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ALTERNATIVE POSITIONING, NAVIGATION & TIMING (PNT) STUDY

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SUMMARY

This flimsy was developed to document the work being accomplished by the FAA to assess alternatives for providing PNT services when GNSS is not available due to RFI.

Purpose

This paper will summarize the scope and initial results of an alternative analysis being performed by the Federal Aviation Administration (FAA), Navigation Services Directorate to assess various Non-GNSS navigation system architectures to provide alternate positioning, navigation, and timing (APNT) services for aviation users in the US National Airspace System (NAS) to mitigate for the vulnerability of GNSS to radio frequency interference (RFI).

APNT Mission Statement

According to U.S. National Policy, the FAA needs to provide an Alternative Positioning Navigation and Timing (APNT) service to maintain safety, and minimize economic impacts from GNSS interference outages within the national airspace system (NAS). APNT is assumed to be provided for aircraft flying under Instrument Flight Rules (IFR). Aircraft flying under Visual Flight Rules (VFR) may use APNT for navigation, but are not considered in this analysis.

Background

The United States is pursuing an air traffic modernization program, referred to as the Next Generation Air Transportation System (NextGen), to support a predicted increase in operations by a factor of 2-3 times by 2025. Many of the operation improvements necessary to meet the predicted capacity and efficiency improvements are dependent on widespread use of PNT services provided by global navigation satellite system (GNSS). GNSS provides PNT services utilizing the global positioning system (GPS) along with satellite-based augmentation systems (SBAS), and ground-based augmentation system (GBAS) are expected to be the primary enablers of performance-based navigation (PBN) and dependent surveillance (ADS-B) services that in turn enable trajectory-based operations, area navigation (RNAV), required navigation performance (RNP), precision approach, closely spaced parallel operations (CSPO), and other operational improvements. As NextGen modernization and implementation progresses, the U.S. NAS dependence on GNSS services will increase and therefore appropriate mitigations for the vulnerability of GNSS to RFI also must be assessed and implemented where necessary.

Current APNT Infrastructure

The FAA currently relies on the legacy VHF omni-directional radio (VOR), Non-directional radio beacon (NDB) and distance measuring equipment (DME) to provide alternative PNT service to GNSS even though the GNSS services were originally intended to replace the legacy navigation systems. The VOR and NDB systems support point-to-point navigation, but are not compatible with PBN operations for RNAV and RNP. Currently, the majority of Air Carriers do not use the VORs for approach and most are equipped to fly the VOR/NDB-based routes using RNAV enabled by GPS. Flight management systems (FMS) use multiple DMEs to provide a position solution suitable for RNAV enroute and terminal operations at busy airports. However, most general aviation aircraft are not equipped with DME or inertial and therefore rely on the

VORs and NDBs for alternate positioning. The VORs and NDBs are very old and either need to be replaced at a significant cost or a suitable alternative approach needs to be identified to avoid unnecessary investment in legacy systems that are not compatible with NextGen.

APNT Assumptions

The APNT study group established the following set of assumptions to guide the analysis activity.

1. In 2025, there will be "RNAV and RNP where beneficial". It is recognized that there will likely be many different variants of RNAV and RNP that are yet to be defined.
2. Alternative PNT (APNT) is a means to continue RNAV and RNP operations to a safe landing during periods when it is discovered that GNSS services are unavailable, due to interference.
3. Users equipped for APNT will be able to continue conducting RNAV and RNP operations (dispatch, departure, cruise, arrival) during the GNSS outage after the transition to APNT.
4. Users not equipped for APNT may not be able to continue RNAV and RNP operations (dispatch, departure, cruise, arrival) in areas where GNSS is required during the GNSS outage.
5. APNT must provide RNAV or RNP 2 en route, between RNAV or RNP 1.0 to 0.3 for terminal Class B and C airspace, LNAV or RNP 0.3 for approaches, and RNAV or RNP 1 for missed approach, where economically beneficial or required for safety.
6. APNT service volume consists of the conterminous 48 states. Altitude of coverage includes FL 600 down to 5,000 feet AGL, and sufficient coverage to support RNP-0.3 approaches wherever required for safety or economically justified.
7. ADS-B Out will be mandated by 2020 anywhere a transponder is required today.
8. APNT services will provide backup positioning to support 3nm separation in terminal area operations for dependent surveillance, wherever required for safety or economically justified.
9. APNT will provide backup timing services for CNS and other aviation applications.

10. APNT will ensure backward compatibility for existing DME and DME/DME users. Based on current plans, DME will be provided RNP 2 above FL 180 and RNP 1 at all OEP airports.

11. APNT service performance may not be equivalent to GPS performance (coverage, accuracy, integrity, availability, continuity).

12. At least one Instrument Landing System (ILS) will be retained at airports wherever required for safety or economically justified.

13. APNT supports position reporting for conformance monitoring for security.

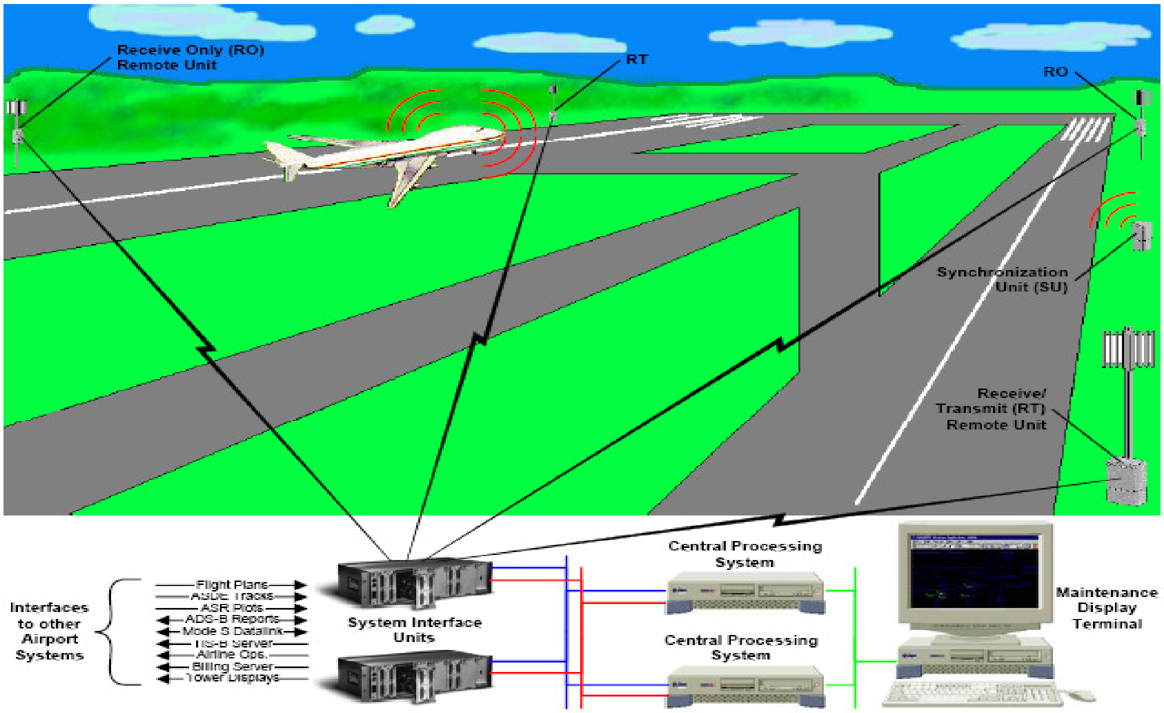
APNT Analysis Objectives

- Provide a Cost Effective Alternative PNT service that Enables Performance Based Navigation (PBN) RNAV and RNP for enroute, terminal, and non-precision approach operations equivalent to RNP-0.3
- Provide service for all users (GA, Business, Regional, Air Carrier)
- Minimize Impact on User Avionics Equipage by Leveraging existing or planned equipage upgrades as much as possible
- Minimize need for multiple avionics updates for users
- Ensure Backward compatibility for Legacy DME-DME Users
- Provide long lead transition time (Circa 2020 transition)
- Avoids Recapitalization Costs for VORs - ~$1.0B
- Disestablish all VORs and NDBs by 2025

APNT Alternatives

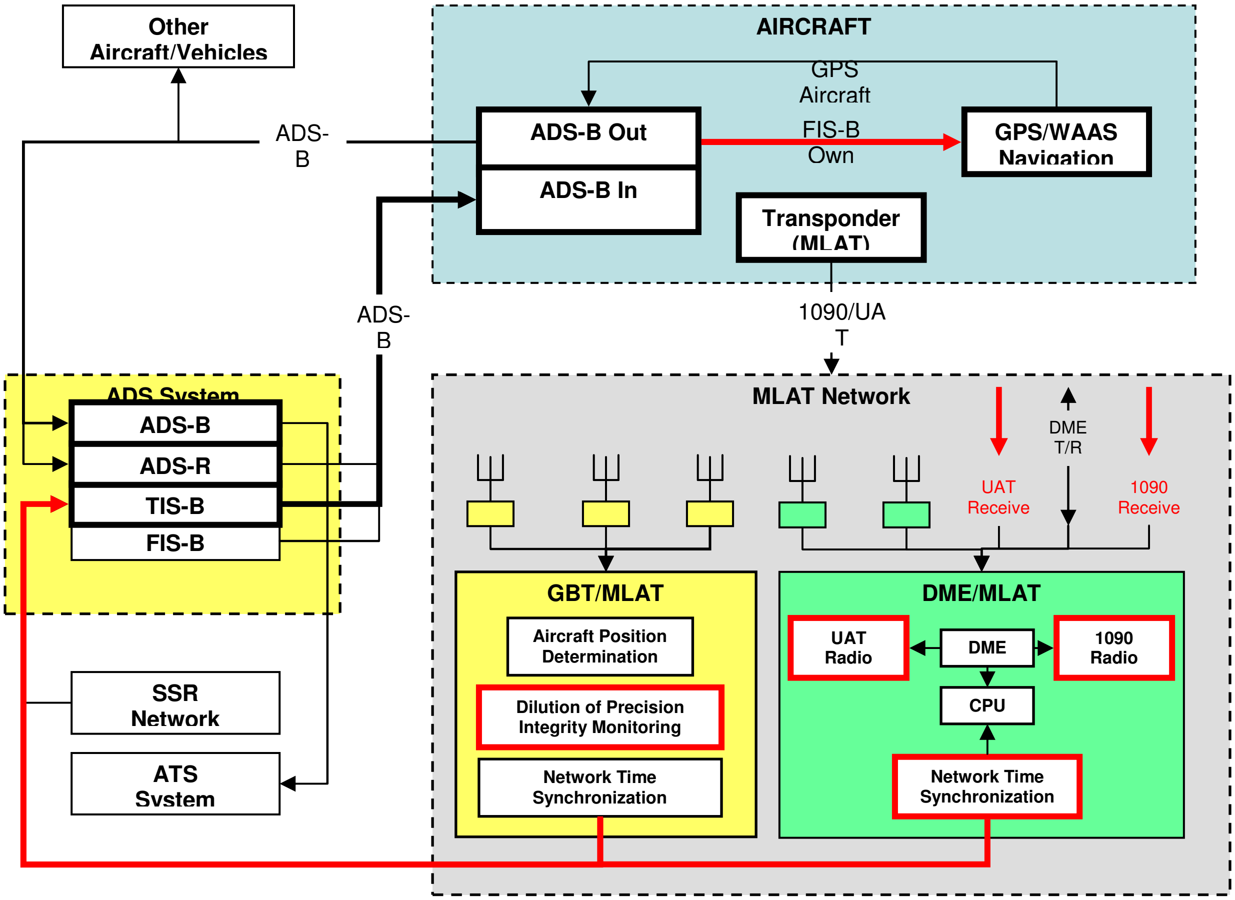
Three architectures were selected for further consideration: Passive Wide-area Multi-lateration, Pseudolite-based multi-lateration, and optimized DME-DME. All of the alternatives seek to leverage the existing DME facilities, which have exceeded their design life and require recapitalization.

Passive Wide-Area Multi-lateration (WAM)



Passive wide area multi-lateration systems are in use today to provide aircraft position for air traffic control is areas where sufficient radar surveillance coverage is lacking. WAM systems consist of multiple receive antennas that listen to replies from the aircraft transponder to compute ranges that are forwarded to a processing facility where the aircraft position is computed. The WAM forwards the aircraft position to the air traffic control system where it is used to provide a target on the controllers display for surveillance purposes. Analysis of this architecture will focus on adapting WAM to compute aircraft positions with integrity and then uplink this information to the aircraft for use as an alternate positioning source for navigation. The WAM alternative would leverage all of the existing 1100 DME facilities plus the planned ADS-B ground-based transmitter (GBT) facilities to provide a combined network of approximately 1900 sites.

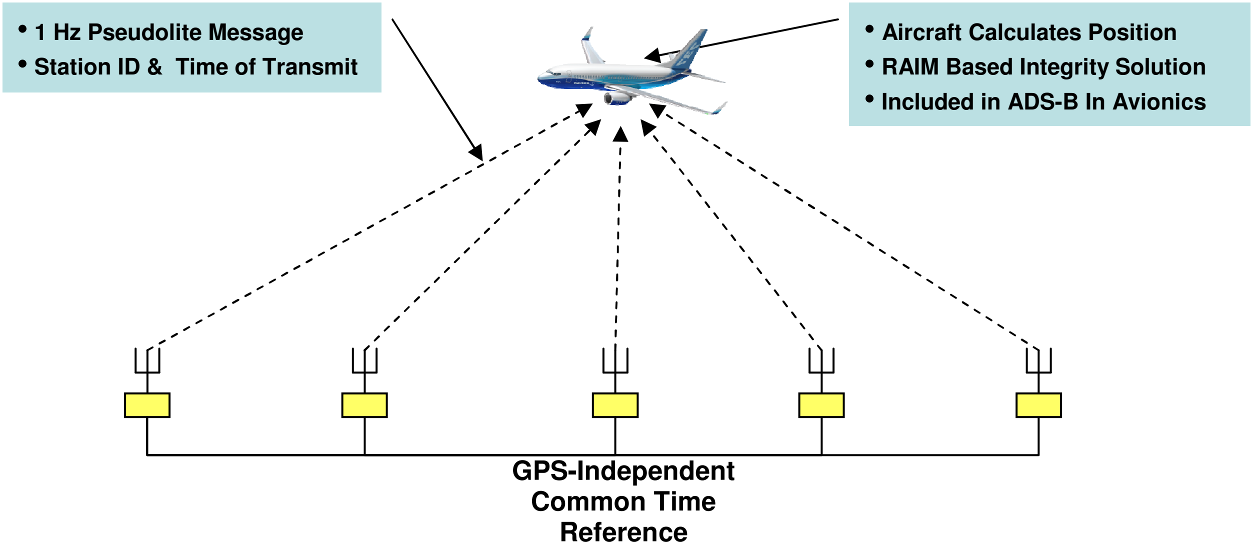
MLAT Alternative Block Diagram



The WAM architecture relies on ADS-B infrastructure and DME facilities. The DME and GBT facilities would be modified to listen to the aircraft transponder replies and forward the ranges over a terrestrial network to processing facilities where aircraft position and integrity would be computed based on a common time reference, and then forwarded to the aircraft over the TIS-B broadcast via the 1090ES and UAT data-links. A new interface from the ADS-B avionics to the navigation avionics would be needed to pass the aircraft position to the navigation function.

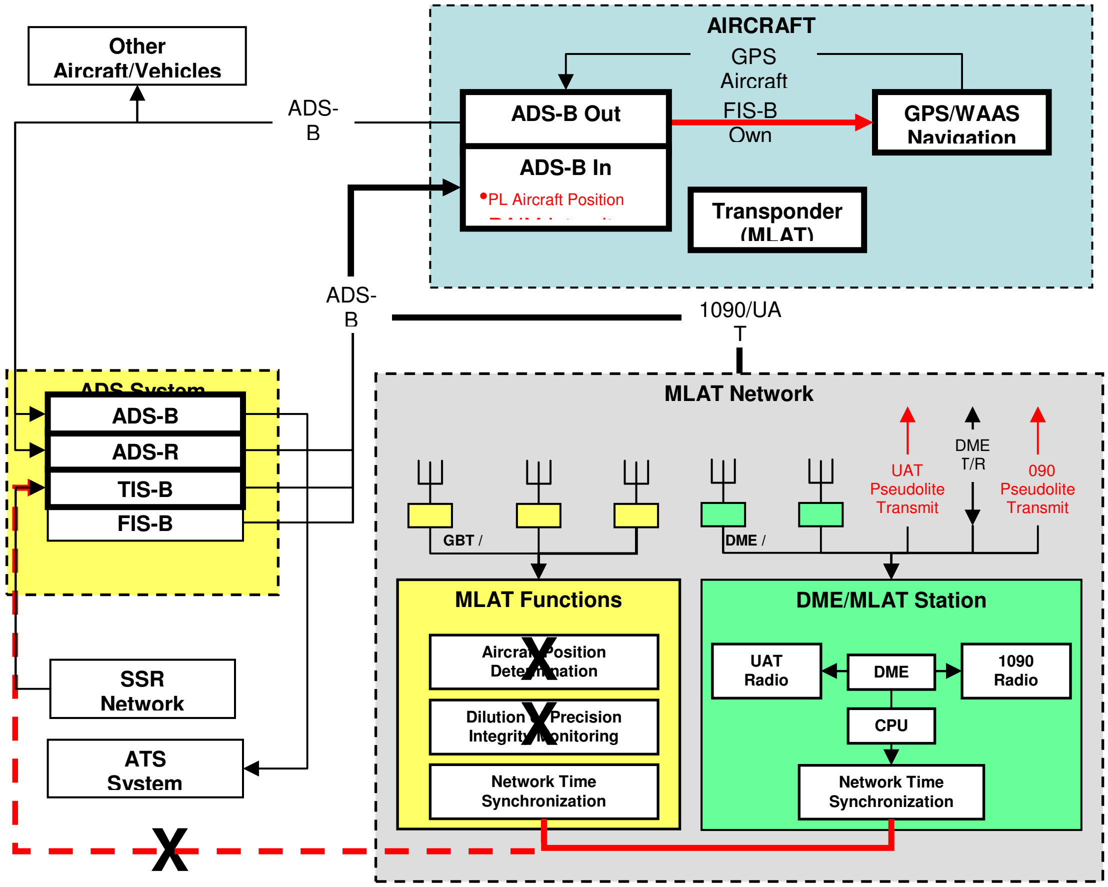
The advantage of the WAM alternative is that there are minimal changes to the user avionics and use of a relatively mature technology. However WAM will likely require a high reliability terrestrial network, a Non-GNSS time reference, may have difficulty meeting time to alarm, availability, and may require complex integrity monitoring algorithms to provide sufficient protection from hazardously misleading information (HMI) reaching the aircraft. Other issues are the density of MLAT stations that are needed to satisfy the performance and coverage requirements; and the threat/susceptibility to jamming and spoofing of the TIS-B messages. In addition, there may be capacity issues of overloading TIS-B and/or the 1090ES channel.

Pseudolite-Based Multi-lateration



The Pseudolite (PL) architecture reverses the flow of the WAM architecture and allocates the position and integrity functions to the aircraft similar to how GPS receiver autonomous integrity monitoring (RAIM) works. The Pseudolite alternative would leverage all of the existing 1100 DME facilities plus the planned ADS-B ground-based transmitter (GBT) facilities to provide a combined network of approximately 1900 sites.

DME/GBT Pseudolite Alternative Block Diagram



The PL architecture requires the GBT and DME sites to be synchronized to a common time standard so each facility can generate and transmit a "heartbeat" message consisting of the station identification and an accurate time stamp. The ADS-B in avionics would host the position calculation and integrity monitoring functions and pass this information to the aircraft navigation over a new interface, if GPS becomes unavailable.

The potential advantages of this alternative include a simpler architecture that does not require ground based aircraft position/integrity computation or a high reliability network. A common Non-GNSS time reference is required.

Straw Man Signal Design for DME Pseudolites

In this section, we propose a straw man signal design for the broadcast of one-way ranging signals from existing DME transmitters. Our goal is not to provide a final design for such a signal. We recognize that many modifications and improvements will be required to bring such a function to fruition. Rather, we offer this early proposal as a catalyst for the community, and hope that it will serve as a starting point for a vigorous discussion on this critical topic.

The signal design, described herein, is directed at the following goals.

1. The new signals should be added to the existing broadcast from operational DME beacons without significant degradation to the two-way ranging accuracy provided by the DME beacon to legacy users. The new signals would overlay the existing replies that complete the traditional two-way DME transactions. More specifically, they could be implemented by triggering the existing beacon with requests from a "pseudo-aircraft" located nearby the operational DME beacon. Thus, we hope to avoid any changes to existing ground hardware and by so doing realize benefit from the entire set of DME beacons in operation today.
2. The new signals should provide one-way ranging to modified avionics. In other words, we do not wish to modify the ground equipment, but do recognize that one-way ranging from a DME station will require new avionics.
3. In addition to one-way ranging, the new signals should also support a modest data capability. This data would include the DME location, DME identification, time information and a parity field to ensure data integrity. We target a data capacity of around 150 bits per second (bps), because similar capacity has served well for other one-way ranging systems such as GNSS and SBAS.
4. Finally, the new signal should also enable source authentication. We feel that signal authentication is needed, because radio navigation may be subject to electromagnetic attack in the decades ahead.

Our straw man signal design is depicted in Figures 1 through 9.

Figure 1 defines the most microscopic aspect of our signal design. Following the spread spectrum literature, this atomic signal element is called a “chip.” Note that this chip includes the traditional pulse pair generated by the beacon responding to a request. It also includes the beacon recovery time. Inclusive of the recovery time, this chip has duration of approximately 75 microseconds. In the figures that follow, this chip will be shown as a rectangle. The average time between such chips will be the inverse of the average chip repetition rate (chipping rate). Indeed, these chips shall not be sent periodically, but will be sent at pseudorandom times. They will be characterized by an average chipping rate.

Figure 1: Definition of a DME “Chip”

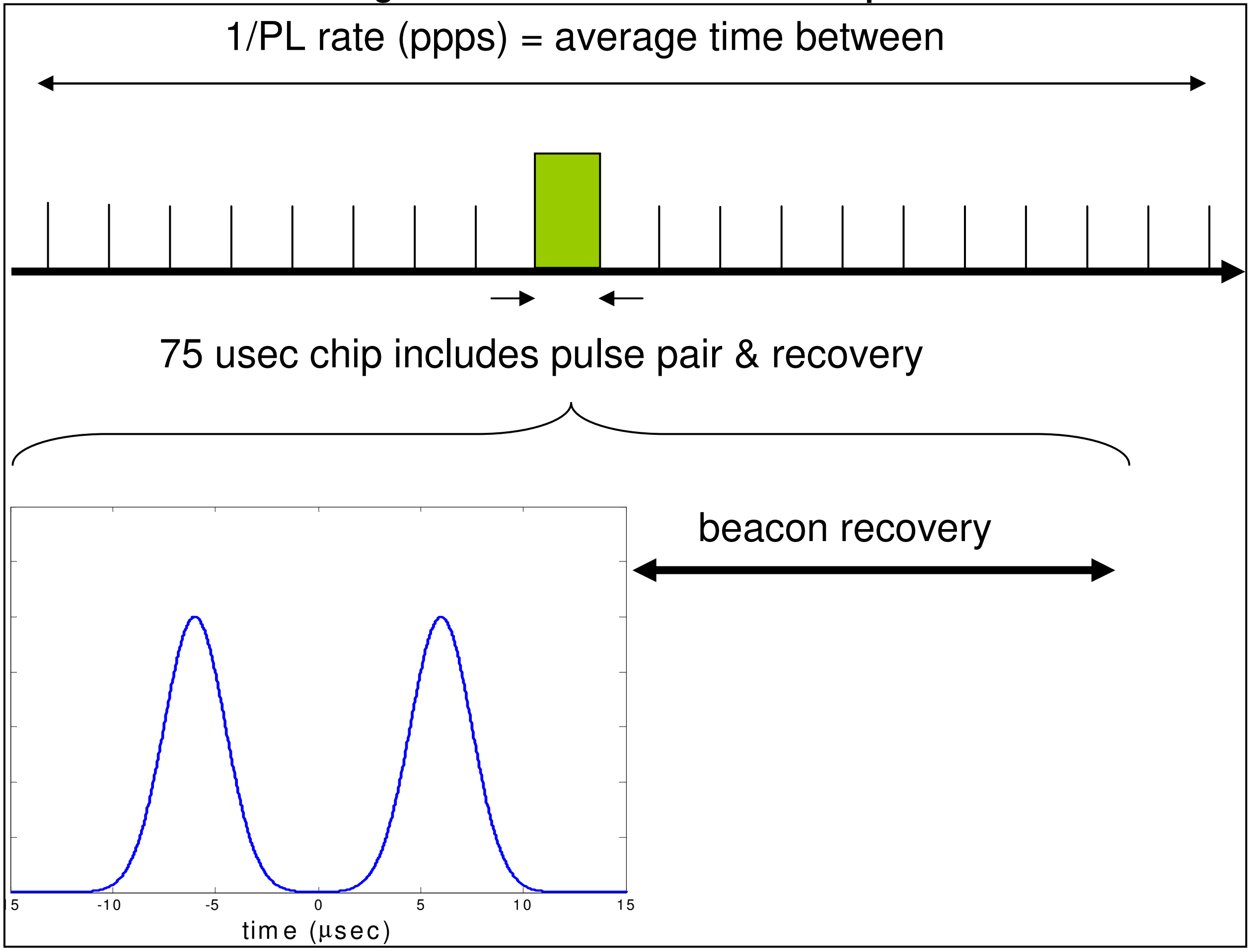
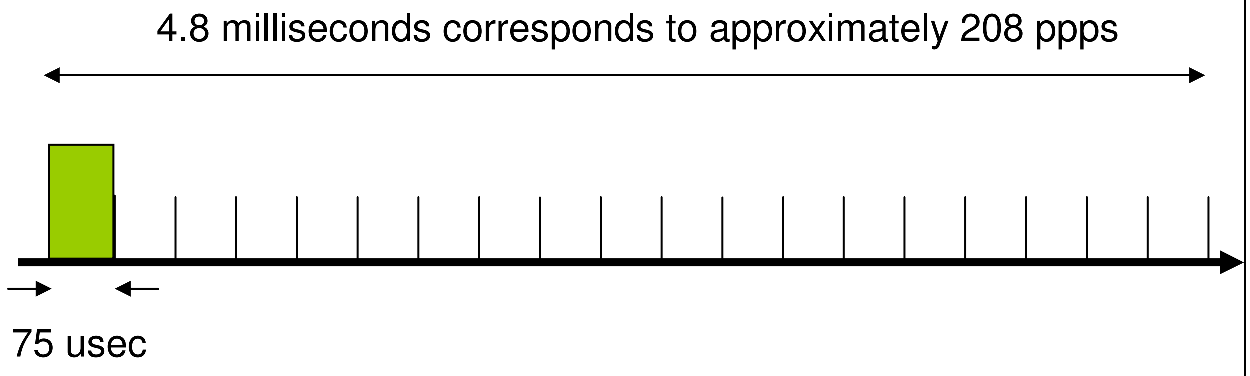


Figure 2 connects the average chipping rate to our wish to do no harm to the existing DME function. As shown, we tentatively recommend a chipping rate of approximately 200 chips per second (cps). In DME language, we wish to dedicate approximately 200 pulse pairs per second (ppps) to the one-way pseudolite function. To simplify our later analysis, we adjust this value to 208 cps or ppps. We feel that this is a likely value for the chipping rate for two reasons. First, we note that an aircraft attempting to acquire the DME signal requests approximately 150 ppps. Thus our new signal could be regarded as one slightly greedy aircraft trying to acquire a DME transaction. Second, we note that fractional occupancy of the DME output will be approximately 1.5%, because we broadcast 208 chips per second and each chip has a duration of 75 microseconds. In general, systems that use time domain random access to provide multiple access to a radio channel do not saturate until the fractional occupancy approaches 30%.

Figure 2: Do-no-harm Criterion



Fractional occupancy (4.8 ms for PL)

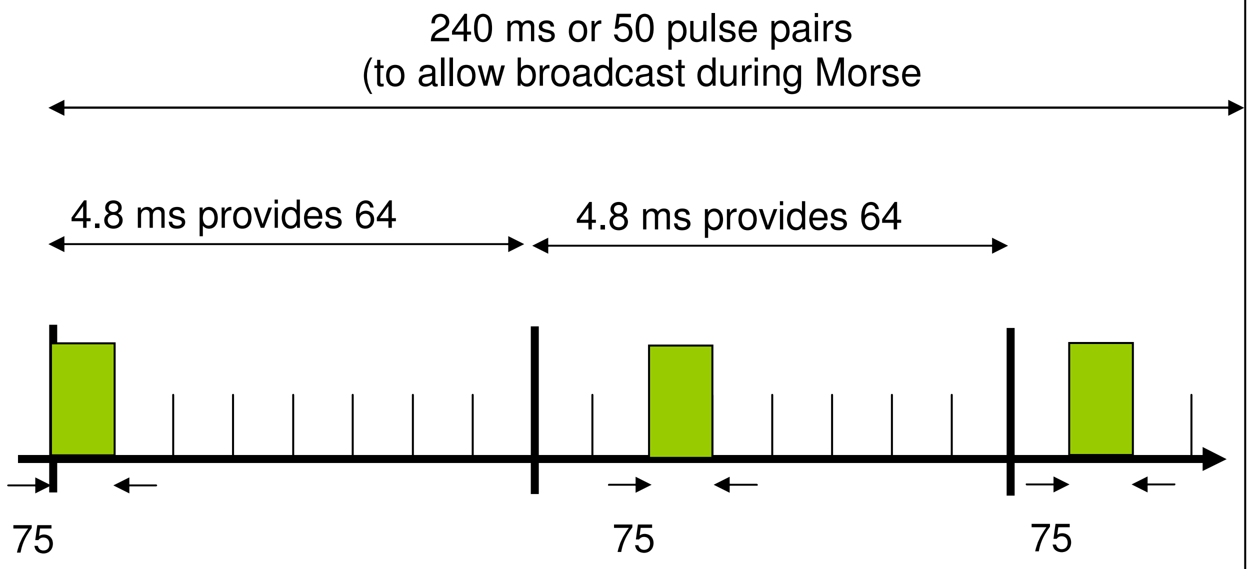
$$\frac{75\times10^{-6}}{4.8\times10^{-3}}=0.015625\times10^{-3}\approx1.5\%$$

Random access enables 30% occupancy

Also, 208 ppps is equivalent to one
(slightly greedy) aircraft during DME signal acquisition.

Figure 3 sketches the synchronization sequence to be broadcast as part of our proposed DME one-way signal. This is a time-hopping sequence with chips sent on a fixed schedule. Given that we wish to send approximately 208 ppps, the average time between pulses is 4.8 ms, which means that there are 64 possible time slots for each chip. Each DME would have a pseudorandom time hopping sequence, and the aircraft would search for this DME specific pattern. This pattern would be chosen to facilitate this search. In the language of spread spectrum radio, the pattern would be chosen to yield a auto-correlation function with a sharp peak. With such a property, the avionics would have little difficulty locking a replica code to the one-way signal from the DME. Once locked, each one-way signal would provide one pseudorange measurement. Three such measurements would allow the aircraft to estimate its latitude, longitude and clock offset relative to the DME system time. The distribution of time across the DME network is the subject for a later paper.

Figure 3: Synchronization Sequence

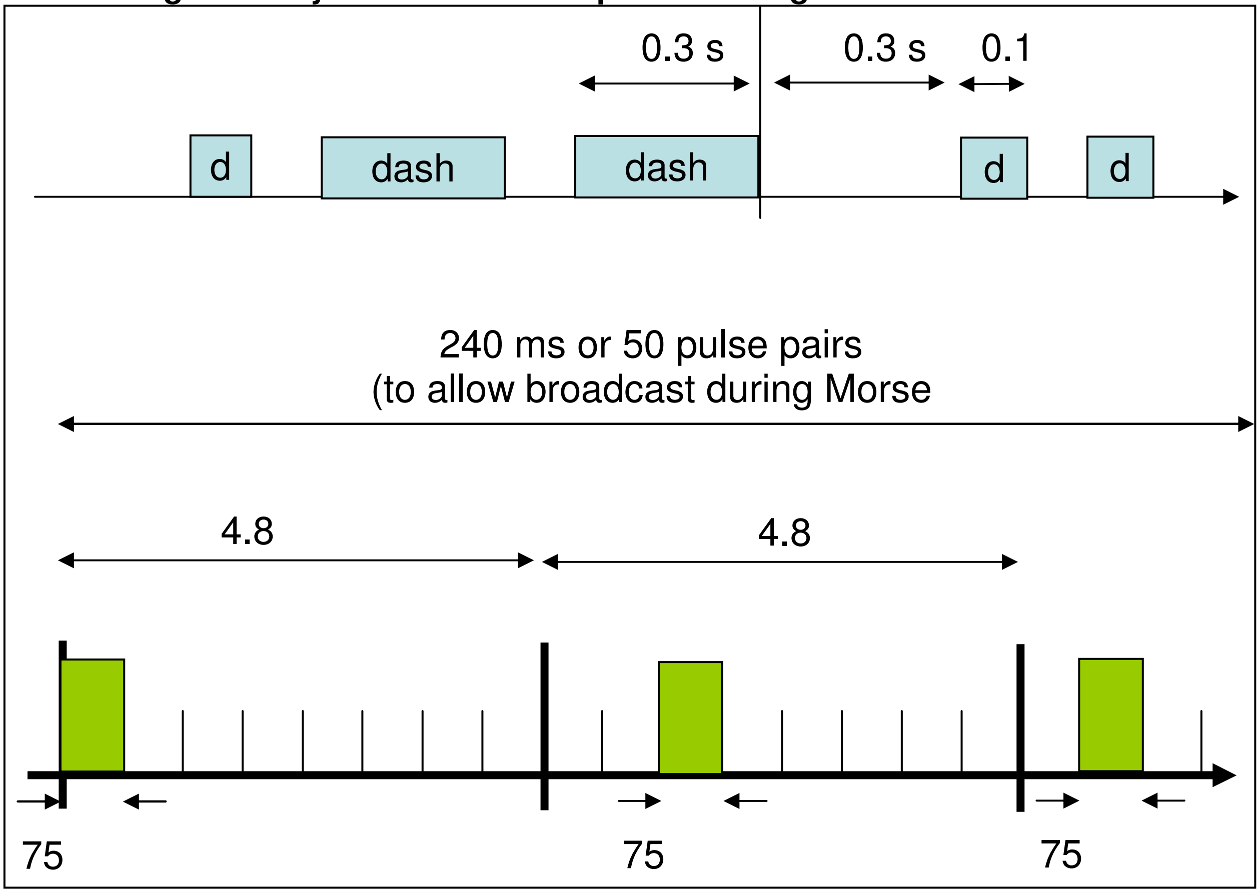


Slot boundaries may have additional dither beyond n75 usec to whiten spectrum.

Slots chosen based on spread spectrum codes to enable near optimum auto-correlation function.

Figure 4 addresses the duration of the synchronization sequence. We propose a relatively short sequence of only 50 pulse pairs which gives a duration of 240 ms (50 chips times an average spacing of 4.8 ms). We prefer this short length, because such a sequence could be transmitted in the intervals between characters in the DME Morse identification. Indeed, the characters are separated by 300 ms, and so the synchronization sequence could usually be completed in this short window of time.

Figure 4: Synchronization Sequence During Morse Identification



The synchronization pattern described above would be broadcast during the Morse identification period and approximately half the time during the normal un-keyed DME broadcast. A data carrying pattern would be broadcast during the other half of the time. Indeed, the data capacity would be 6 symbols per chip (or pulse pair), because the chips can occupy any of 64 time slots. Figure 5 depicts this data carrying pattern. For the synchronization pattern, the chips are placed in fixed time slots associated with each DME. For the data-carrying pattern, the chips are not placed in fixed time slots. The chip position is modulated to carry time-varying data. The data capacity can also be expressed as symbols per unit time. In this case, the data capacity is 1248 symbols per second (208 ppps times 6 symbols per pulse pair). Importantly this quantity is akin to "baud" not "bits per second," because we will need redundancy to compensate for erasures and errors introduced by the channel traffic devoted to the legacy DME function.

Figure 5: Data Field

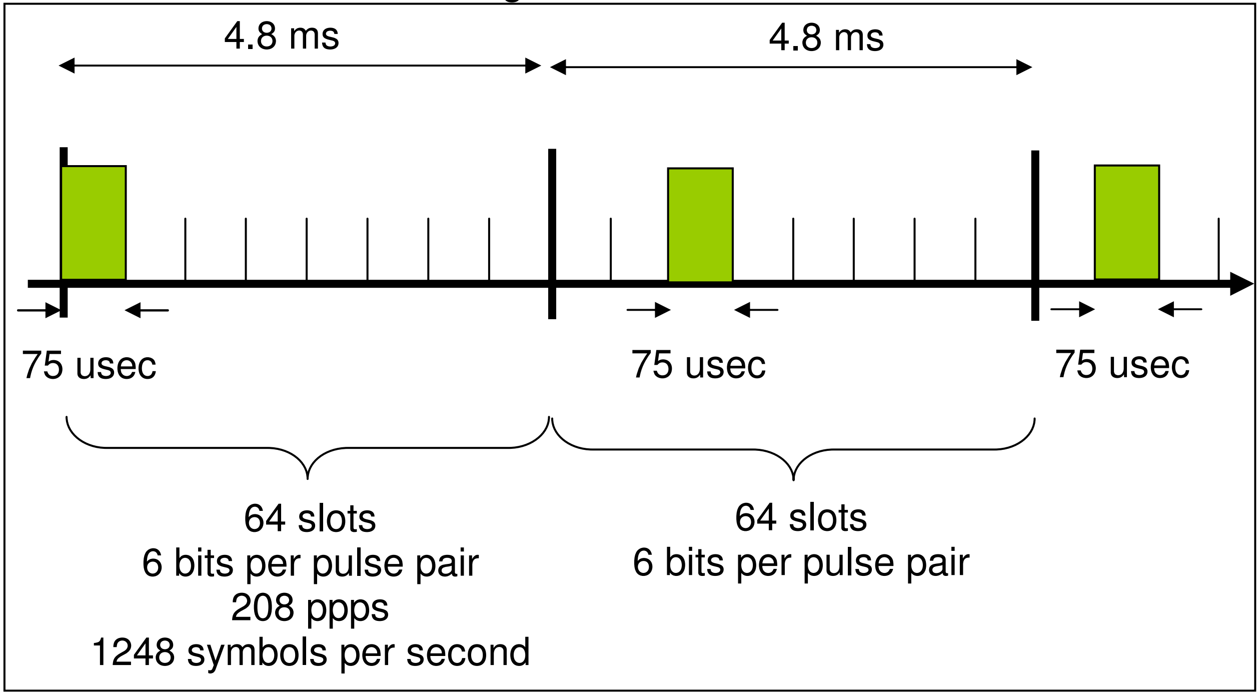
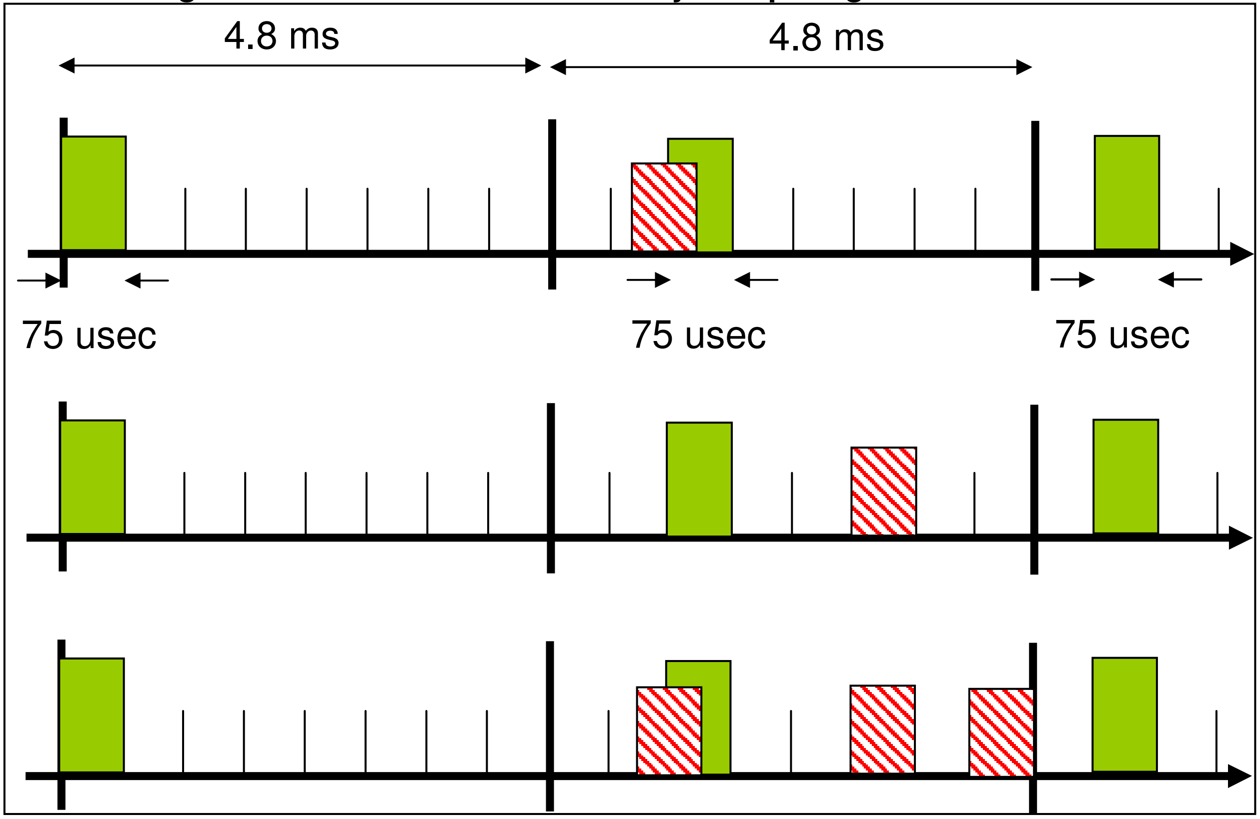


Figure 6 shows so-called “erasures” and begins our analysis of the data-carrying function. Erasures are data symbols destroyed by legacy users. As shown, at least three mechanisms exist to erase our new data symbols. In the top trace, a legacy response occurs immediately prior to our desired data slot, and so our symbol is erased. Importantly the synchronized avionics recognizes that no chip occurs during any of the allowed time slots for data, and so the legacy pulse is not mis-interpreted as data, but does erase our intended data pulse. In the middle trace, our new data symbol does occur on schedule, but a legacy pulse also occurs in one of our allowed time slots. Faced with two allowable data pulses, the avionics can only erase the symbol. In the bottom trace, the intended pulse is blocked by a legacy pulse, and two (or more) legacy pulses occur. Once again, the avionics must concede an erasure.

Figure 6: Data Erasures Caused by Competing Channel Traffic

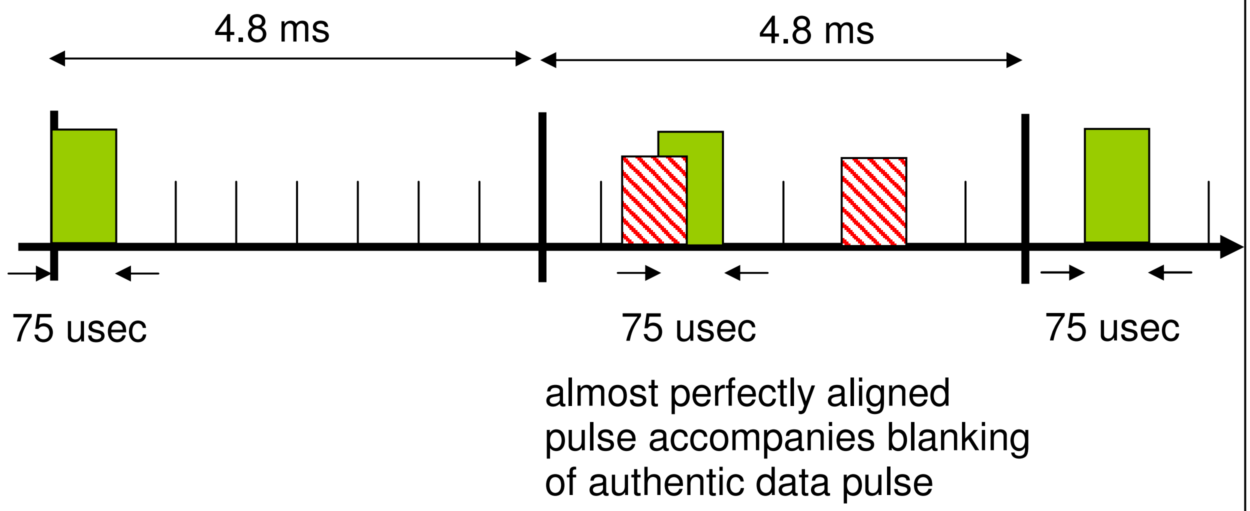


In contrast to Figure 6, Figure 7 shows the situation that would give rise to a data error. In this case, the intended pulse is blocked by a legacy response and a second legacy pulse occurs precisely aligned with a time slot allowed for data.

Fortunately, data erasures will occur much more frequently than data errors. Thus, we propose the use of a very strong fountain code to compensate for erasures, and a more modest Reed Solomon code to compensate for errors. The fountain code introduces 8 symbols for each data bit to be transmitted. In other words, we propose a rate 1/8 fountain code to cure erasures, which means that 7 redundant symbols are broadcast for each intended data bit. The Reed Solomon code is included to correct the data errors suggested by Figure 7. It only introduces one redundant symbol for every seven data symbols. As such, it is a rate 7/8 code.

As shown at the bottom of Figure 7, the net data rate is approximately 136 bits per second (208 ppps times 6 symbols per pulse pair times 1/8 times 7/8). This data rate seems well suited for radio navigation given that GNSS and SBAS both support data rates in this realm.

Figure 7: Data Errors Caused by Competing Channel Traffic



Data erasures

- very common
- Fountain code with 8:1 redundancy

Data errors

- very rare
- Reed Solomon forward error correction of 8:7 redundancy

Resulting data rate: 208 ppps x 6 bits/pp x 1/8 x 7/8
approximately 136 bps

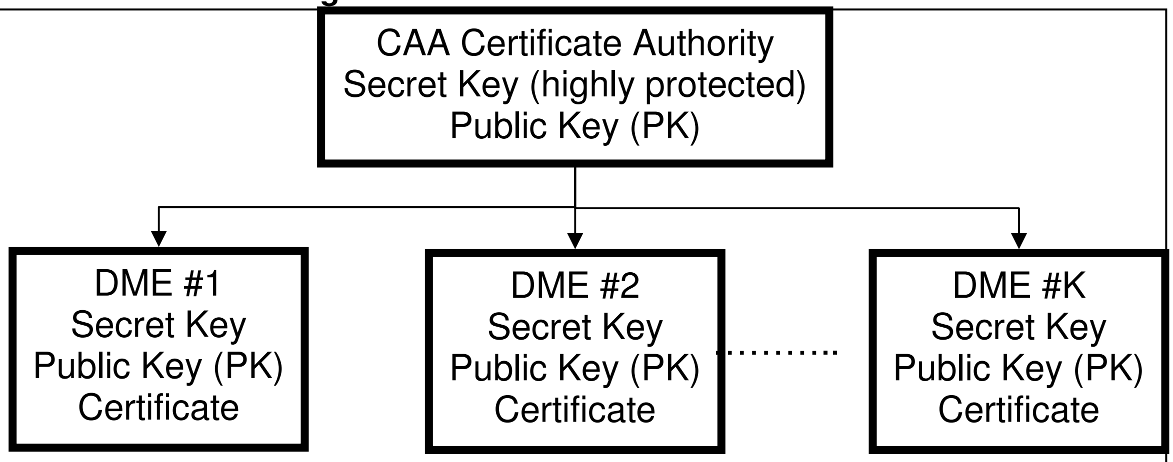
Figure 8 shows the data that we propose to broadcast on the new one-way signal. It includes six bits for message type to enable 64 different message types. It also includes 66 bits to specify the location of the DME. More specifically, this location description includes 26 bits for longitude, 26 bits for latitude and 14 bits for the height of the DME. These fields enable a location resolution of approximately 1 meter. Our proposed format also allows for an estimate of the time offset of the DME transmission. It includes 20 bits to resolve the week into the 0.6 second increments used by the GPS Z count, and 10 bits to specify the week. Finally, we include 24 bits for a cyclic redundancy check (CRC). This last field is vital and guarantees data integrity. Indeed, it would flag messages that have suffered erasures and errors that elude detection by the concatenation of the fountain and Reed Solomon codes.

Figure 8: Data Content

Data	Number of bits	Comments
Message type	6	e.g. 000000=don't use
Latitude	26	1 meter resolution
Longitude	26	1 meter resolution
Height	14	5000 meter range with 1 meter resolution
Time of week	20	corresponds to the GPS Z count
Week	10	could correspond to the GPS week
DME identification	24	may not be needed in addition to lat/long
CRC	24	same as WAAS

Finally, Figure 9 considers source authentication. It ensures that no malevolent agent can readily produce a mock DME broadcast to spoof aircraft navigation. We feel that such a function may well be needed in our future, based on current trends in cyber terrorism. The figure shows an authentication authority maintained by the civil aviation administration of the cognizant nation-state. This authority would have a well-protected secret key and a public key. The latter could be made available on the internet or in the appropriate ICAO documentation. The CAA would also generate a secret key, public key and certificate for each DME within its jurisdiction. This latter data would be used to sign the one-way data messages from the DME to the airborne fleet. As shown, the data message would include a "nonce" to introduce randomness into the transmitted data. This randomness would impede the actions of an attacker that simply copied and re-broadcast a recent transmission from a DME. All told, this authentication data would occupy approximately 320 bits, and so each authentication would require approximately 2.35 seconds for broadcast to the airborne fleet. While this seems lengthy compared to the time-to-alarm for lateral navigation, it may be adequate for this authentication function. Importantly, the avionics need not have its own keys to authenticate the source of the one-way signal.

Figure 9: Source Authentication



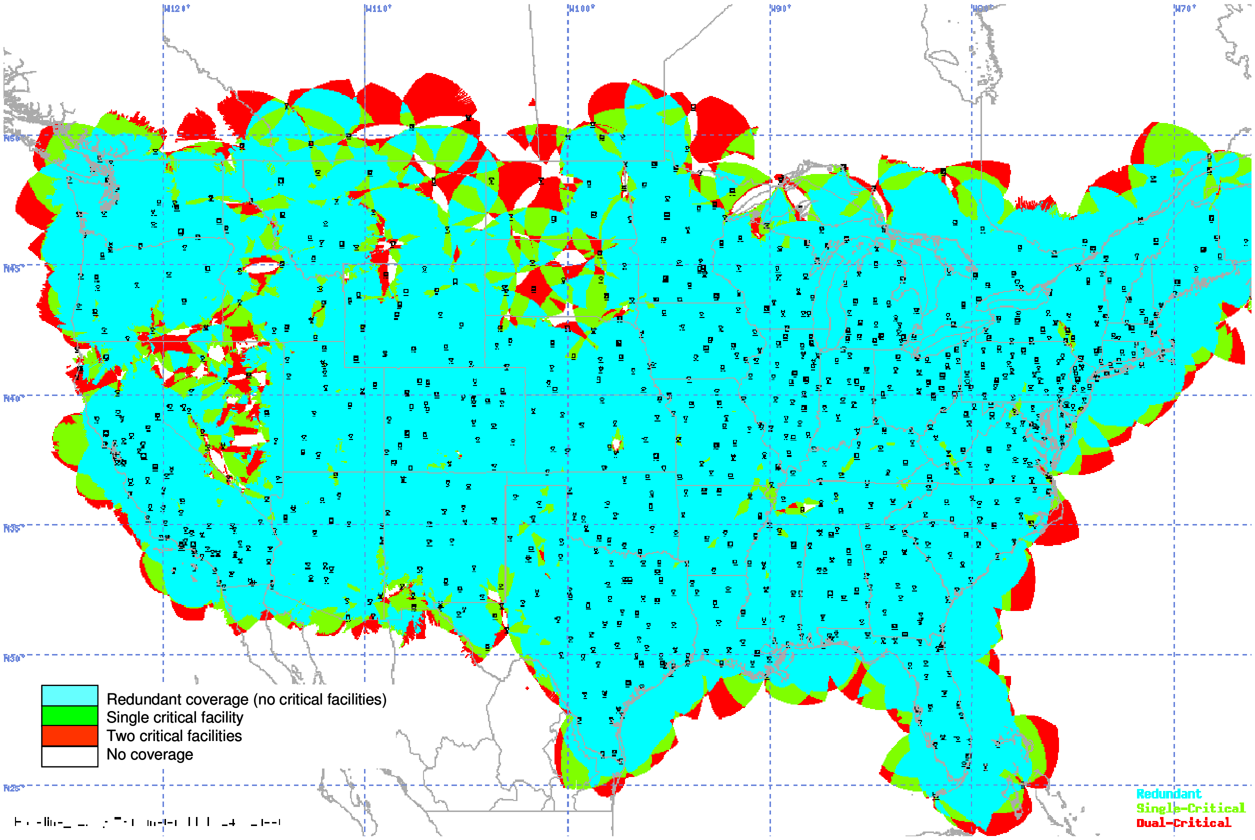
[data | time | nonce (32 random b) | DME signature, PK & certificate]

Avionics:

- decode data
- get data, time, nonce, DME signature, PK & certificate
- verify DME certificate (i.e. verify CAA’s signature on DME PK)
- verify DME signature on data

Authentication data is 320 bits so it would take 2.35 seconds to send

DME/DME Network Optimization



The DME optimization alternative would improve the service currently provided by DMEs and optimizing the network to fill gaps, eliminate critical DMEs, and investigate technical improvements to improve service.

DMEs do not depend on a common time reference and are standard equipment on most FMS-equipped aircraft. They are relatively cheap to purchase and operate. However, general aviation users do not equip with DMEs and RNAV using DMEs does not support non-precision approach, except the possible use of the DME-P that was designed for use with the original MLS.

Future Activities

- Develop the Project Plan for Full Investigation
- Develop and Validate Backup Requirements
- System Engineering Analysis
- Potential to provide RNP-0.3 approach service with MLAT, Pseudolite, or DME/DME
- Coverage for Enroute Operations
- Terminal (RNP-1.0) and Approach (RNP-0.3) at Busiest Airports
- Communications Latency and Throughput
- Infrastructure Impacts and Transition Issues

- R&D Prototyping
- Establish a Test Bed with Modified DME/GBT Stations
- Prototype Avionics
- Conduct Flight Evaluations