Signal Structure Study for a Passive Ranging System using Existing Distance Measuring Equipment (DME)

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BIOGRAPHY

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1. ABSTRACT

The US Federal Aviation Administration (FAA) is developing alternative navigation concepts to maintain operational capacity and efficiency even in the presence of a degradation of the Global Positioning System (GPS). One concept being studied for this alternate position navigation and timing (APNT) is a ground based passive ranging system. Such a system can achieve many benefits. It has few capacity constraints, has a simpler architecture than other alternatives, can better utilize aviation spectrum, and can provide improved position navigation and timing (PNT) capabilities. One design being considered seeks to implement a passive ranging broadcast using existing distance measuring equipment (DME) ground transponders without the need for any changes. This concept, known as DME based passive ranging (DMPR), has the benefit being compatible with existing DME operations and can utilize the existing DME infrastructure. This paper develops and assesses the signal structure design to support accuracy and overall data capacity goals.

OUTLINE

This paper is focused on the design of the signal and its signal structure as well as the ability of the design to support APNT accuracy and data targets. The background section covers basic DME operations, the basic concept of DME passive ranging and how these systems differ and complement each other. Also discussed are the requirements and desired capabilities for the design.

The body of the paper focuses on the performance of the DMPR signal design when it functions alongside current DME. The first part assesses the signal precision and whether the design supports the desired accuracy targets. Measurement of on air DME signals are taken and analyzed for the determination.

The second part focuses on the determining the best signal structure design in terms of effective data rate. While the raw data rate can be easily determined, the signal design needs to account for the effects of the interaction between DMPR and nominal DME signals. To understand the interaction, both an analytic and simulation channel models are developed. As the interference causes data symbol erasures and errors to the passive ranging signal, the model evaluates the rates of these occurrences. The results are used to determine an adequate level of error and erasure correction for the message design. From that the effective data rate for different designs can be determined and the best design can be selected. As there are different parameters and factors that can affect the design, sensitivity studies on the important parameters are presented.

A final section discusses signal design concepts to handle unique DME interference. In particular, DME Morse code transmissions, sent every 40 seconds [1], can be problematic for DMPR if it is not accounted for. The section discusses how DMPR would be modified during these occurrences to retain its ranging capabilities.

2. BACKGROUND

The APNT group was formed to determine and develop the promising solutions for providing FAA navigation, surveillance and other services in the event of a GPS degradation event. The need for APNT is particularly important as aviation use of GPS will increase in the coming years. Under Next Generation Air Transport System (NextGen), GPS will be the primary means of navigation and surveillance for aviation. And it is GPS that enables the operations that are needed to handle the increased capacity anticipated in the 2025 time frame. And GPS is often the only system capable of supporting many envisioned operations. Current terrestrial based navigation system 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 provide capability to sustaining operations in the event of GPS outage. The solution will provide RNAV capability. Additionally, the solution must support en route coverage in CONUS and terminal coverage in major airspace. For terminal operations, the APNT should be able to support Required Navigation Performance (RNP) or RNAV operations down to 0.3 nautical miles (RNP/RNAV 0.3). Additionally to sustain operations and provide safety, it must be able to support the full level of air traffic anticipated in the future. Two candidate technologies being examined are DME and terrestrial passive ranging.

DISTANCE MEASURING EQUIPMENT

DME is a two-way ranging system where the aircraft calculates its range to a DME ground station or beacon by the sending an interrogation and receiving a corresponding reply. Figure 1 shows this operation of the DME beacon in receiving the interrogation and responding to it. The beacon identifies the interrogation as a DME transmission by locating a second pulse at a set offset relative to the first pulse - 12 µsec in the figure. This is because the interrogation, like all DME transmissions, comes in the form of a pulse pair. When the beacon accepts that interrogation request, it becomes non responsive to other requests for a short period or dead time. Acceptance occurs upon receipt of the second pulse of the pair. After a fixed delay from the receipt of the first pulse or the interrogation, the ground broadcasts a reply, also in the form of a pulse pair. Note that the dead time extends beyond the reply transmission period to allow the beacon antenna to return to a more quiescent state for receiving aircraft interrogations. One consequence of operation seen in the figure takes about 75 µsec to receive an interrogation and complete the response process. This means that the minimum time between replies is 75 µsec.

An aircraft can determine the round trip time and calculate the range to the DME beacon if it knows the interrogation time of transmission and the reception time of the corresponding reply. So while all aircraft can receive the reply broadcast, it is only useful to the aircraft making the interrogation. More than one reply is needed to verify correspondence. An aircraft in tracking mode typically uses 5-15 interrogation pulse pairs per second (ppps) to make its range measurements. Note that in search mode, prior to the aircraft determining its approximate range to the beacon, up to 150 pulse pairs per second may be used.

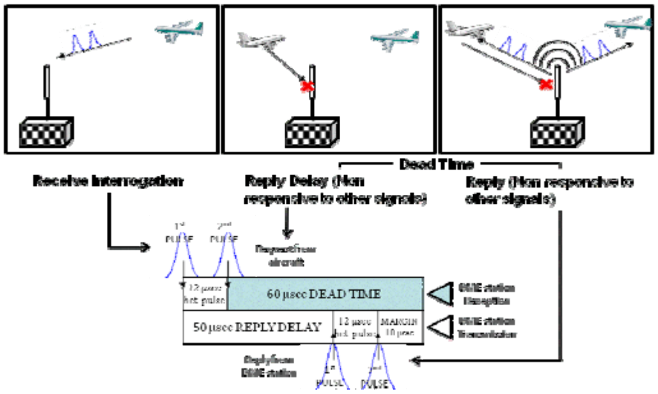

Figure 1. DME Beacon Response to Interrogations

An interrogation may also emanate comes from a local ground transmitter. In today's DME, a ground monitor exists that sends interrogations and monitors replies to check if the system is performing within tolerance. The ground monitor uses 120 ppps for its tests [1].

DME beacons currently generate up to 2700 reply and should be capable of supporting over 100 aircraft. In the future, DME beacons may be capable of up to 5400 replies. To ensure that the beacon only transmits up to it reply limit, the beacon automatically squelches - setting its threshold so that it only responds to its reply limit. Hence, closer aircraft will have higher availability than aircraft that are further away. Even without the reply limit, not all interrogations will result in a reply due to dead time and interference. Reply efficiency (RE) is the ratio of replies to interrogations and in general RE decreases with increasing number of interrogations. Model results based on [2] and presented in Figure 2 shows the relationship between incoming interrogations and replies.

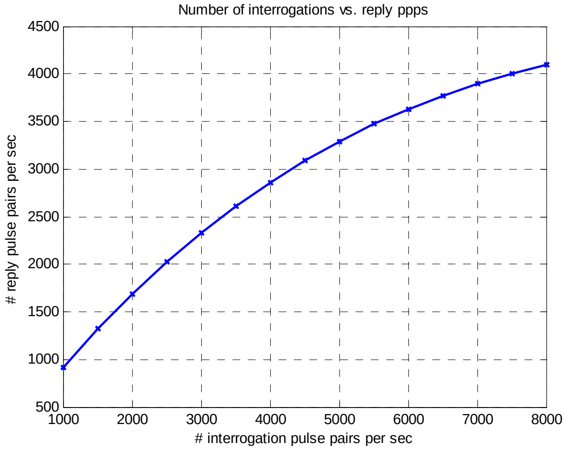

Figure 2. DME Interrogation per second vs. Replies

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). The infrastructure consists of nearly 1100 ground beacons with additions and modernization coming soon. Full en route coverage for DME/DME/IRU will be provided with this infrastructure.

However, the current DME system has limitations with regards to its utility for APNT. Specifically, it may not have the capacity, accuracy and integrity needed to support future airspace.

In future high-density airspace, a beacon may need to support 260 aircraft [3][4]. Newer DME can transmit more replies, which will improve capacity but it also reduces the reply efficiency. Avionics are specified to operate with at least 70% reply efficiency to though many can handle lower levels. From the figure, the 70% RE level is at about 4000 interrogations to (or 2800 replies from) the beacon. The result is that increasing DME capacity by increasing the number of beacon replies has a limit and depends on avionics ability to handle lower percentages of replies.

Current specifications and standards for DME accuracy only allow the system to support en route operations such as RNAV 1.0. The APNT team has found that the existing DME system performs better than those specifications. The team is evaluating whether the actual performance can support desired approach operations or if improved signals are needed. Even if credit can be taken for DME performance that is better than current specifications, safe use of this improved DME will require a mechanism for alerting users of out of tolerance performance. Currently out of tolerance conditions are alerted by taking the beacon signal off air. However, this may not be reasonable if there are two standards by which the beacon will operate – current (DME/N) or improved (for APNT). A beacon may be out of tolerance for APNT but within the current specifications. Taking a beacon off air due to the condition above would eliminate a perfectly fine beacon for existing DME users. So a future improved DME could use a data channel to provide an integrity warning for both existing and future standards.

DME BASED PASSIVE RANGING

DME based passive ranging (DMPR) uses fundamental DME operations to generate a passive ranging and data signal. As seen in Figure 3, the DMPR ground interrogator would transmit interrogations to elicit replies and appear much like DME avionics or the current DME ground monitor. The difference is that these interrogations are sent at set times creating a pseudorandom sequence of DME signals in time. The interrogation causes the DME beacon to broadcast a series of reply pulse pairs that can be used as a ranging signal and to communicate data. Furthermore, the signal can be used by any individual receiving it. The beauty of DMPR is that it does not adulterate the existing DME ground beacons or signal. And so, normal DME functions can still be performed with the additional interrogations from DMPR appearing as an increase in traffic.

Figure 3. Similarity between DME and DMPR Operations

However, there are two major drawbacks with passive ranging system such as DMPR relative to DME. First it requires accurate time synchronization of ground stations – something not required by DME. This means having a robust time source and perhaps an accurate clock. One of many means being studied is discussed in [5]. Second, passive ranging requires measurements from at least three stations (instead of two) for horizontal positioning. This allows the user to have a low cost, unsynchronized clock (as in normal DME). The geometry burden may be mitigated with mixed DME/DMPR operations [6].

DMPR SIGNAL STRUCTURE

The DMPR design seeks to meet performance goals while maintaining a small footprint on nominal DME operations. The DMPR signal design uses 500 ppps and represents the load of about 20 aircraft. This burden is even less if the DMPR ground interrogator can be used to replace the existing DME ground monitor.

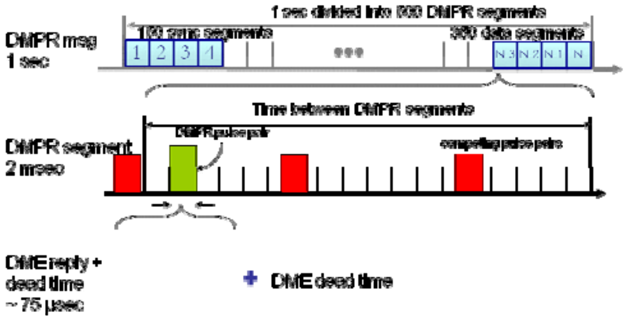

Figure 4. DMPR Overall Signal Structure

The DMPR signal structure uses a one second frame which is divided into 500 two millisecond (ms) segments. One DMPR pulse pair is transmitted in each two ms segment resulting in 500 DMPR ppps. Of these pulse pairs, 150 are dedicated to synchronization (with a priori known time offsets) and 350 ppps for data. The segments within the one second frame are seen in the top of Figure 4. While shown to be consecutive, the synchronization (sync) and data segments may be interleaved.

The DMPR pulse pairs are transmitted only at specific times (start opportunities) within the segment which allows them to be differentiated from a DME reply to an aircraft. In the synchronization segments, the specific times (relative to the start of the segment or frame) are known and form a pseudo random sequence that the avionics can correlate to and lock on to the DMPR signal. This allows for ranging with and synchronization to the DMPR transmission. In a data segment, they are not known but can be in one of several possible start opportunities. Once synchronized, all possible DMPR start opportunities can be identified and a pulse pair landing at an acceptable DMPR start time can be determined. This allows for data decoding and ranging. DMPR design was support APNT needs for accuracy and data while still maintaining compatibility with and having a low impact on existing DMEs.

REQUIREMENTS: ACCURACY & DATA

An APNT system needs to have high accuracy to support for RNP/RNAV 0.3 (approach) and surveillance. Of relevance to DME and DMPR transmission is the derived signal ranging accuracy. Note that in this paper, all mention of accuracy refers to the 95% or two standard deviation level of error. The signal ranging accuracy calculated is the accuracy of the signal measurement exclusive of the timing errors. Table 1 derives the signal ranging accuracy needed to support those operations. The calculation assumes a horizontal dilution of precision (HDOP) of 2.8, an assumption of 50 nanoseconds (nsec) time synchronization accuracy. Additionally, as RNP/RNAV specifications are in terms of total system error (TSE), the flight technical error (FTE) must be accounted for and an assumption of 0.25 nautical miles (nm) FTE accuracy is used. This is FTE when coupled to a flight director [7].

Table 1. Derived Signal Accuracy for Different Operations

Operation	Navigation accuracy required	Range accuracy required, (HDOP 2.8)	Time sync accuracy (estimated)	Derived signal accuracy required
RNP/RNAV 1.0	1793 m	634.0 m	50 ns (15 m)	633.8 m
RNP/RNAV 0.3	307.2 m	108.6 m	50 ns (15 m)	107.5 m
Surveillance (3 mile separation)	92.6 m	32.7 m	50 ns (15 m)	29.1 m

The result shows that for RNP/RNAV 0.3, a signal accuracy of 107 m or less is desired. While the most stringent accuracy requirement is 3 mile separation, this number is not final. For reference, derived ranging accuracy for RNP/RNAV 1.0 is included and the comparison shows the significant range accuracy improvement needed for the operations desired by APNT. A second area of interest is data capacity to support integrity and other benefits. APNT is targeting about 900 bits per second (bps) to support several capabilities, as seen in Table 2. The first capability is support of DME/DMPR based navigation. Supporting navigation means providing location information about the DME beacon which allows for operations without a pre-loaded database. It also includes providing time information for absolute time and DME/DMPR integrity. This capability does not require a lot of data – less than 100 bps. A second capability is additional signal security through authentication. Authentication verifies the data, time and source of the signal to reduce the potential of spoofing. As APNT is about improving the safety and security of the airspace this is a natural feature. The third capability is providing value added benefits that can help users during nominal periods. In the table, three services that can be of value to improving GPS/GNSS operations and providing operators with benefits that can translate into cost or time savings are illustrated. From the operator standpoint, these benefits may be the reason to equip.

Table 2. Data Required for Different Desired Features

Message type	# bits	capacity (bps)	Comments
DME identification with lat/lon/ height & time, integrity flag	144	72 bps	every 2 s
Security/Authentication [8]		~ 300 bps	
1. Authentication	512	256 bps	every 2 s
2. Certificate revocation list	512	51.2	every 10 s
GNSS Value Added Benefits		~ 540 bps	
1. Integrity support message	256	25.6	multi-constellation GNSS
2. Assisted GNSS	256	256	strengthen GNSS
3. Wide area GBAS (ΔΦ)	~512	~256	Cat II & III
Other new applications	?	?	
Total		~900-1000 bps	

DMPR TO SUPPORT DME & APNT

The DMPR design has many benefits for supporting the high performance standards targeted by APNT. In terms, of accuracy, it can improve upon current DME performance in couple of ways. First, DMPR avionics can take credit for the better performance of today's transmitters. Furthermore, DMPR provides more pulse pairs for avionics to average. It also uses only the ground beacon signal which is more tightly specified and typically better controlled than the interrogation signal. DMPR has unlimited capacity and can off load some of the DME use. DMPR provides self contained data to support navigation and integrity. This data capability can also benefit an improved DME by providing a means of communicating integrity to flag when the DME is out of tolerance relative to the new accuracy specifications while not affecting users operating on the current standards. Just as important, DMPR data can provide value added benefits that could incentivize operations to buy a new improved DME/DMPR receiver.

3. DME/DMPR RANGING DESIGN & ANALYSIS

DMPR is targeted to support the accuracy required for RNP/RNAV 0.3 and surveillance. The DMPR ranging signal has some advantages over traditional DME such as use of up to 500 pulse pairs per second for ranging and the cleaner beacon transmission. To assess the accuracy of the signal and design, measurements from the DME/TACAN station in Woodside, California (CA) were taken.

The signal measurement precision is used as a proxy for evaluating the ability to meet the derived signal accuracy. The ranging error (ε_r) is composed of ground station timing (ε_t), propagation (ε_p), multipath (ε_m) and signal measurement error (ε_s). This is seen in Equation 1. The derived signal accuracy as defined in requirements section is inclusive of these errors except timing which has been accounted for. Assuming that propagation and multipath are negligible, the derived signal accuracy is then essentially the signal measurement error which is the precision with which the signal can be measured and depends on the signal to noise ratio (SNR) and processing. Propagation effects should be small due to the short propagation distances and error levels targeted. Multipath, which is location and processing dependent, can be an issue and merits further investigation.

$$\varepsilon_r = \varepsilon_t + \varepsilon_p + \varepsilon_m + \varepsilon_s \qquad (1)$$

DATA COLLECTION

Data was collected from the Woodside TACAN beacon located 5.55 nautical miles from the roof of the Stanford University Aeronautics building. This is seen in Figure 5. Data collection equipment was developed with a DME antenna, front end filtering, and low noise amplifier in that order. This is used to receive, filter and amplify the signal prior to the digitalization to an intermediate frequency. Additional filtering, down conversion and analog to digital conversion is conducted using both an Agilent 89600 vector signal analyzer (VSA) and Universal Software Radio Peripheral 2 (USRP2). The equipment up is based on that used in [9] and is shown in Figure 6. The VSA is used when possible as it has cleaner filtering. For the measurement analysis, data was collected on 40 different days from July 2011 to February 2012.

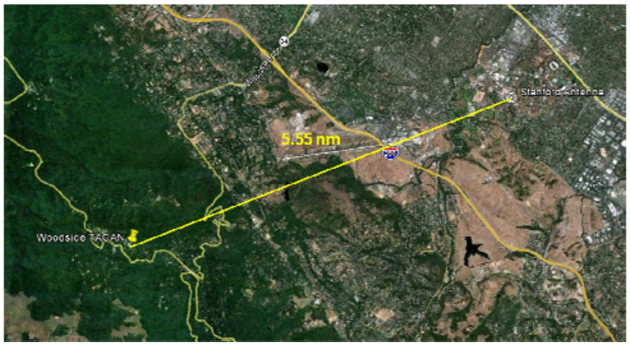

Figure 5. Woodside TACAN and Data Collection Site

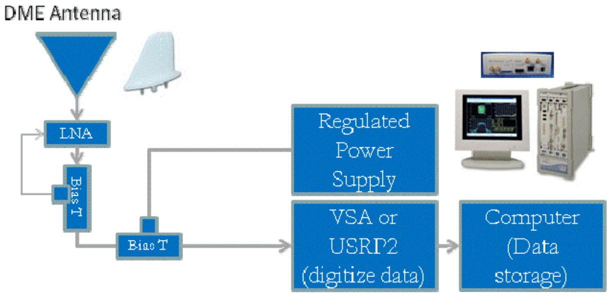

Figure 6. DME/TACAN Data Collection Set Up

Signal precision is determined by measuring the variation of the signal from a reference value. The transmission time cannot be used as it is not known. DME signals are random and not synchronized to coordinated time universal (UTC). Instead, a single difference os used to get the estimate of how well the signal time of arrival has been measured. One method is to take measurements using two, time synchronized receivers akin to GPS single differencing (spatial difference). Another method is to use the regular TACAN pulse pairs bursts to produce a time difference. The latter is used for most of the tests and is seen in the results.

TACAN MEASUREMENTS

A TACAN beacon, in addition to DME reply pulse pairs, also generates 900 additional pulse pairs each second to provide azimuth functionality. These pulse pairs come in two forms of bursts: 1) 15 Hz North burst which consists of 12 pulse pairs spaced every 30 µsec and 2) 135 Hz Auxiliary burst which consists of 6 pulse pairs spaced every 24 µsec [10]. These bursts are seen in Figure 7. Note that these bursts cannot be used for high accuracy ranging as our measurements indicate that their frequencies are not adequately controlled for that purpose.

The measurements are then processed to assess the signal precision. The processing identifies all peaks to identify pulse pairs peaks and the TACAN bursts. From the pulse pairs in the TACAN burst, the processing determines the time of arrival relative to the start of the data collection. The determination is based on traditional half amplitude processing which finds the pulse peak and calculates the half amplitude point. The half amplitude point is determined by either interpolation or using a Gaussian fit. Interpolation generally worked better. Note that while half amplitude processing is reasonably simple and straight-forward, greater accuracy can be achieved with other processing techniques [11]. An example of the identification of the TACAN bursts and accompanying measurement is seen in Figure 8.

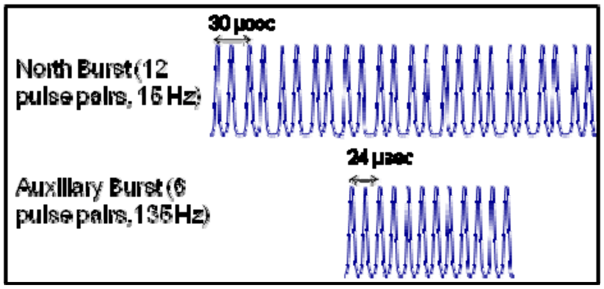

Figure 7. TACAN Pulse Pair Bursts

The difference between the arrival times of the first pulse of consecutive pairs is then calculated. Since these pulse pairs should nominally be 24 or 30 µsec apart, deviations from this value represents signal measurement error and beacon clock error. Given the short period, it is assumed that the beacon clock does not drift much and so all error is presumed to be due to signal measurement.

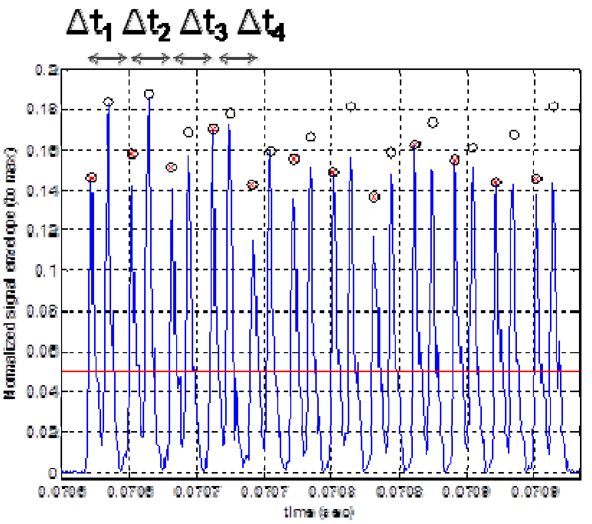

Figure 8. Single Difference with TACAN Bursts

SIGNAL IN SPACE ANALYSIS & RESULTS

From the processing, the precision (two standard deviations) when measuring a single signal (one pulse pair) was found to be about 24 m (80 ns) and 30 m (100 ns) for the 15 and 135 Hz bursts pulse pairs, respectively. When averaged over all pulse pairs in a burst, (11 and 5 differences for the 15 Hz and 135 Hz bursts), the results indicate a precision of 2.1 and 5.2 m meters, respectively. This averaged precision is lower by a factor of approximately 1/11th and 1/5th that of the single pulse pair value. If the averaging solely reduces the white noise, one would expect the precision to improve by the inverse square root of the number of pulses averaged.

The results can be applied to assess if DMPR has the accuracy at the limits of coverage. To support terminal area, the DMPR signal should meet accuracy requirements at least 30-50 nm from the beacon. Additionally, the DMPR user will have more pulse pairs to average. Even just the 150 synchronization ppps are used, given RE of about 70%, 100 of those should be received. The measurement results are extrapolated to greater distance using the standard inverse distance squared signal attenuation and Woodward's equation. Hence the extrapolated precision is proportional to distance. The additional pulse pairs are accounted for by modifying the results by the square root of 9.09 (100/11). The root reduction comes from assuming that the noise is uncorrelated and being averaged down. Table 3 shows the basic measurement result and the extrapolated precisions at different distances and with more pulse pairs. The results are encouraging and even receiving 11 pulse pairs seem adequate for meeting the targets. Additional validation is needed and measurements at more locations and distances will be conducted.

Table 3. Measured and Estimated DME/DMPR Signal Precision

Signal	Measured (distance from tx)	Estimated at 50 nm	Estimated at 100 nm
DME (11 pulse pairs)	2.1 m (at 5.6 nm)	18.6 m	37.1 m
DME (100 pp)	N/A	6.2 m	12.3 m

4. DATA TRANSMISSION ANALYSIS & DESIGN

Another goal of DMPR design is to be capable of providing data to support navigation, integrity and other benefits. The signal structure was designed to make the best use of the pulse pairs dedicated to DMPR in terms of data rate. Developing the best design given the 350 ppps to support data involves selecting the signal structure parameters that allows for maximum effective data rate. Additionally, the effective data rate depends on the amount of erasure and error correction needed to contend with DME operations.

The methodology to determine the design yields the best overall or effective data rate starts by calculating the raw data rate for each design. Modeling is then used to find effect of DME interference – specifically the erasure and error rate. An appropriate level of correction is applied to account for the interference and then the effective data rate, which is raw data rate minus data to correct for the effect of interference, is calculated. The design is optimized over different design parameters and factors.

DATA DESIGN

The signal structure design has several parameters in its trade space which affect data rate. First is the number of data segment. Since 350 ppps is dedicated to data and one pulse pair is used per segment, this value is taken as set. Second is the tolerance for deciding that a pulse pair has fallen into an accepted DMPR transmission time. The acceptance depends on achievable single pulse pair DMPR ranging accuracy. Values at or below 250 ns seem reasonable given the previous measurement results. Recall that single pulse pair accuracy is 80-100 ns but this is at close range (5.5 nm). Different acceptance tolerance levels lead to different interference rates and so sensitivity to this value is studied. The primary parameter that can be adjusted is the number of bits per segment which determines the number of acceptable DMPR start opportunities within a segment. For easier data encoding and decoding, the design is constrained to have an integer number of bits per segment. In developing the data design, the effect of changing this number on effective data rate is assessed to determine the best value given different traffic and tolerance levels. These three parameters are seen in Figure 9.

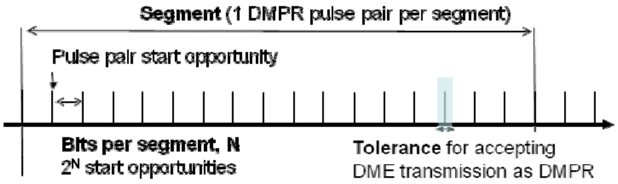

Figure 9. Segment Structure and Parameters Effecting Data Rate

Figure 10 shows some illustrative examples of signal structure design. The segment design shown on the top of the figure shows an example with 4 bits per segment (16 start opportunities) and uses 75 µsec between start opportunities. Each start opportunity represents a possible symbol with the figure showing the data bits that is encoded by the symbol. The spacing between start opportunities allows a DME beacon to transmit a reply at each opportunity. However, since only one DMPR pulse pair is transmitted per segment, the design does not have to ensure that a DMPR pulse pair can be sent from consecutive or even multiple start opportunities within the segment. The only concern occurs at the junction between two segments and the design must allow for a DMPR transmission on the last start opportunity of one segment and the first start opportunity of the next segment. Hence, only the first start opportunity needs to take place at least 75 µsec after the last start opportunity of the previous segment. This is seen in the bottom of the figure which has nearly the same segment length but provides 5 bits per symbol and spaces each start opportunity by 37.5 µsec with the one exception noted.

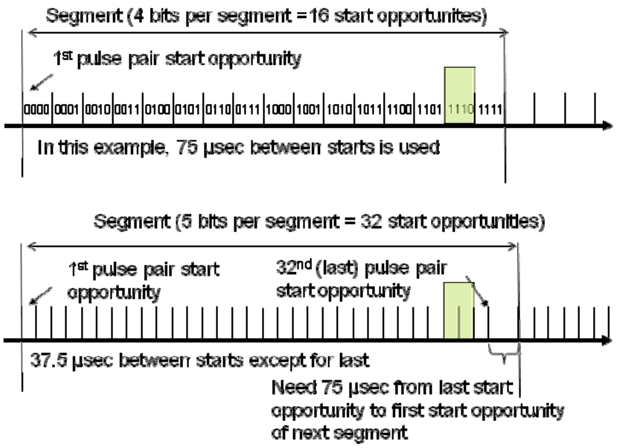

Figure 10. Illustrative Examples of Segment Structure Designs

ERASURES & ERRORS

Since DMPR will operate alongside DME, there is the possibility of interference from DME replies to aircraft and the corresponding dead time that follows. The dead time will prevents the DMPR ground interrogator from eliciting a broadcast from the DME beacon. This interference can result in erasures and errors in determining the DMPR symbol.

An erasure occurs when one cannot unambiguously decipher the correct symbol. There are three ways this can happen which is shown at the top of Figure 11. The first type occurs when there are no symbols found due to interference to the transmission of DMPR. The two other types occur when there are two or more acceptable symbols. The second type occurs when the DMPR transmission is sent but there is at least one DME reply that can also be interpreted as a DMPR transmission, albeit incorrect. This is due to having at least one DME reply fall within the acceptance tolerance of a DMPR start opportunity. The third type occurs when the DMPR transmission is possibly interfered with and two or more DME replies fall into acceptable DMPR start opportunities resulting in multiple incorrect symbols. As will be seen later, these erasure types are listed in order of decreasing likelihood. An error occurs when the correct DMPR transmission is interfered with and there is one DME reply that falls into an acceptable DMPR start opportunity. This is seen at the bottom of Figure 11. The DMPR correction scheme must protect against these possibilities and should be scaled to be appropriate the actual level of errors and erasures.

The amount of erasures and errors depend on several factors such as the acceptance tolerance, the number of interrogations (which corresponds to the number of DME replies and the signal structure design. Hence these effects of these factors are considered in the analysis.

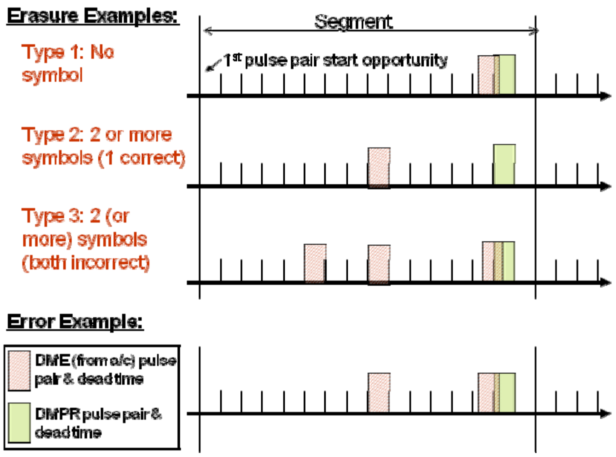

Figure 11. DMPR Symbol Interference from DME: Erasures and Errors

ANALYSIS METHODOLOGY

To develop the segment design, we must account for all these factors to determine the best design in terms of actual data received (post correction). For the analysis, different levels of bits per segment, tolerance (for sensitivity) and number of incoming interrogations are examined. These variations are used to conduct the analysis and simulations used to determine the expected error and erasure rates. Given the resultant error and erasure rates, the data bits needed for correction is determined. The rates are rounded up to the nearest half integer level. Two symbols are assumed to be necessary to correct for each symbol error and one symbol is needed to correct for each symbol erasure. The effective data rate is then calculated. From that the best level of bits per segment given tolerance and interrogation traffic level was determined

INTERFERENCE MODEL

Both analytic and simulation models are developed to determine the effect of acceptance tolerance, the number of interrogations and signal design on error and erasure rate.

The analytic model is developed by modeling the interaction between one DME and one DMPR transmission. This model is seen in Figure 12. Two basic probabilities are derived: 1) the probability of interference with DMPR and 2) the probability of a DME reply being (mis)interpreted as DMPR. The first is calculated by looking at overlap time relative to the overall time which is the likelihood of that DME reply cancelling out the DMPR signal and is seen in Equation 2. Based on the previous descriptions, a time of a pulse pair (t_{pp}) is 15 µsec, $t_{segment}$ is 2 ms and *deadtime* of 60 µsec is used for the analysis. Equation 3 shows this probability given that the interfering DME signal does not get interpreted as the DMPR signal (essentially replacing it). This equation includes the acceptance tolerance (*tol*) and various values for the factor are tested. The second probability is essentially the probability of a random DME signal falling into an acceptable DMPR start opportunity but not the actual start opportunity that the DMPR resides in. This is seen in Equation 4 with N_{bits} being the number of bits per segment. Equation 5 presents the probability when two start opportunities are excluded. From these basic probabilities, the probabilities for each type of erasure and error can be determined. Equations 6-8 show the probability of erasure for each of the three types mentioned while Equation 9 is the probability of error. Note that the effect of tolerance (*tol*) is explicitly seen in the derivations.

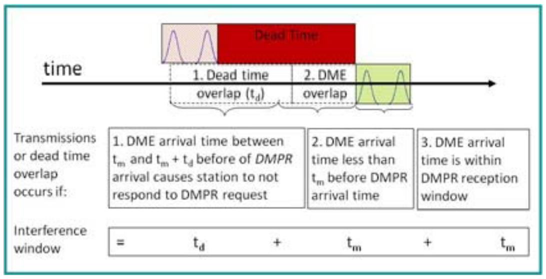

Figure 12. Basic Interference Model between one DMPR and DME pulse pair

$$P_{int} = \frac{\left(deadtime + 2t_{pp}\right)}{t_{segment}} \qquad (2)$$

$$P_{int,nosymbolerr} = \frac{\left(deadtime + 2t_{pp} - tol\right)}{t_{segment}} \qquad (3)$$

$$P_{symbolerr,1} = \frac{\left[\left(N_{bits} - 1\right) * 2 * tol\right]}{t_{segment}} \qquad (4)$$

$$P_{symbolerr,2} = \frac{\left[\left(N_{bits} - 2\right) * 2 * tol\right]}{t_{segment}} \qquad (5)$$

$$P_{erase,1} = N * P_{int,nosymbol} * \left(1 - \left[P_{symbolerr,2} + P_{int}\right]\right)^{N-1} \qquad (6)$$

$$P_{erase,2} = N * P_{symbolerr,1} * \left(1 - 2P_{int}\right)^{N-1} \qquad (7)$$

$$P_{erase,3} = \binom{N}{2} P_{symbolerr,1} * P_{symbolerr,2} * \left(1 - 2P_{int}\right)^{N-2} \qquad (8)$$

$$P_{err} = N * P_{int,nosymbolerr} * \left(N-1\right) * P_{symbolerr,1} * \left(1 - \left[2P_{int} + P_{symbolerr,2}\right]\right)^{N-2} \quad (9)$$

CALCULATED ERASURE & ERROR RATES

The Monte Carlo simulations (500 segments for 100 simulations) and the analytic model are conducted for different levels of interrogations per second into the DME into the DME beacon. Additionally, there are 500 interrogations for DMPR. These are not part of the count of aircraft interrogations. Figure 13 and Figure 14 shows the mean erasure and 99.5% (mean plus three standard deviations) probabilities of erasure for 6 bits per segment, respectively. The 99.5% value is more useful for setting the correction level than the mean as the level used should ensure that the data is receivable with high availability.

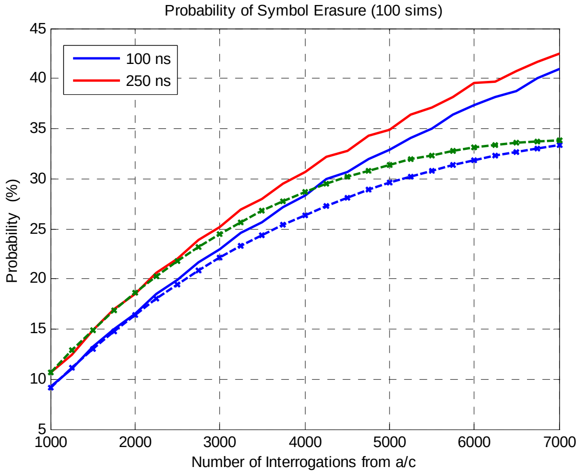

Figure 13. Mean Erasure Rate for 6 Bits per Segment

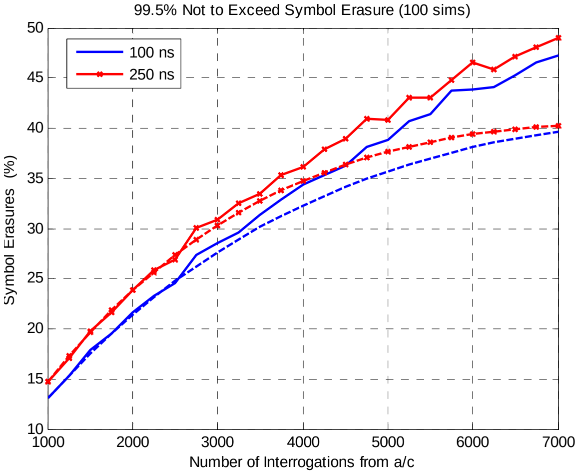

Figure 14. 99.5% (Mean + 3 Standard Deviation) Erasure Rate for 6 Bits per Segment

Figure 15 shows the break down the probability of erasures by type using the analytic model. From the figure, it is seen that most of the erasures come from interference with the DMPR transmission (type 1).

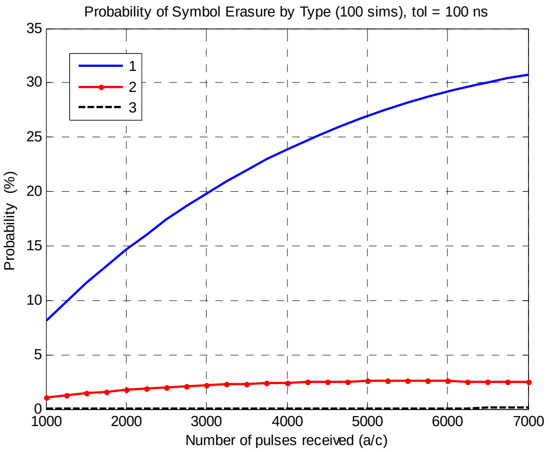

Figure 15. Mean Percentage of Each Erasure Type (1-3) for 6 Bits per Segment Case

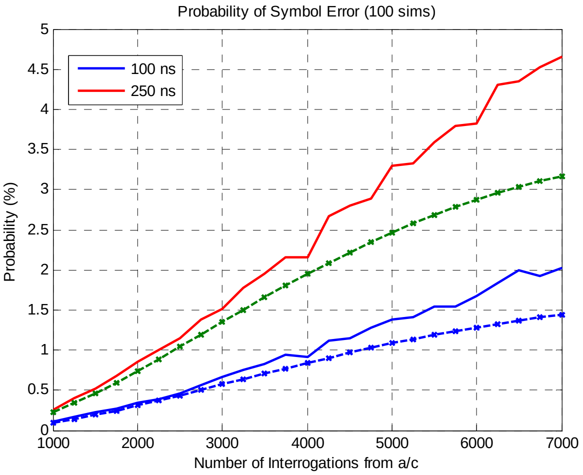

Figure 16. Mean Error Rate for 6 Bits per Segment

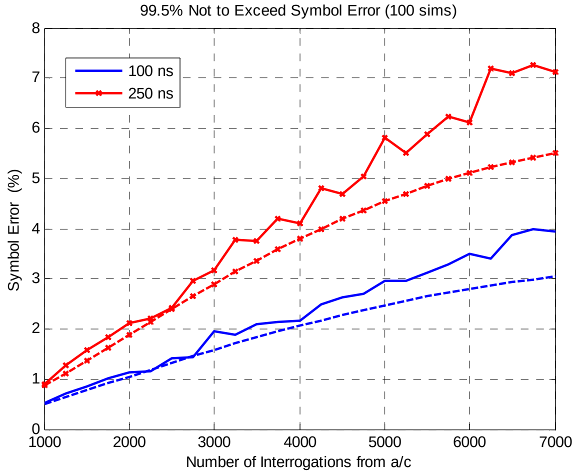

Figure 17. 99.5% (Mean + 3 Standard Deviation) Error Rate for 6 Bits per Segment

A similar result for errors is shown in Figure 16 and Figure 17 indicating the mean and 99.5% (mean plus three standard deviations) level for 6 bits per segment, respectively. Error levels are much lower than erasure levels. Also seen in the analysis is that as the number of bits per segment increases, the erasure and error rates also increase.

HIGHEST EFFECTIVE DATA RATE DESIGN

The results from different levels of bits per segment are then used to apply the appropriate levels of error and erasure correction. It is assumed that for erasure correction takes one symbol is needed to correct each erasure. This is consistent with technique such as fountain codes can be used for such a purpose. It is assumed that error correction takes two symbols to correct for each error. This is consistent with a technique such Reed Solomon forward error correction. The 99.5% level of erasure and error, rounded accordingly, is used to set the amount of corrections used.

From that, the effective data available at each level of bits per segment is calculated. Figure 18 shows some of the resultant curve. The solid blue and dashed red lines on each figure show the performance assuming 5000 and 7000 aircraft interrogations, respectively. DMPR adds 500 more interrogations. The left figure uses an acceptance tolerance of 100 ns while the right uses 250 ns. The results consistently show that 6 bits per segment yielded the highest effective data rates. While the effective data rates seen vary depending on assumptions on interrogations and tolerance, 900 bps seems like an achievable target. The worst case seen in below is about 650 bps.

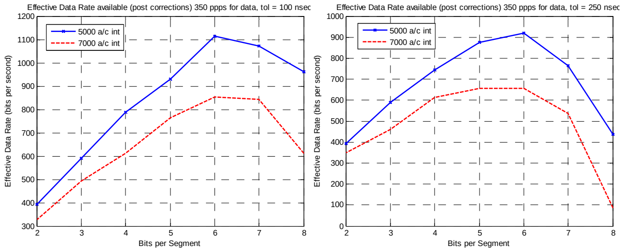

Figure 18. Effective Data Rate vs. Bits Per Segment: 100 ns (Left) and 250 ns (Right) Acceptance Tolerance

5. OTHER CONSIDERATIONS

Another consideration of DMPR design is how it can operate during the transmission of the DME Morse code. The DME Morse code is sent every 40 seconds and allows for an audible identification of the DME beacon identity. It comes in the form of sequence of pulse pairs sent at 1350 Hz that spell out the three of four character station identifier in Morse code. A dot typically lasts 0.1 (up to 0.16) seconds while a dash last three times longer [1]. However, unlike during a TACAN burst, the DME beacon is not responsive during that time period which results in DMPR not being transmitted. The only time available for replies is in between transmissions of the dots and dashes. Dots and dashes within the same character are separated 0.1 seconds by while two Morse code characters are separated by 0.3 seconds [12]. DME Morse code is seen in Figure 19 with the dot and dash period showing the regular Morse code pulse pairs and the time in between showing random pulse pairs transmission.

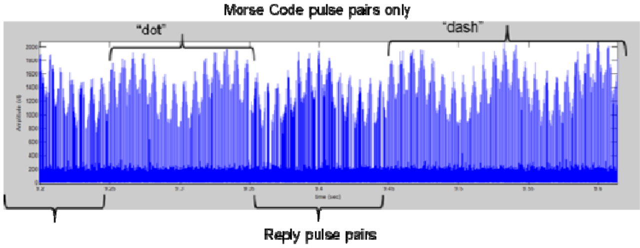

Figure 19. Morse Code Measured in Providence, RI

DMPR design needs to operate during the Morse code transmission period. This is important as the Morse code may last up to 6.5 or 10 seconds in the worst case as determined using on actual longest four character sequence or specifications. One implementation of DMPR to handle DME Morse code transmissions is to have a short 25 segments (50 ms) synchronization that would start every 1/20th of a second. This guarantees that one such synchronization sequence segment will exist in between each Morse code dot or dash even if the Morse code is not synchronized to the DMPR second. Short synchronization and data transmission, say 25 and 100 segments respectively over 250 ms may be sent starting on the nearest 1/20th of a second between Morse code characters and provide synchronization and essential data such as navigation and authentication information.

6. CONCLUSIONS

This paper develops a passive ranging system, DMPR, based on the existing DME signals and transmitters that may be suitable for APNT goals. The system leverages existing DME equipment, signals and operations and is designed to work alongside current DME beacons with low impact. DMPR, like other passive ranging system, requires accurate time synchronization. It also requires an additional station for positioning when compared to DME.

This paper designs and assesses the DMPR signals structure to support APNT accuracy and data targets. DMPR accuracy based on measurement results meet targeted levels. The measurements taken from a distance of 5.5 nm to the Woodside, CA TACAN beacon shows a signal measurement precision of 2 meters (2 standard deviations). Analysis based on this result indicates a precision of approximately 12 m at 100 nm when using 100 pulse pairs. More measurements are needed to validate the performance at different distances and with different beacon types. Results so far give a positive indication of DMPR accuracy for APNT. The signal structure design and optimization shows that DMPR can provide data rates around those desired by APNT. It provides at least 650 bps under some of the worst assumptions. The best design uses 6 bits per segment and accounts for erasure and error correction. The signal structure also can be made to function during the Morse code transmission period of today's DME beacon.

There are still many challenges to the use of DMPR. A major challenge is providing low cost avionics as DMPR needs to serve the most cost sensitive users who cannot afford DME/DME/IRU. Being able to transmit the DMPR signal on one frequency from all beacons will enable simpler and, hopefully, lower cost equipment. Another challenge is to mitigate the increased geometry requirement for DMPR relative to DME by using mixed ranging from both DME and DMPR. A challenge applicable to both DMPR and DME is mitigating multipath. The APNT team is studying how to address these challenges.

ACKNOWLEDGMENTS

The authors would like to thank the FAA Navigation Services Directorate for supporting this work. We would also like to acknowledge the rest of the APNT Team for their inputs. We would also like to acknowledge Prof. Peter Swaszek, Grant Wyman and Simon Barr from the University of Rhode Island for the data showing DME Morse code.

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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