requirements. Monitors reduce reply efficiency.	Reduce the monitor interrogation rate. Need to determine the minimum rate needed to insure integrity.	Under study
Facility Identification	Ground system blanks replies during Morse code “key-down” intervals. Occurs ~5 seconds every 30 seconds. Audio ident is pulse-pair bursts at 1,350 Hz rate.	Allow replies to interrogations decoded between 1,350-Hz ident pulse pairs either during “key-up” or “key-down.” Test for avionics impact.	Reduction in short nav outages caused by reduced reply efficiency during ident, and avionics “catch-up” or search after ident.
WAM and Pseudolite Use	For DME to act as a data- or time-transmission host for other elements of a potential APNT system of systems, added load is placed on the ground system, reducing reply efficiency for range users.	Increase capacity so that both DME navigation and data-transfer services may co-exist.	Support other APNT services with no effect on legacy DME services. Reuse of existing DME broadcasts, with fewer new installations

* Estimated averages, based on DME Capacity Model and APNT analysis. One “user” ~22 replies per second.
** RTCA Minimum Operational Performance Standards

Table 4: DME Capacity Limitations and Potential for Improvement

When the DME is part of a TACtical Air Navigation (TACAN) facility, the TACAN azimuth signals also use a portion of the maximum pulse-transmission capacity. This affects the distance reply efficiency of current VORTAC facilities, but is not a factor for current and future FAA procurements, which will provide DME-only functions. An increase in the capacity of DME ground facilities supports directly the expected increase in traffic as the NextGen era approaches, and it also is a positive factor when DME is used as a host for pseudolite data transmission.

APNT team members created a DME Capacity model [28] that has helped to identify areas where capacity may be increased. An Ohio University capacity study in the field [29] revealed a potential for ident-caused navigational outages due to avionics high-rate interrogations at the end of the Morse-code identification interval. Reduction or elimination of outages of any length is an important factor in relaxation of IRU requirements for use of DME/DME RNAV operations. Table 4 shows a variety of engineering tests and analyses which address the interrelated factors which determine achievable DME ground-system capacity. Current assessments are positive, but work continues in each area. The table outlines tasks which are an integral part of the DME testing program plan.

SUMMARY

APNT DME findings to date encourage continued effort to achieve RNAV and RNP 0.3 using multiple-DME-range position fixes as the basis for navigation in terminal airspace. Work continues on the even higher accuracy required for DME-based

position-fixing in support of surveillance-based three-mile separation.

The DME constellation and avionics presently deployed are producing range measurement precision which far exceed today's modest demands. Considerable increases in performance may be claimed simply by updating specifications and standards to reflect today's routinely achieved performance. The DME team also projects that relatively modest changes to ground system timing and monitoring can move system accuracy to the RNAV 0.3 level.

Possible relaxation of the requirement for IRU as part of DME-based navigation is not yet settled. An APNT objective is to allow terminal operations to proceed without IRU. Work continues to define cost-effective solutions for coverage gaps and feasible changes to airborne systems to provide suitable signal processing, error modeling and filtering to achieve RNP approvals.

DME ground transponders are being considered as possible hosts for data and timing transmissions that support other APNT alternatives. It is possible that Wide-Area Multilateration and Pseudolite systems can benefit from existing DME sites by adding data-broadcast pulses to the DME reply transmissions. Various options also exist for distribution of precise time to DME sites for these functions.

Distance Measuring Equipment enjoys a long and successful history of service to the National Airspace System. Further, it enjoys excellent stakeholder confidence and support. Changes to DME for APNT services do not require system redesign. The APNT directive is to "do no harm" to today's DME users throughout the fleet, as we improve and document accuracy and capacity while insuring no negative impact on reliability and safety.

NEXT STEPS

Continue to refine error allocations (ref. Table 2) for DME components and propagation error, using APNT and industry measurements, analyses and literature references.

Investigate all-in-view methods and potential benefits of multiple-DME position fixing. Initiate a DME test program to identify further improvements to ground facilities and avionics to insure APNT goals for navigation and surveillance can be met.

Continue to seek industry assessment and acceptance of proposed improvements – cost and time to implement, and expected benefits. The process is underway, seeking improvements in DME systems soon to be delivered to the FAA under an existing procurement.

Continue research on facility location and documentation, for recommendations on accuracy increases to support DME/DME positioning operations.

Continue discussions with FAA Flight Inspection representatives to define DME measurement and truth-system accuracy. Propose flight-inspection procedures and tolerances for DME facilities supporting APNT airspace.

Establish plans, a timeline and milestones for necessary standards and specifications changes to meet APNT DME goals and achieve operational benefits.

Bring new ideas and techniques to the DME activity. Presentations at APNT Industry-Day events have outlined more than one interesting signal-processing method with great potential for future high-accuracy DME.

Continue close coordination with other APNT studies of Wide-Area Multilateration and Pseudolite alternatives, plus Low-Frequency Time Distribution services. DME can be a platform for transmitting messages and timing for any or all of the system-of-systems elements in APNT airspace.

REFERENCES

[1] Federal Aviation Administration, http://aspmhelp.faa.gov/index.php/Core_30, visited December 18, 2012.

[2] DOT-FAA, "Performance Specification, Distance Measuring Equipment (DME)", FAA E-2996, April 1, 2008.

[3] RTCA, "Minimum Operational Performance Standards for Airborne Distance Measuring Equipment (DME) Operating Within the Radio Frequency Range of 960-1215 Megahertz," DO-189, September 20, 1985.

[4] Lilley, R., "DME/DME for NextGen APNT: System, Program, Measured Data," APNT Presentation, June 13, 2011.

[5] Murphy, T., "APNT – Industry Perspective: Instrumented DME Flight Test Data Analysis," presented September 18, 2011 to the APNT team in Portland, OR. Data were provided by Boeing, but the interpretations from the data are those of the APNT DME team.

[6] FAA, Advisory Circular AC 90-100A, "U.S. Terminal and En Route Area Navigation (RNAV) Operations", March 1, 2007.

[7] RTCA, "DO-208 Minimum Operational Performance Standards for Airborne Supplemental Navigation Equipment Using the Global Positioning System," DO-208 Change 1, 9-21-9 and 3 3-16-95.

[8] RTCA, "Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation," DO-236B, October 28, 2003.

[9] RTCA, "Minimum Operational Performance Standards for Required Navigation Performance for Area Navigation," DO- 283A, October 28, 2003.

[10] FAA, T. Pearsall, Personal contact, December 17, 2011.

[11] Kelly, R:, and Cusick, D., (1986), "Distance Measuring Equipment and Its Evolving Role in Aviation," Advances in Electronics and Electron

Physics, Vol. 68, Academic Press, New York, p. 118.

[12] Personal correspondence, T. Murphy, Boeing, December 6, 2011.

[13 Rockwell Collins DME-900 Specifications: visited December 19, 2011: http://www.rockwellcollins.com/sitecore/content/Data/Products/Navigation_and_Guidance/Direction-Finding_Equipment/DME-900_Distance_Measuring_Equipment.aspx.

[14] Rockwell Tacan-550: visited December 19, 2011: http://www.rockwellcollins.com/sitecore/content/Data/Products/Navigation_and_Guidance/Direction-Finding_Equipment/TCN-550_TACAN_Beacon_System.aspx.

[15] Li, K., Pelgrum, W., "Optimal Time-of-Arrival Estimation for Enhanced DME," ION GNSS, Portland, OR, September, 2011.

[16] Evans, J.E., "L-Band DME Multipath Environment in the Microwave Landing System (MLS) Approach and Landing Region," MIT Lincoln Laboratory, Lexington, MA, Report ATC-116, April 13,, 1982.

[17] Erikson, R., "DME Testing at DFW: A Quick Look," APNT Presentation, May 16, 2011.

[18] Murphy, T., "APNT – Industry Perspective: DME Lab Test Data Summary," presented September 18, 2011 to the APNT team in Portland, OR. Data were provided by Boeing, but the interpretations from the data are those of the APNT DME team.

[19] Personal Correspondence, Aviation Management Associates, December 2, 2011.

[20] Kelly, R.J. and LaBerge, E.F.C., "Guidance Accuracy Considerations for the Microwave Landing System Precision DME," Navigation, Vol. 27, No. 1, Spring, 1980, p. 1.

[21] International Civil Aviation Organization, "Aeronautical Telecommunications," Annex 10, Volume I, Radio Navigation Aids, Section 3-36 and Attachment C, July, 2006.

[22] Braasch, M., "Current Developments in Signal Modeling of the Precision Distance Measuring Equipment, M.S. Thesis, Ohio University, November, 1989.

[23] Manning, P., Smith, A., "Testing of Precision DME," 6th Annual Flight Inspection Symposium, June 25-29, 1990, Washington, DC.

[24] Lilley, R., "DME/DME for NextGen APNT : DME Data Reduction – A Second Look at Olympia, WA DME," APNT Presentation, August 22, 2011.

[25] Bigham, T., Snelling, B., "Investigation of Terminal Area Distance Measuring Equipment Signal Interference: A Case Study," FAA, Oklahoma City, 2010.

[26] FAA, "Aeronautical Information Manual," p. 1-1-5, visited December 19, 2011: http://www.faa.gov/air_traffic/publications/ATPubs/AIM/aim.pdf.

[27] FAA AFS-450, "Standard vs Hybrid Service Volume," Flight Systems Laboratory, June 6, 2011.

[28] Lo., S., Enge, P., "Assessing the Capability of Distance Measuring Equipment (DME to Support Future Air Traffic Capacity, Stanford University. Presented at APNT Technical Meeting, April 9, 2010; to be published in "Navigation" (ION).

[29] Alder, F., Thomas, R., Hawes, C., DiBenedetto, M., "Distance Measuring Equipment (DME) - Interrogation Rate Measurements, Observations, and Results: Elyria, OH; Atlanta, GA; and Chicago, Il," Technical Memorandum, OU/AEC 08-23TM00071/3.3-3, December 2008.