Existing Navigation Capabilities for Upper Class E Traffic Management (ETM)

Peter Markus
Robert Eftekari

Regulus Group

October 2019

Contents

1. Abstract

Unmanned Free Balloons (UFBs), High Altitude Long Endurance (HALE) unmanned systems, and reintroduced supersonic passenger aircraft are expected to be increasingly active above Flight Level 600 (FL600). Upper Class E Traffic Management (ETM) is the system envisioned to support these operations. Similar to the Air Traffic Management (ATM) environment below 60,000 feet (ft), ETM vehicles will employ navigation. This paper discusses existing ground, satellite and aircraft-based navigation alternatives and applicability to ETM. These systems include Very High Frequency (VHF) Omni-directional Range (VOR), Distance Measuring Equipment (DME), Tactical Air Navigation (TACAN), and Global Navigation Satellite Systems (GNSS), including the Global Positioning System (GPS, both with and without augmentation). In addition, aircraft-based technologies, such as Inertial Navigation Systems (INS) are discussed. These navigation technologies were assessed in terms of general advantages, disadvantages, current level of support for ETM, and changes necessary to enable or enhance ETM support.

2. Introduction

2.1. Background

Operations above 60,000 feet (ft) in upper class E airspace are expected to increase significantly in the near future. Multiple vehicle types are anticipated to be active in this volume. Unmanned Free Balloons (UFBs) with minimal flight path control and short mission durations are expected to operate up to altitudes of 160,000 ft. High Altitude Long Endurance (HALE) balloons, operating up to similar altitudes, will extend mission durations to an average of 100 days and employ some degree of altitude control allowing changes on the order of 10,000 ft [1]. Solar powered, HALE fixed wing aircraft are expected to loiter between Flight Level 600 (FL600) and FL900 for three to six months with daily climbs during daylight and minimally powered descents at night to maintain airspeed. HALE airships, controllable in both direction and altitude, are also expected in this airspace. Current HALE airship designs are capable of operating up to 60,000 ft.

Multiple airframe manufacturers are developing Supersonic Transports (SSTs) and Supersonic Business Jets (SSBJs). These passenger aircraft are expected to cruise at speeds between Mach 1.0 and Mach 2.5 at altitudes between FL550 and FL700. Subsequently developed aircraft may be capable of even greater speeds. Hypersonic aircraft, while still mostly in the concept phase, are also vehicles that should be considered. Carrier aircraft for air launched space vehicles are also potential ETM candidates. Figure 2-1 depicts a rendering of the Boom SST concept and a Loon HALE telecommunications balloon.

Figure 2-1. High Altitude Vehicles

The policies, regulatory framework, infrastructure, and procedures in place today may not cost-effectively scale to accommodate the disparate vehicle performance characteristics and operational diversity expected in this environment. The Upper Class E Traffic Management (ETM) concept addresses these shortfalls with principles drawn from Air Traffic Management (ATM), Unmanned Traffic Management (UTM), and operations currently performed above FL600 [1]. Figure 2-2 contains a notional depiction of the UTM, ATM, and ETM environments.

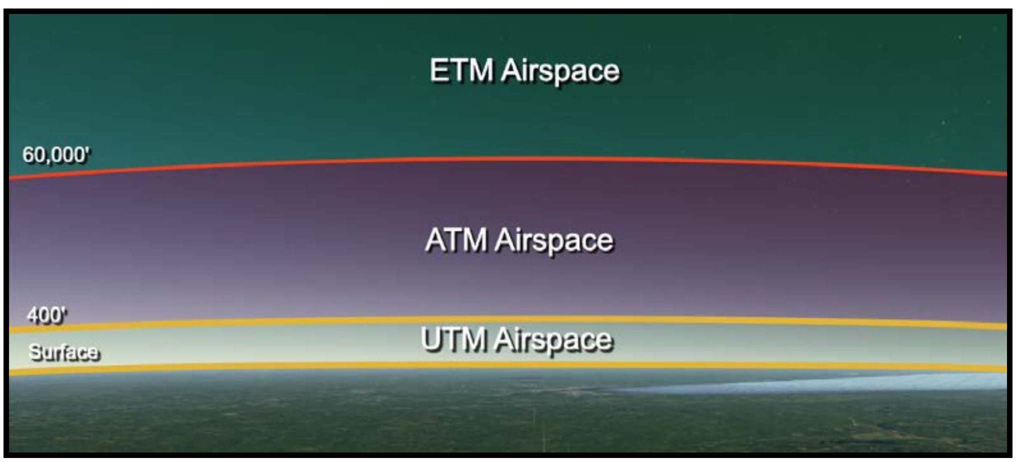


Figure 2-2. Notional Depiction of UTM, ATM, and ETM Environments

This document focuses on the navigation component of the ETM concept. As described in the 2017 Federal Radionavigation Plan, “Aircraft navigation includes determining position, orientation, course and distance to the desired destination, and deviation from the desired track.” [17] This has been accomplished for many years in the ATM environment using a variety of systems, some based solely in the aircraft, and some using ground or satellite-based components with aircraft components.

The aircraft-based systems were the first instruments used for navigation beyond visual acquisition of landmarks. Initially, these included compasses, altitude indicators, and gyroscopedriven attitude and turn-and-slip indicators. Later came more sophisticated gyroscopic systems such as the Inertial Navigation System (INS).

Ground-based systems requiring communication with an aircraft component via radio waves are referred to as "ground-based navigation" systems. These began with the Low Frequency (LF) Ranges installed by the U.S. government in the 1920s. They used a transmitting system on the ground which sent a signal to a receiver on the aircraft. This signal was modulated with Morse Code, and conveyed to the pilot whether or not the aircraft was flying on a course toward the station. Due to the lack of versatility and the fact that the low frequencies were subject to considerable noise, the LF Ranges were replaced by Very High Frequency Omni-directional Ranges (VORs) in the 1940's [31]. VORs are still being used and are described in additional detail later in this document. Other ground-based navigation aids were developed and fielded after World War II, including Non-Directional-Beacons (NDBs), Instrument Landing Systems (ILSs), and Long Range Navigation (LORAN).

Satellite-based navigation has its origins in the beginning of the space age. Scientists were able to track the Russian satellite Sputnik with shifts in its radio signal known as the Doppler effect. The U.S. Navy conducted initial satellite navigation experiments in the mid-1960s to track submarines carrying nuclear missiles.

The Navigation System with Timing and Ranging (NAVSTAR) program was established to develop a robust, stable satellite navigation system. The first NAVSTAR satellite was launched in 1978. In 1983, Korean Airlines (KAL) flight 007 entered prohibited Soviet airspace due to navigational errors and was subsequently shot down. As a result of this incident, President Ronald Reagan announced that NAVSTAR would be made available for civilian use once it was completed. In 1993, the system, at that point renamed GPS, achieved initial operational capability (IOC) with a constellation of 24 satellites. Full Operational Capability (FOC) was declared by Air Force Space Command (AFSPC) in 1995. However, accuracy in civilian applications was intentionally degraded with a feature known as Selective Availability (SA). In 2000, the use of SA was discontinued.

Today, the GPS constellation consists of 32 Block II/IIA/IIR/IIR-M satellites. GPS provides two levels of service: the Standard Positioning Service (SPS) which uses the coarse acquisition (C/A) code on the L1 frequency, and Precise Positioning Service (PPS) which uses the P(Y) code on both the L1 and L2 frequencies. Access to the PPS is restricted to the U.S. Armed Forces, U.S. federal agencies, and select allied forces/governments. The SPS is available to all users on a continuous, worldwide basis, free of any direct user charges.

2.2. Performance Based Navigation

With the proliferation of different navigation systems, and the introduction of Area Navigation (RNAV) equipment, which integrates data from multiple navigation systems to provide direct-route guidance to the pilot and autopilot, there arose a need to move from sensor-based performance requirements to unified performance requirements. This concept, known as

Performance Based Navigation (PBN), specifies that aircraft RNAV system performance requirements be defined in terms of accuracy, integrity, availability, and other parameters needed for a particular airspace operation. PBN is a shift from sensor-based to performance-based navigation. Performance requirements are captured in navigation specifications, which also identify the choice of navigation equipment that may be used to meet the performance requirements [32].

Along with RNAV, another concept captured under the PBN umbrella is Required Navigation Performance (RNP). "RNP is RNAV with the addition of onboard performance monitoring and alerting capability. A defining characteristic of RNP operations is the ability of the aircraft navigation system to monitor the navigation performance it achieves and inform the pilot if the requirement is not met during an operation." [9]

RNAV and RNP can refer to operations, airspace, routes, and procedures. When used this way, a number often follows the acronyms "RNAV" and "RNP." This number is a figure of merit that corresponds to the performance required of the RNAV/RNP navigation system for that procedure or operation (Figure 2-3).

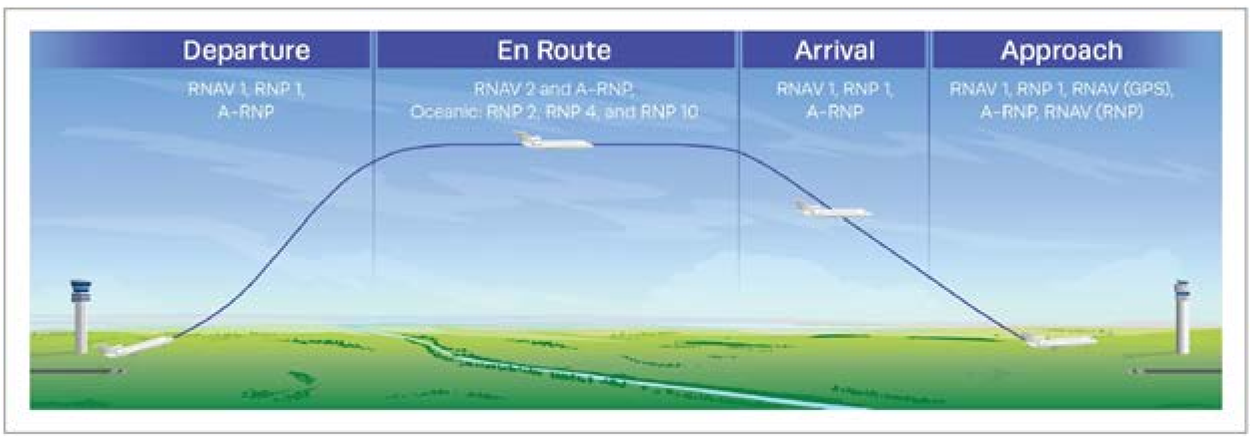


Figure 2-3. Different RNAV/RNP Specifications for Different Operations [9]

Table 2-1 shows the values of the performance requirements for different phases of flight / operations. For example, under the En Route phase of flight in Figure 2-3, oceanic operations can use an RNP 10 specification. This corresponds to a performance requirement for lateral and along-track accuracies within $\pm$10 nm, for at least 95 percent (%) of total flight time [21].

Table 2-1. RNP Performance Requirements for Different Airspaces / Operations [17]

REQUIREMENTS	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS						
	ACCURACY (95%)		AVAILABILITY	CONTINUITY	INTEGRITY	TIME TO ALERT	COVERAGE**
	Horizontal	Vertical					
Oceanic	10 or 4 nmi***	N/A	0.99 – 0.99999		$1\text{-}1\times10^{-7}$//hr	N/A	N/A
Enroute	2 nmi	N/A	0.99 – 0.99999	$1\text{-}1\times10^{-4}$/hr to $1\text{-}1\times10^{-8}$/hr	$1\text{-}1\times10^{-7}$/hr	5 min	N/A
Terminal	1 nmi	N/A	0.99 – 0.99999	$1\text{-}1\times10^{-4}$/hr to $1\text{-}1\times10^{-8}$/hr	$1\text{-}1\times10^{-7}$/hr	15 s	N/A
Non Precision Approach	220 m	N/A	0.99 – 0.99999	$1\text{-}1\times10^{-4}$/hr to $1\text{-}1\times10^{-8}$/hr	$1\text{-}1\times10^{-7}$/hr	10 s	N/A
APV-I	16 m	20 m	0.99 – 0.99999	$1\text{-}8\times10^{-6}$/15 s	$1\text{-}2\times10^{-7}$ in any approach	10 s	N/A
APV-II	16 m	8 m	0.99 – 0.99999	$1\text{-}8\times10^{-6}$/15 s	$1\text{-}2\times10^{-7}$ in any approach	6 s	N/A
CAT I	16 m	6 – 4 m	0.99 – 0.99999	$1\text{-}8\times10^{-6}$/15 s	$1\text{-}2\times10^{-7}$ in any approach	6 s	N/A

* From ICAO Annex 10 Vol 1 Table 3.7.2.4-1. ICAO is in the process of changing approach definitions of the APV classification and including LPV-200 as a precision approach.
** Not Specified by ICAO, Annex 10, Vol. 1, Table 3.7.2.4-1, Signal-in-Space Performance Requirements.
*** Depends on the navigation specification (RNP 10 or RNP 4) employed in the oceanic area.

Accuracy, in the context of RNAV and RNP, defines the 95% Total System Error (TSE). Total System Error is a composite mainly made up of three errors: Navigation System Error (NSE), Flight Technical Error (FTE), and Path Definition Error (PDE) (Figure 2-4) [32].

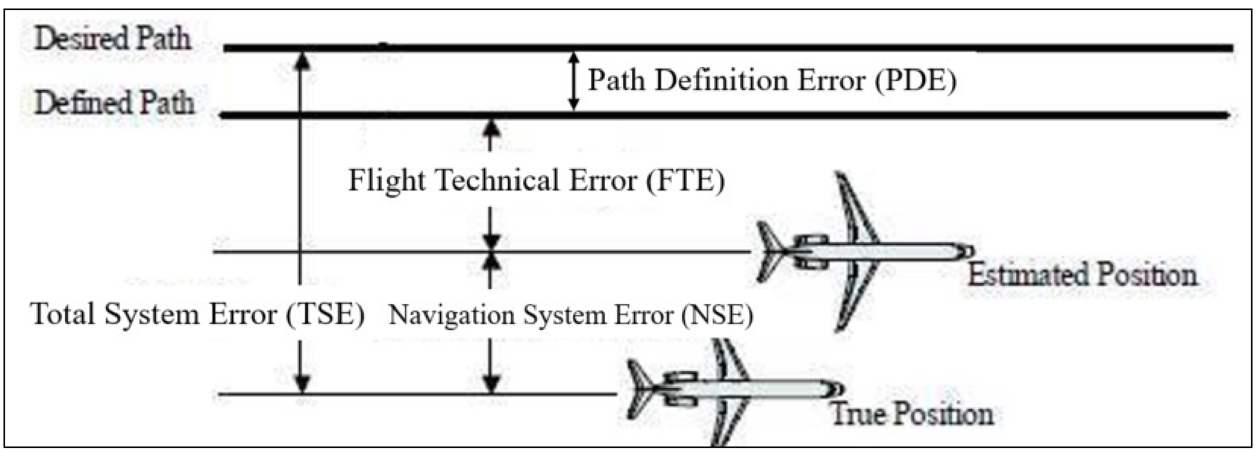


Figure 2-4. The Components of Total System Error (TSE)

Navigation System Error (NSE) is the position estimation error that is presented by the navigation system (e.g., GNSS, DME, etc.) to the pilot or autopilot. This could be due to problems in the electronics or the signal-in-space.

Flight Technical Error (FTE) has to do with pilot or autopilot capability to maintain (steer onto) the defined path. FTE is primarily caused by atmospheric effects such as wind gusts or minor turbulence.

Path Definition Error (PDE) is the RNAVs system's ability to correctly define the desired path. Errors here could be due to errors in the system's database of fix, waypoint, and nav-aid locations.

This document describes the most common systems currently used for navigation and PBN in the upper ATM environment, their advantages and disadvantages, their current support for ETM, and what would be necessary of these systems for greater ETM support.

3. Existing Navigation Capabilities

3.1. Ground-Based Navigation Systems

3.1.1. Very High Frequency (VHF) Omni-directional Range (VOR)

The Very High Frequency Omni-Directional Range (VOR) is a ground-based navigation system that provides azimuth information to a receiver on the aircraft (Figure 3-1).

Figure 3-1. VOR Station

Two signals are broadcast by the ground station: an omni-directional Frequency Modulated (FM) reference signal and an Amplitude Modulated (AM) variable signal. The latter has a modulation phase that varies depending on the azimuth the aircraft has with respect to the ground station and magnetic north (Figure 3-2). The VOR receiver on the aircraft detects the phase relationship between the FM reference and the AM variable signals and drives an indicator which gives the azimuth information to the pilot (or autopilot). Using this information, the aircraft can stay on a course toward or away from the station. This concept was used to develop the Victor and Jet Airway structure of the U.S. (the so-called "highways in the sky" – Figure 3-3).

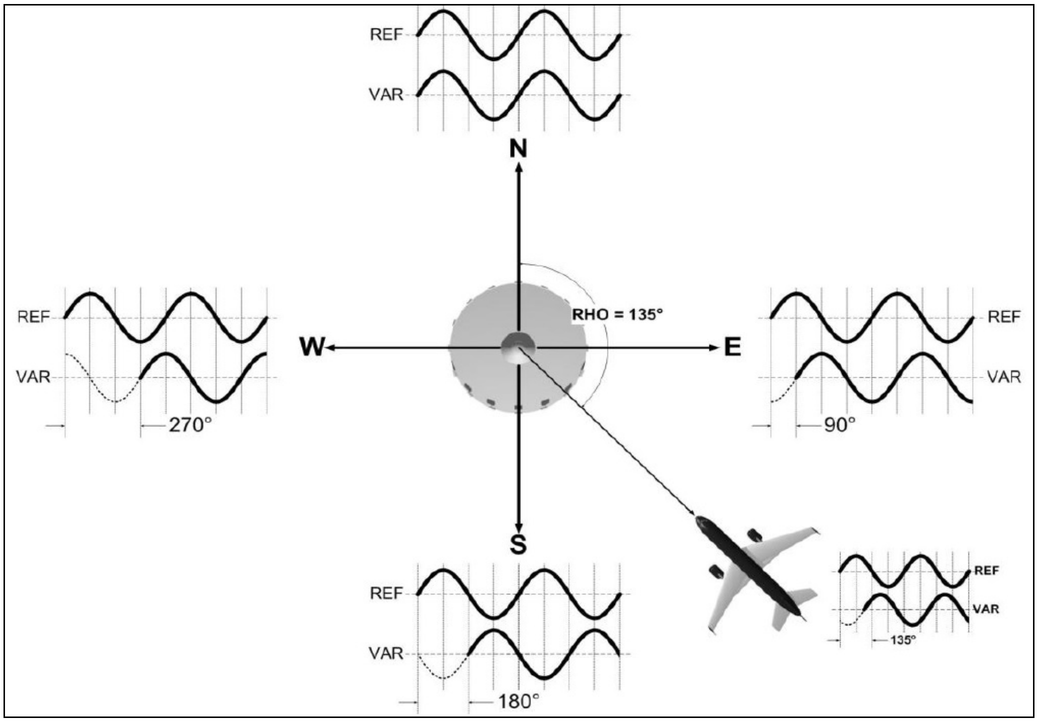


Figure 3-2. Phase Relationships between FM Reference and AM Variable Signals [13]

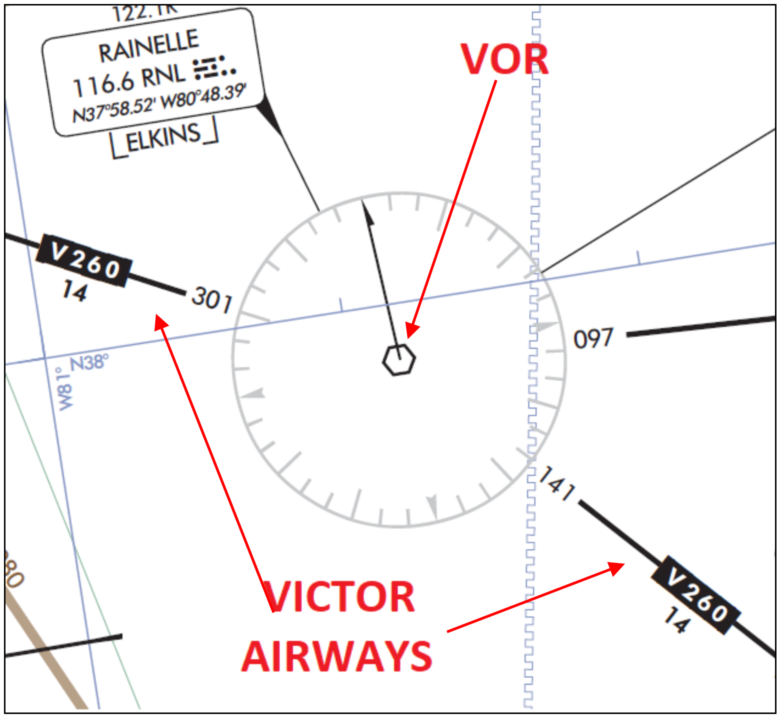


Figure 3-3. VOR and Victor Airways on Aeronautical Chart

Most VOR ground systems are co-located with one of two systems which provide distance information to other instruments in the aircraft: a Distance Measuring Equipment (DME) or a Tactical Air Navigation (TACAN) system. The combination provide the pilot (or autopilot) with the aircraft's two-dimensional location, in azimuth and distance with respect to the VOR station. When a VOR is co-located with a TACAN, the ground station is known as a VORTAC. When collocated with a DME, it is known as a VOR-DME. The DME and TACAN systems will be discussed in-depth in later sections. The VOR receiver can also feed an Area Navigation (RNAV) system which can collect information from other VOR receivers and other sensors in the aircraft, perform calculations on the information and provide the pilot with a more sophisticated display. This can enable the pilot to follow paths that do not terminate on a VOR, allowing more direct flights.

3.1.1.1. Advantages of VOR Include:

- Decades of use supporting navigation of civilian and military aircraft in all phases of flight.
- Wide ranging coverage (Figure 3-4).

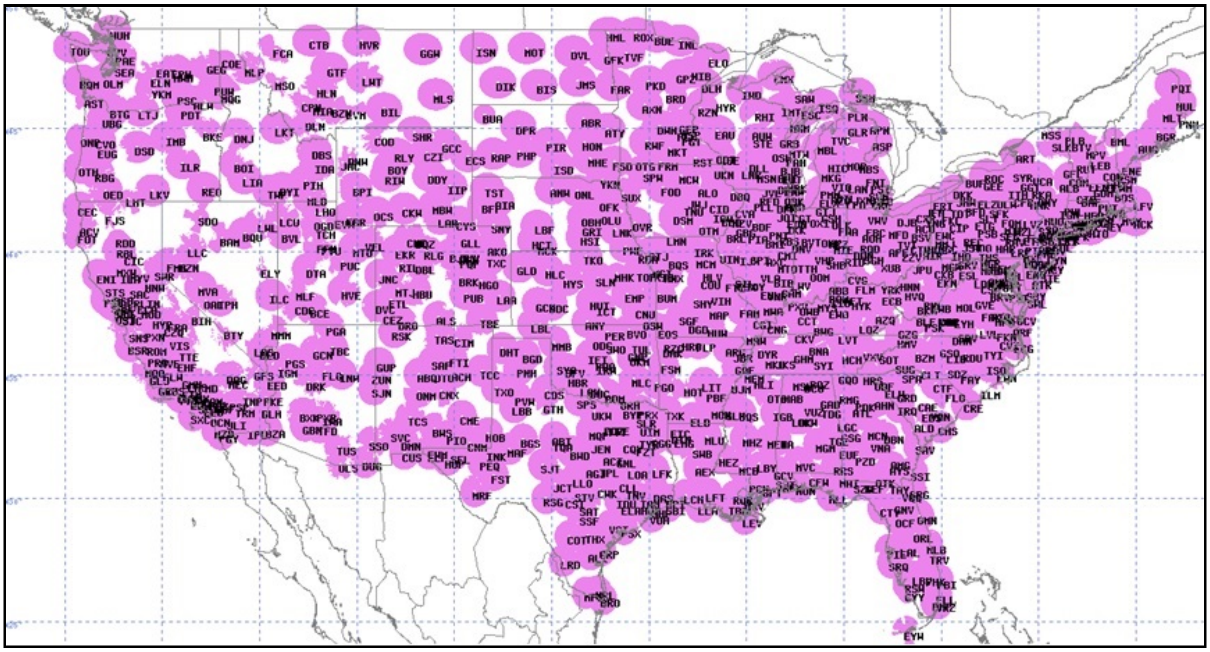


Figure 3-4. 2016 VOR Network 40 NM Service Volume at 5,000’ AGL[1] [2]

- Able to withstand jamming and spoofing, due to the relatively high signal strength and local proximity of the aircraft (as opposed to GPS). In recognition of this, there presently exists a program, the VOR Minimum Operational Network (MON) Program, which is to serve as an Alternate Positioning, Navigation and Timing (APNT) method in the event GPS is jammed. One objective of the Program is to reduce the current number of VORs in the U.S. by approximately 30%, but effectively increase coverage by increasing the size of the service volume from 40 nm to 70 nm at 5000 ft MSL and higher (Figure 3-5) [3].
- An established infrastructure supported by FAA logistics and maintenance programs.
- Total System Error of $\pm$4.5 degrees (95% probability) [4][17].
- Many VORs have an available signal at least up to 60,000 ft Above Transmitter Height (ATH). As shown in Figure 3-6, the current Frequency Protected Service Volumes (FPSVs)[2] of some VORs - the “VOR High” class - reach a maximum elevation of 60,000 ft ATH. (Figure 3-6) [5].

---

[1] Note that figure 3-4 gives coverage at 5000 ft Above Ground Level (AGL). Whether there is coverage in the ETM airspace, above FL 600, would need to be determined on a case by case basis.

[2] A volume protected from frequency interference by adjacent facilities. It is essentially the same as the operational service volume, which is the volume advertised to be available and have sufficient signal strength (greater than -123 dBW) for use by the flying public [5].

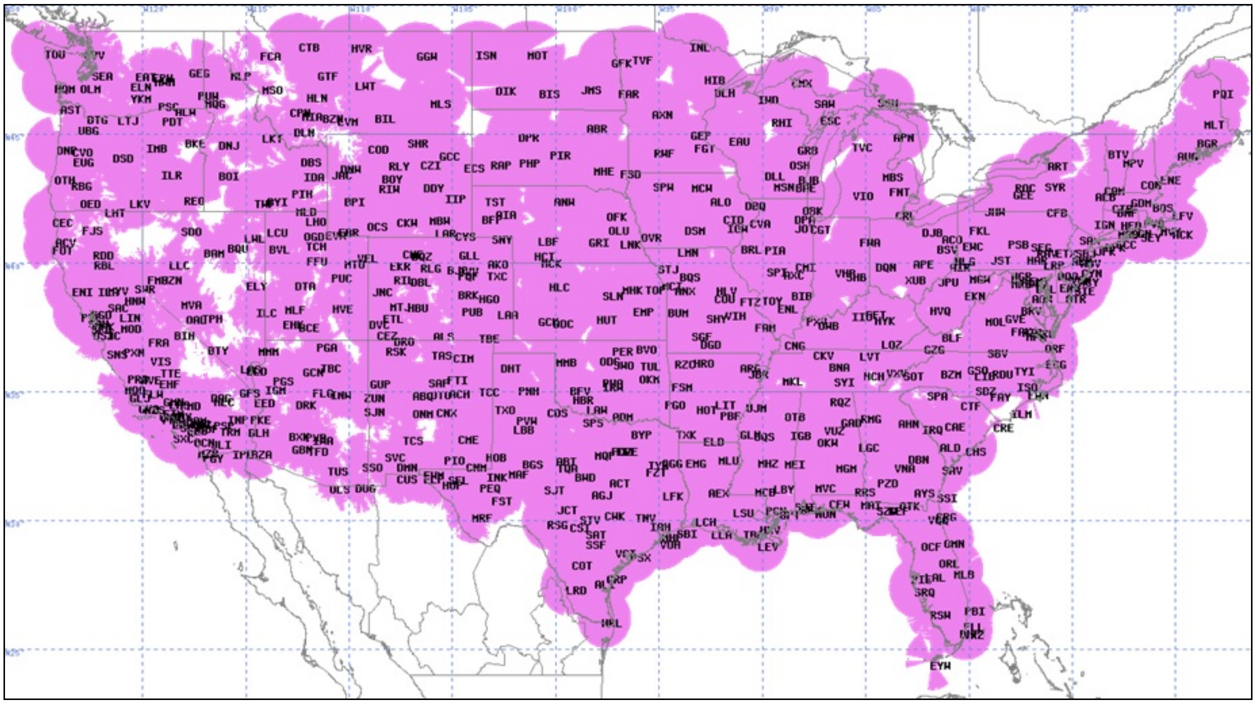
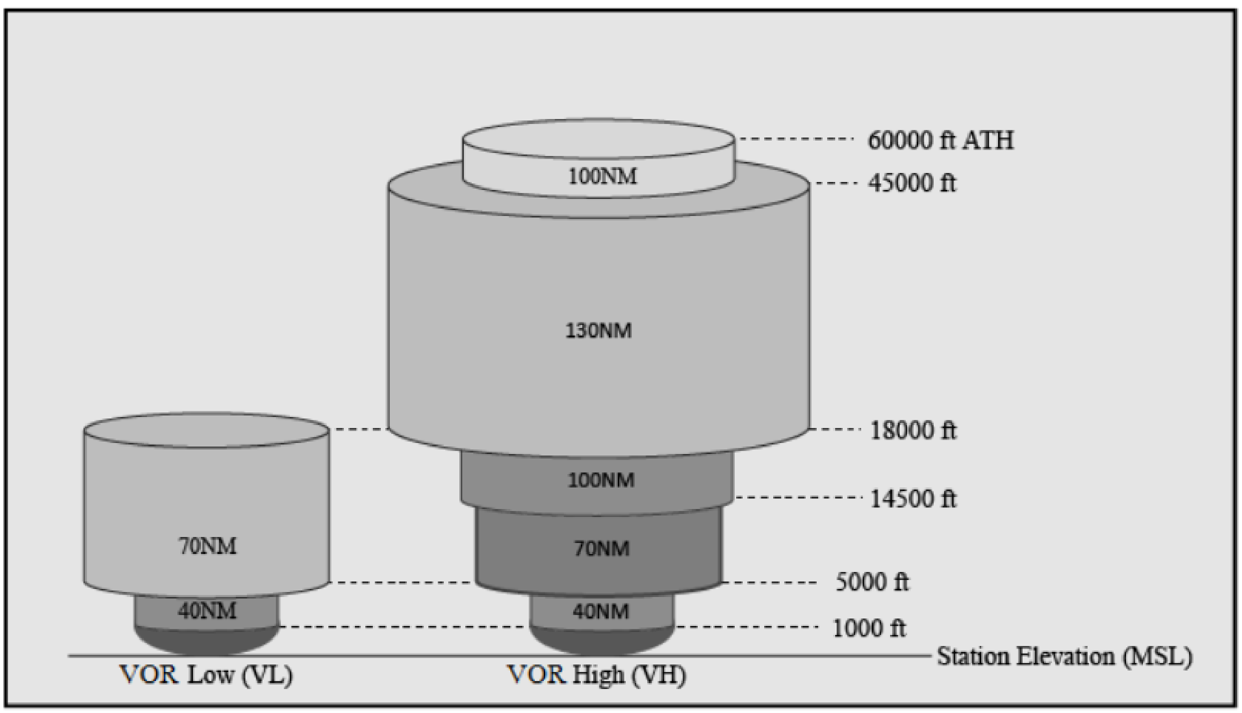


Figure 3-5. Planned VOR MON 70 NM Service Volume at 5,000' AGL [2]



Mean Sea level (MSL)
Above Transmitter Height (ATH)

Figure 3-6. VOR Frequency Protected Service Volumes [5]

3.1.1.2. Disadvantages of VOR Navigation Include:

- Its normal range of operation is only up to about 60 degrees in elevation angle [4]. Aircraft above this elevation angle can enter the so-called "cone-of-confusion, where the pilot's indicator becomes unreliable and erratic.
- It only provides azimuth information –altitude and distance information are still needed for complete navigation.
- Nearby objects can cause an erratic indication. Structures or foliage near a VOR facility can cause reflections, or "multipath," of the signal that interfere with the directly propagated signal. This can then cause the pilot's indication to become unreliable and erratic. To mitigate this, there normally exists a restrictive easement around the facility. However, this can be costly (next bullet).
- The system and the infrastructure are costly. The equipment and infrastructure are getting old (many were installed in the 1980s), causing the need for expensive refurbishments. Also, land leases and easements can be expensive.
  Cross-track (distance) accuracy decreases with distance from the station (e.g., 4.5 degrees at 130 nm from the VOR station corresponds to a cross-track accuracy of 10.21 nm.)

3.1.1.3. Current VOR Navigation Support for ETM:

The main factor limiting VOR navigation support for ETM is the elevation of the top of its Frequency Protected Service Volume (FPSV). Figure 3-6 shows that the highest FPSV is . 60,000 ft Above Transmitter Height (ATH), which, practically speaking, is the same as 60,000 ft Above Ground Level (AGL)[3]. Note that it is possible that the FPSV exists above FL600 for a VOR with a ground elevation higher than 0 ft Mean Sea Level (MSL)[4]. For example, consider the highest VOR in the CONUS, Red Table (DBL), near Eagle, CO. It has a VOR High FPSV and its ground elevation is 11,800 MSL. Therefore, the top of its FPSV is 11,800 + 60,000 = 71,800 ft MSL. This is certainly above the lower limit for ETM (FL 600).

Furthermore, although the top of the FPSV for a High VOR is at 60,000 ft ATL, there could still be sufficient signal strength above that level to drive the VOR receiver on the aircraft. Figure 3-6A shows it is possible to have more than the required level of signal strength (-123 dBW) above 60,000 ft ATL [5]. Thus, it is possible to use VORs for the lower levels of ETM airspace.[5]

---

[3] Most VOR antennas are at about 16 ft AGL; however, there are a very small number of VORs which are on tall structures, placing them at about 100 ft AGL.

[4] Note that FL600 is not necessarily 60k ft MSL. FL600 is the point at which the aircraft's barometric (pressure) altimeter reads 60k ft when its Kollsman window is set to 29.92 in. (Standard Pressure), thus the MSL elevation of FL 600 could vary.

[5] Note, that only about 45% of all VORs are presently of the High category [12], and the amount of the High VOR's FPSV that is above FL 600 depends on the ground elevation of the VOR.

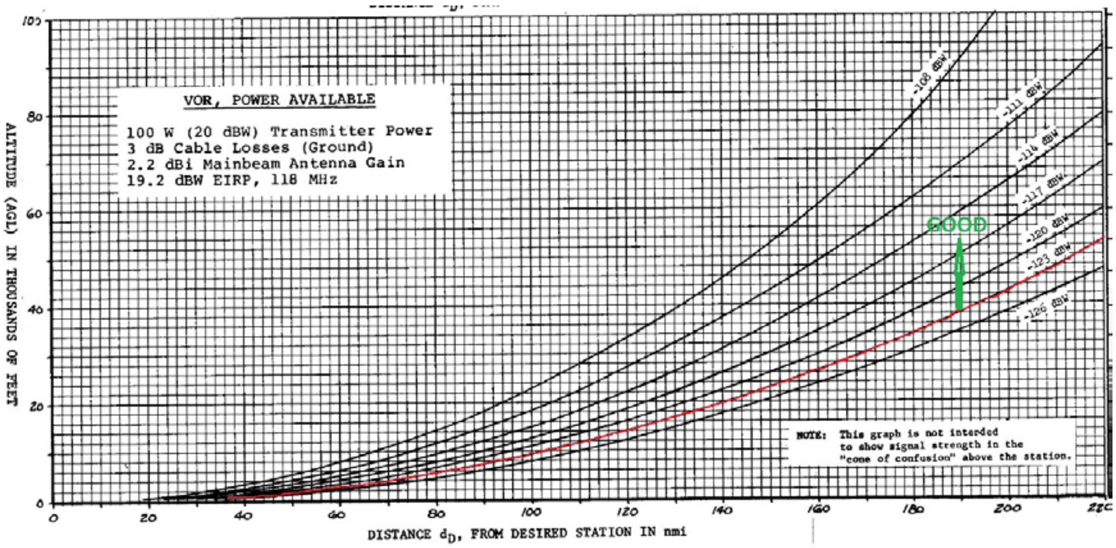


Figure 3-6A. Power Available Curve – VOR – 100W [5]

An investigation would be needed to ensure that there actually exists sufficient signal strength and protection from signal interference at that elevation for a particular VOR. (See later discussion about Expanded Service Volumes - ESVs.)

3.1.2. Distance Measuring Equipment (DME)

Distance Measuring Equipment (DME) is a ground-based navigation system which uses the two-way travel time of pulse pairs to provide distance information to the pilot (or autopilot) (Figure 3-7).

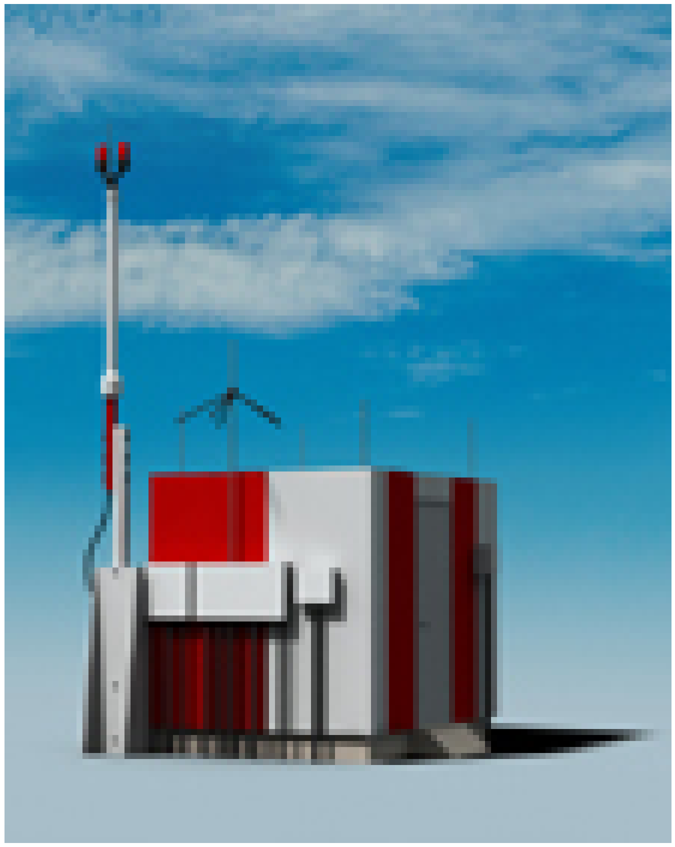


Figure 3-7. Distance Measuring Equipment (DME) Ground Installation [14]

Determination of distance is initiated by the “interrogator” on the aircraft transmitting two pulses, separated by a specific time interval, 12×10^{-6} sec (12 microseconds) (Figure 3-7A). These pulses are received by the ground-based “transponder,” which takes a fixed time (50 microseconds) to process the two pulses and then replies with another pair of pulses, also separated by 12 microseconds[6]. The interrogator determines the overall time elapsed from initial pulse transmission, and, by using the speed of light and the familiar formula:

$$\text{Distance} = \text{Time} \times (\text{Speed of Light}),$$

the straight-line distance[7] between the aircraft and the ground station can be determined. The 50 microseconds processing time of the transponder is accounted for by the interrogator [8]. The distance can be presented to the pilot as a digital display and/or sent to a Flight Management

[6] 12 microseconds separation between the two pulses is the standard for the “X” mode of operation. The other mode, “Y,” uses 36 microseconds on the downlink and 30 microseconds on the uplink. Also, the fixed processing time of the transponder for the “Y” mode is 56 microseconds.

[7] The straight-line distance, also known as “Slant Range,” is important to distinguish from ground distance, as they can be substantially different if the aircraft is at high elevation angles with respect to the ground station.

System (FMS – to be described later) for integration with other navigational aids (e.g., VOR) data.

Nearly all DMEs are presently collocated with a facility that provides azimuth data (e.g., a VOR), to enable the pilot to determine the aircraft's two-dimensional position in both distance and azimuth. This is changing, however, with the VOR MON and NextGen DME Programs. The former program, as mentioned earlier, is reducing the number of VORs, leaving stand-alone DMEs. The latter program "…will expand DME coverage in the en route and terminal domains to provide a resilient complementary system to support PBN operations in the event of a GNSS disruption…" [9] This will result in an increase in DME-only coverage at higher elevations in Class A Airspace.

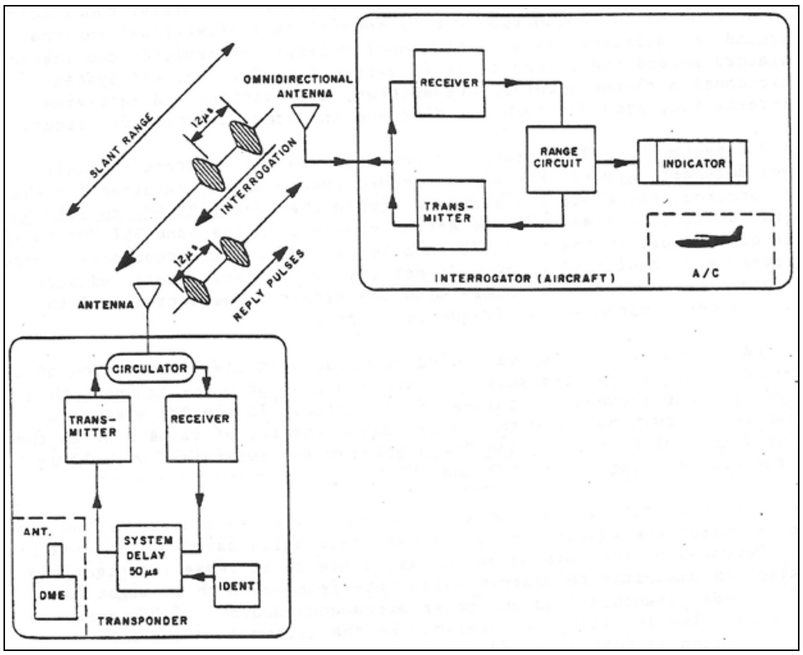


Figure 3-7A. Block Diagram of the Distance Measuring Equipment (DME) [8]

3.1.2.1. Advantages of DME Include:

- Decades of use supporting navigation of civilian and military aircraft in all phases of flight.
- Wide ranging coverage in CONUS (Figure 3-8). This coverage is expected to increase, due to the NextGen DME program (Figure 3-9). Due to relatively high signal strength, the ability to withstand jamming and spoofing, as with the VOR.
- An established infrastructure supported by FAA logistics and maintenance programs, with continued support.

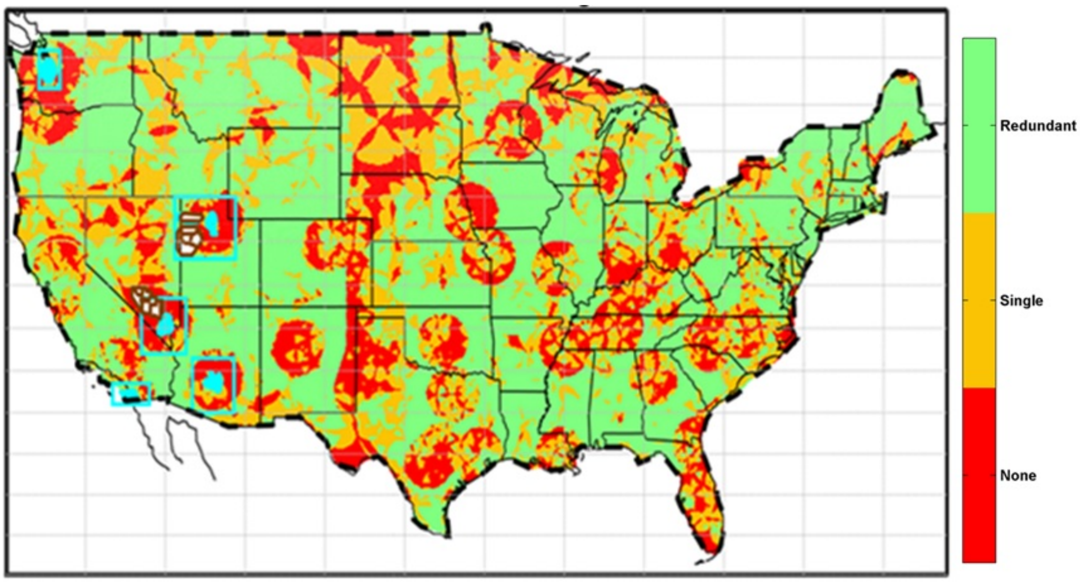


Figure 3-8. Existing[8] DME Coverage for DME/DME RNAV, Above 24,000 Ft USWMA and 18,000 ft Elsewhere [10][9]

- There exists an established program, the NextGen DME Program which, by increasing the number of DMEs and by changing their frequencies and FPSVs, seeks to provide DME coverage in much of Class A Airspace (from 18k ft / 24k ft up to FL 450) by late 2021 (Figure 3-9) [9][33][36].
- The required Nav System Error is $\underline{+}0.5$ nmi (926 m) or 3 percent of the slant range distance, whichever is greater (95 percent probability). This is required when the airborne system error and the ground system error (considered as no greater than 0.1 nmi) are combined by the root-sum-square method [4][17].

[8] There likely has been an increase in coverage since this picture was first published, due to the NexGen DME Program.

[9] Note that the coverage depicted in this figure is not necessarily above FL 600. The upper limit is determined by power, antenna pattern, and any signal blockage or interference that may be present. USWMA is the United States Western Mountainous Area.

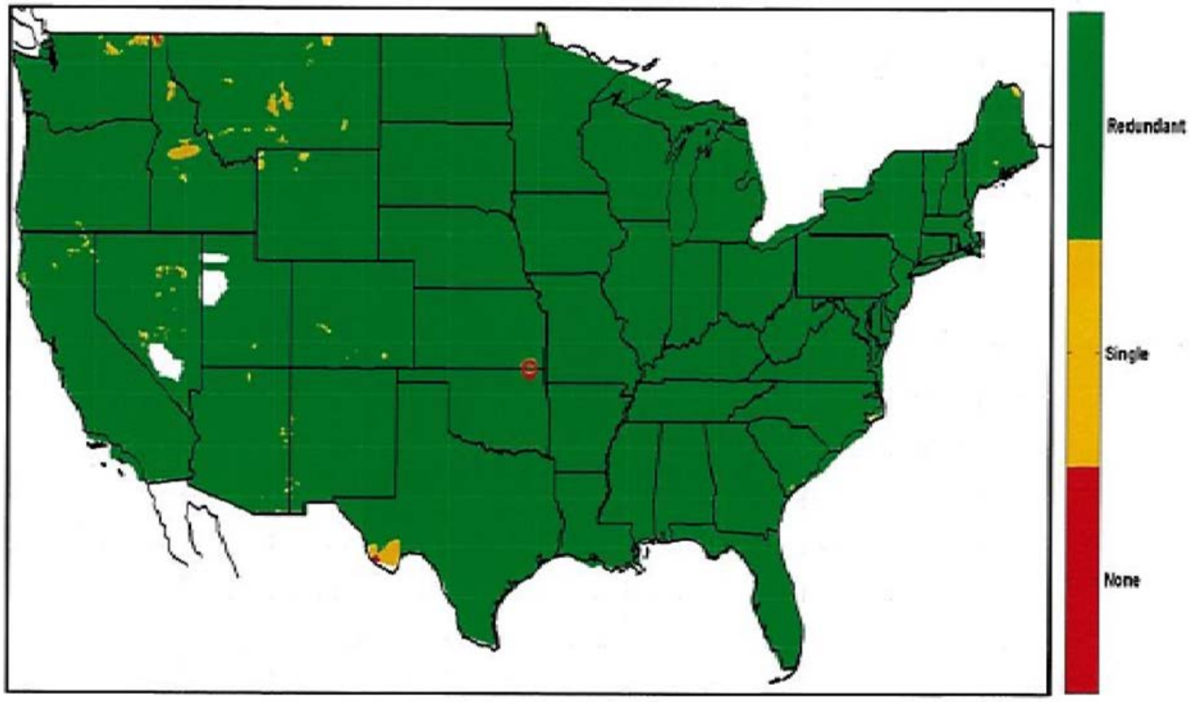


Figure 3-9. Planned DME Coverage for DME/DME RNAV 2, Above 24,000 Ft USWMA and 18,000 ft Elsewhere [3][10]

3.1.2.2. Disadvantages of DME Navigation Include:

- A DME has FPSVs with the same dimensions as those of the collocated VOR (Figure 3-6), unless the DME is used for RNAV operations. In that case, it will have the dimensions shown in Figure 3-10 [5]. In either case, like the VOR, DMEs are only protected up to a maximum of 60,000 ft Above Transmitter Height (ATH).
- It only provides distance information –altitude and azimuth information are still needed for complete navigation. Note that two-dimensional location information can be derived by doing RNAV calculations on information from two or more DMEs (known as "DME/DME RNAV").
- Ground distance is not equivalent to distance presented by the DME receiver. The ground distance is roughly:

  (Slant Range) x (Cosine of Elevation Angle)

  Thus, the higher the elevation angle, the less of a correspondence between Slant Range and ground distance to the DME station.

[10] Note that the coverage depicted in this figure is not necessarily above FL 600. The upper limit is determined by power, antenna pattern, and any signal blockage or interference that may be present. USWMA is the United States Western Mountainous Area.

- Accuracy decreases with increased DME distance by 3%. For example, at 130 nm, the accuracy is 3.9 nm.

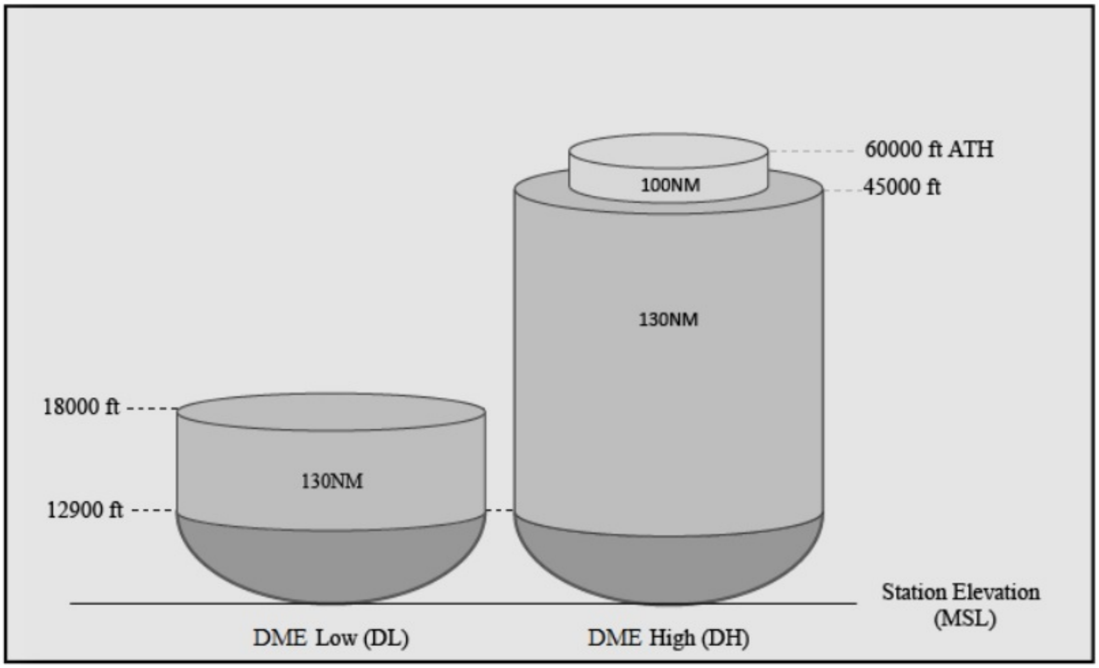


Figure 3-10. DME Frequency Protected Service Volumes for RNAV Operations [5]

3.1.2.3. Current DME Navigation Support for ETM:

As with the VOR, it is possible that the FPSV exists above FL600 for a DME with a ground elevation higher than 0 ft Mean Sea Level (MSL). Also, it is possible that sufficient signal strength is present above the FPSV. This is suggested by the Power Available Curves. As can be seen in figures 3-11 and 3-12, the theoretical power available exceeds the lower limit (-114.5 dBW) above the 60,000 ft AGL level [5] for some DMEs. Considering both of those factors, it may be possible to use DMEs for some ETM operations. As with VORs, only about 45% of all DMEs are presently of the High category [12], and the amounts of those DMEs' FPSVs that are above FL 600 depend on the ground elevations of those DMEs. Also, as with VORs, the DMEs' actual signal strengths above 60,000 ft AGL will need to be verified, possibly by a flight check. Note that the number of High DMEs will be increasing with the NextGen DME Program [36].

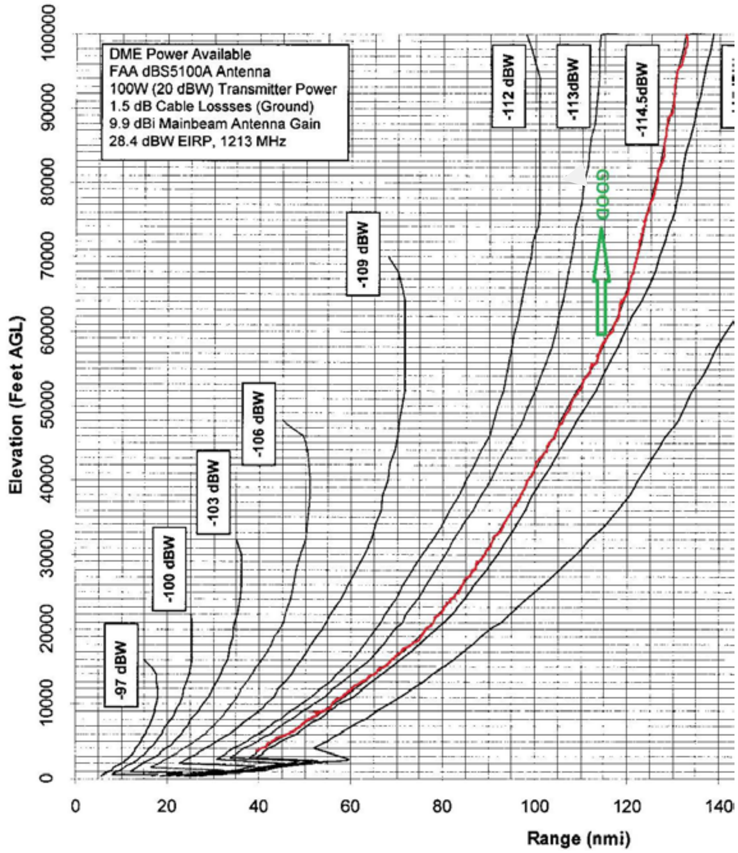


Figure 3-11. Power Available Curves for a dBS5100A – 100W [5]

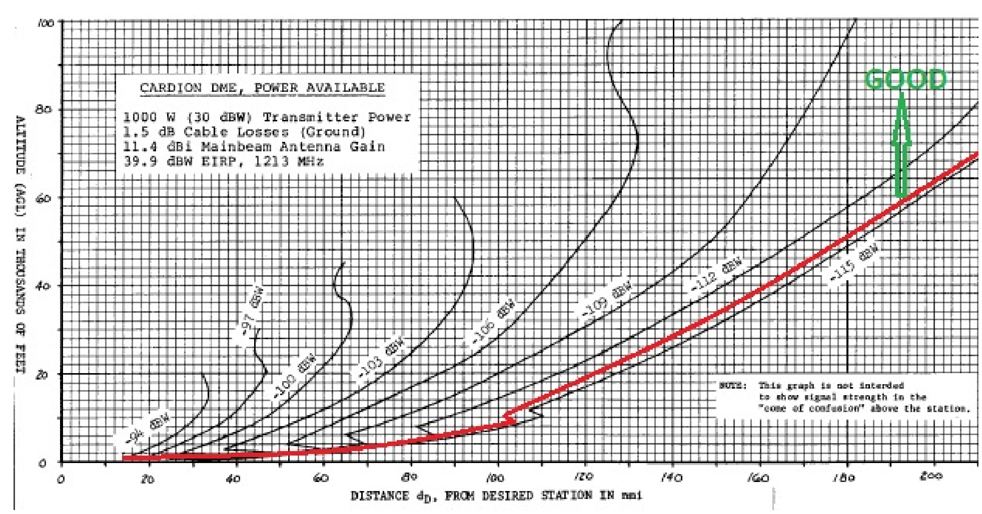


Figure 3-12. Power Available Curves – Cardion DME - 1KW [5]

3.1.3. Tactical Air Navigation System (TACAN)

TACAN is a ground-based navigation system that builds upon DME to provide azimuth information, as well as distance information, to the pilot. The aircraft that can use the azimuth information is limited, however, to military aircraft. Civilian DME receivers can still use the signals transmitted from a TACAN antenna for distance information, but a military receiver is needed to obtain both distance and azimuth information. The ground element of the TACAN system is typically collocated with a VOR, and the two together are known as a VORTAC (Figure 3-13).

Figure 3-13. VORTAC Station, Showing TACAN Antenna on Top

The TACAN antenna amplitude modulates the basic DME signal with rotating elements, so that the airborne TACAN receiver can determine its azimuth with respect to true north and the TACAN station [15].

3.1.3.1. Advantages of TACAN Include:

- Decades of use supporting navigation of civilian (distance) and military aircraft (azimuth and distance) in all phases of flight.
- Wide ranging coverage in the US. Approximately 440 are presently commissioned [16].
- Azimuth Total System Error requirement is the same as the VOR: $\pm$4.5 degrees (95% probability). The distance Nav System Error requirement is the same as the DME, 0.5 nmi (926 m) or 3 percent of the slant range distance, whichever is greater (95 percent probability) [4].
- Due to relatively high signal strength, able to withstand jamming and spoofing, as with the VOR and DME.

- An established infrastructure supported by FAA logistics and maintenance programs. "The DoD requirement for land-based TACAN will continue until military aircraft are properly certified for RNAV/RNP operations." [17]

3.1.3.2. Disadvantages of TACAN Navigation Include:

- As with VORs and DMEs, they are only protected up to a maximum of 60,000 ft Above Transmitter Height (ATH). TACANS have the same FPSVs as the VORs that they are collocated with (Figure 3-6), unless they are used for RNAV operation, then they have one of the FPSVs shown in Figure 3-10 [5].
- It only provides azimuth information to military aircraft. Generally, civilian pilots cannot use TACAN receivers for azimuth information.
- There exists within the FAA the "TACAN Reduction Initiative," which aims to reduce the number of TACANs in the FAA's inventory by either eliminating them or converting them to DME-only [10]. Many TACANS have already been identified for elimination or conversion.
- There is the same decrease in accuracy as with the VOR and DME with an increase in distance from the TACAN.
- It only provides azimuth and distance information –altitude information is still needed for complete navigation.

3.1.3.3. Current TACAN Navigation Support for ETM:

The TACAN's FPSV has the same dimensions as the DME. As with the DME, it is possible that the FPSV exists above FL600 for a TACAN with a ground elevation higher than 0 ft Mean Sea Level (MSL). Also, it is possible that sufficient signal strength is present above the FPSV. Note in figure 3-14, the limits of coverage (the line showing -114.5 dBW) extends above the 60,000 ft AGL level. Thus, it is possible to use TACANS for some ETM operations.

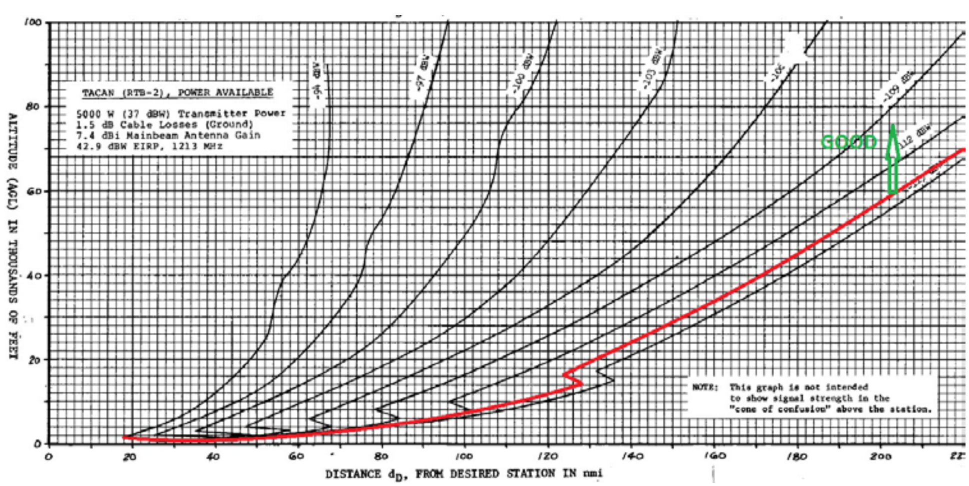


Figure 3-14. Power Available Curves – 5KW – TACAN [5]

3.1.4. VOR, DME, and TACAN Changes Necessary for Greater ETM Support:

Many VORs, DMEs, and TACANs presently provide protected coverage in the lower extents of ETM airspace. These are the ones that are at a ground elevation fairly above 0 ft MSL and are classified as High facilities, since the coverage volume for High facilities reaches (effectively) 60,000 ft AGL. Of course, how much ETM airspace is covered depends on the ground elevation of the facility.

To further enable VOR, DMEs, and TACANS to provide greater ETM support, the following actions could be taken:

- Increase the upper elevation limit of the standard High Frequency Protected Service Volume (FPSV) (e.g., change the limit to 70k ft AGL). This would, however, require extensive frequency interference modelling and flight checks to ensure signal integrity and coverage. This would need to be authorized at high levels of FAA Technical Operations management, since it is a broad-based change. Note that changes to the standard FPSV have recently been done as part of the VOR MON program.

- Increase the upper elevation limit of individual High FPSVs on a case-by-case basis. Increasing the size of FPSVs is done often with individual VORs, DMEs, and TACANs, with the result known as an Expanded Service Volume (ESV). "An ESV merely adds to a standard FPSV. The ESV extends the standard FPSV in a particular direction, distance, altitude, and shape." [5] For this to be done, signal availability must be ensured at the elevation requested. This may require a flight check and an increase in signal level from the transmitter. From an investigation of the power available curves (Figures 3-6A, 3-11, 3-12, and 3-14), it appears that for some types of VORs, DMEs, and TACANs, signal strength above the High FPSV may be sufficient. It is possible to predict future ETM operational areas and request that particular VORs, DMEs, or TACANs have ESVs added to ensure those areas have coverage. This would be similar to designing an "airway" in ATM airspace and then ensuring there is coverage along the airway by VORs, DMEs, or TACANs using ESVs, if necessary.

- DME/DME RNAV (using two or more DMEs to determine aircraft location) appears to be the best, existing ground-based navigation system alternative for ETM operations, since there are programs which aim to decrease the number of VOR and TACANS, but there is a program to increase the high-altitude coverage and number of DMEs. ESVs would likely be needed to enable this. To further enable greater ETM support by DME systems, coverage at higher elevations could be increased by increasing ground-based transponder power outputs or altering their antenna patterns. Also, increases to airborne interrogator sensitivities could be considered.

3.1.5. LORAN

LORAN-C (**LO**ng **RA**nge **N**avigation, version **C**) is a ground-based navigation system that uses pulses transmitted from a master station and two or more secondary stations to enable an aircraft receiver to determine its location. The Time Delay (TD) between the pulses received from the master station and from a secondary station define a hyperbolic Line of Position (LOP) that the aircraft could be on (Figure 3-15). To gain more certainty in the position (to define a point rather than a line), the receiver must measure the TD between the pulses from the same master station and another secondary station. This defines another hyperbolic LOP. The intersection of these two LOPs define an unambiguous location of the aircraft [23].

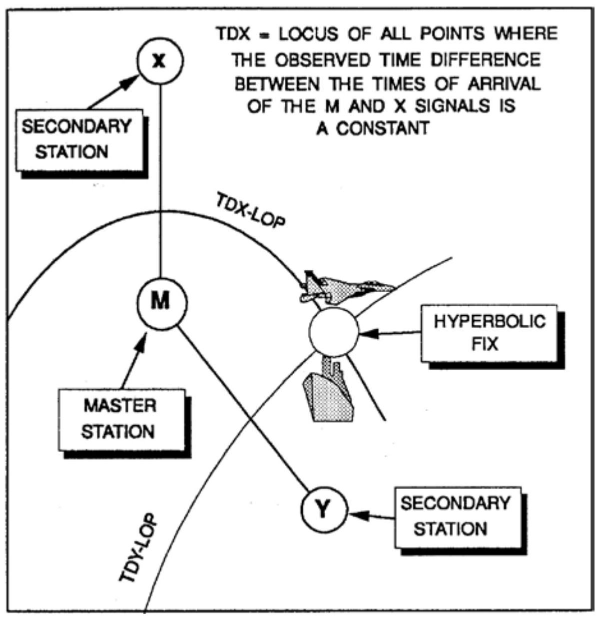


Figure 3-15. LORAN-C Receiver Location Determination [23]

LORAN-C is no longer used in the NAS. It was used widely from the 1970's until February 8th, 2010, when its signal was terminated by the 2010 DHS Appropriations Act due to "…technological advancements over the last 20 years and the emergence of the U.S. Global Positioning System (GPS)…" [24] [25]. However, interest in redeploying a LORAN system has increased since the LORAN-C signal was terminated, due to increased awareness of the vulnerabilities of GPS. This is evidenced by the following language in the Coast Guard Authorization Act of 2015: "…enter into cooperative agreements, contracts, and other agreements with Federal entities and other public or private entities, including academic entities, to develop a positioning, navigation, and timing system to provide redundant capability in the event Global Positioning System signals are disrupted, which may consist of an enhanced LORAN system." Research into potential Alternative Position, Navigation, and Timing (APNT) capabilities has included Cooperative Research and Development Agreements (CRADAs) looking into enhanced LORAN (or "eLORAN") technologies [17]. Note that Section 1606 of the

National Defense Authorization Act for Fiscal Year 2018 directed the Secretary of Defense, the Secretary of Transportation, and the Secretary of Homeland Security to jointly develop a plan for carrying out a backup GPS capability and complementary PNT demonstration, and to conduct the demonstration [27]. The Request for Information (RFI) from potential demonstrators was distributed May 3rd, 2019, and demonstrations are expected to begin Spring of 2020 [47].

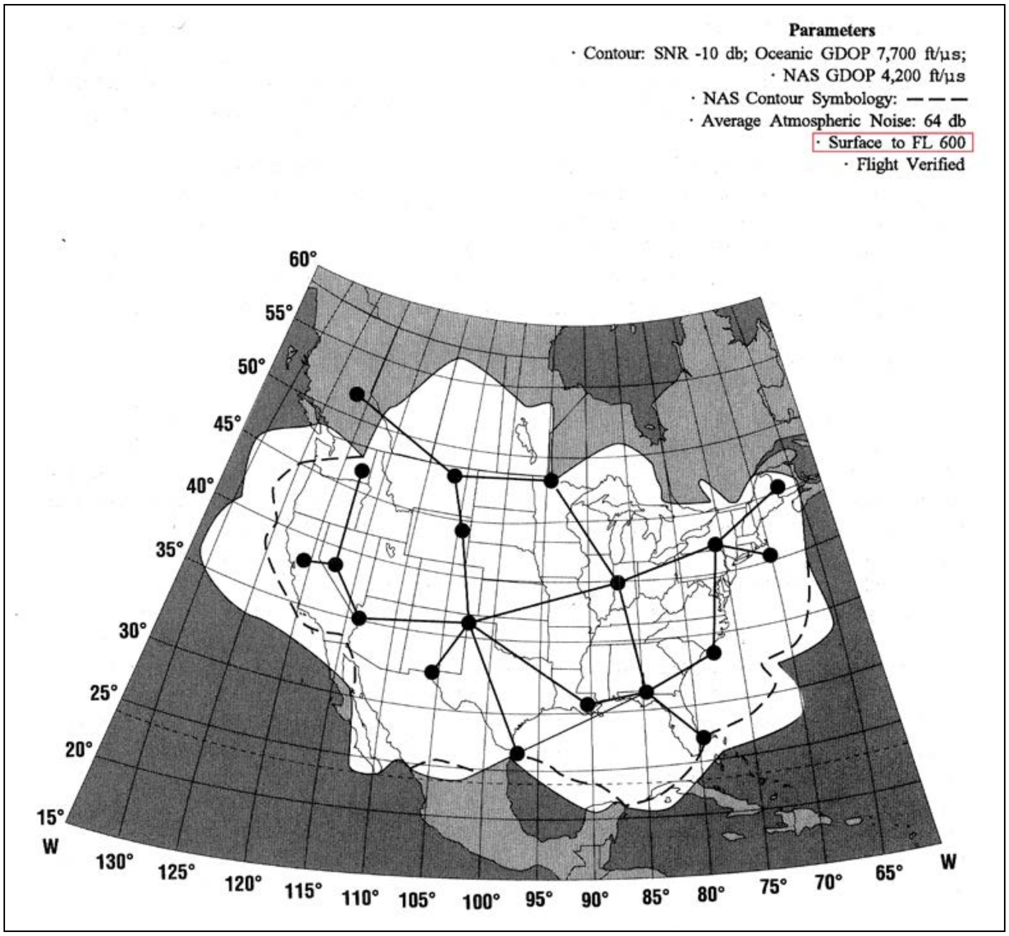


Figure 3-16. Former LORAN-C NAS Coverage [29]

3.1.5.1. Advantages of LORAN-C Include:

- Decades of use supporting navigation of civilian and military aircraft before it was terminated. There was an effort to retain LORAN-C facilities, after termination, to prepare for a potential new LORAN to be fielded [26].
- Wide ranging coverage (Figure 3-16).
- Able to withstand jamming and spoofing. Thus, it is being considered as a back-up to GPS.
- eLORAN Accuracy could be good enough to accomplish RNP .3 performance [34].

- The system is relatively inexpensive due to there being less systems needed than VOR, DME, or TACAN. Anecdotally, a U.S. LORAN system could run for 20 years for the same cost as one GPS satellite [35].

3.1.5.2. Disadvantages of LORAN-C Navigation Include:

- It is no longer available. This discussion depends on the possibility of a LORAN program being reinvigorated.
- Coverage was only guaranteed up to FL 600, as shown in Figure 3-16.
- It only provides location information –altitude information is still needed for complete navigation.

3.1.5.3. LORAN Changes Necessary for Greater ETM Support

Because eLORAN has been identified as a possible future navigation system, the LORAN-C concept was described here to give the reader an understanding in case eLORAN is considered for use in ETM airspace. Since it has yet to be fielded, eLORAN's final specific characteristics are unknown. One likely way that it will differ from LORAN-C is that it will have a data channel, which can transfer differential corrections to the receiver and, thus, make the accuracy high enough for demanding aviation applications, such as non-precision approaches [28].

LORAN-C was used over the U.S. and Oceanic areas, up to FL 600 (Figure 3-16). Whether eLORAN (if it is deployed) could be used at altitudes above FL 600 will need to be investigated. There is some indication that there were inaccuracies in the LORAN-C signal that increased with elevation [30].

3.2. Satellite-Based Navigation

3.2.1. Global Navigation Satellite Systems (GNSS)

Satellite navigation (satnav) in the airborne environment consists of pilot or autopilot control of aircraft based on autonomous geo-spatial positioning enabled by satellites. Electronic receivers onboard aircraft determine vehicle location using radio signals transmitted by satellites. These signals contain satellite locations and precise time measurements.

A satnav receiver calculates its range to a single satellite (pseudorange) using a coded time of transmission, estimated time of reception, and the speed of light. Pseudorange to a single satellite in orbit, combined with transmitted location of the satellite, narrows the receiver position to a sphere surrounding the satellite (i.e., range could be in any direction). Using pseudoranges to three satellites, the principle of trilateration (intersection of spheres) narrows location to two possible positions. One of these possibilities is sometimes infeasible and the correct option is easily selected.

A fourth satellite signal is necessary to address differences in accuracy between receiver and satellite clocks. Additionally, any position ambiguity from a three satellite solution is resolved. The general theory of relativity is also accounted for by factoring in different clock speeds due to location relative to the Earth's center of gravity. Figure 3-17 illustrates satellite based trilateration using four signals.

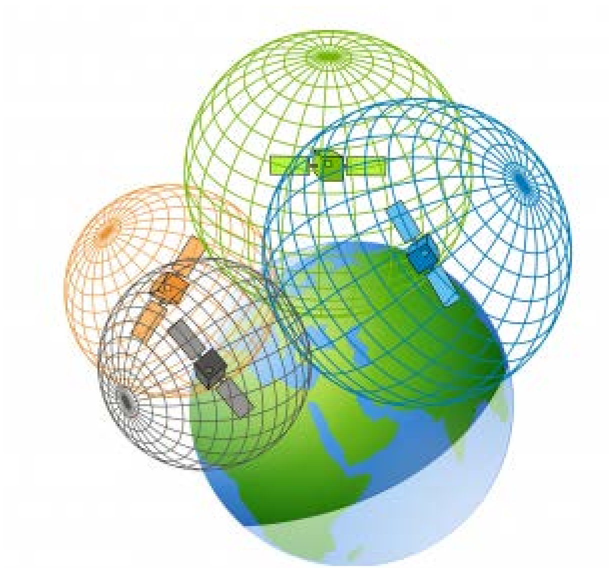


Figure 3-17. Satellite Based Trilateration

A constellation of navigation satellites that provides global coverage is referred to as a global navigation satellite system (GNSS). Two GNSS constellations are fully operational: the Global Positioning System (GPS) operated by the U.S. Air Force and GLONASS operated by the Russian state corporation Roscosmos. Two additional constellations are in development: Galileo (European Union) and BeiDou (China). Global coverage is generally achieved with a constellation of 20 to 35 Medium Earth orbit (MEO) satellites spread between several orbital planes.

3.2.1.1. Global Positioning System (GPS)

GPS receivers typically estimate position using the World Geodetic System 1984 (WGS84) ellipsoidal model of the Earth. WGS84 coordinates consist of latitude, longitude, and height above ellipsoid (HAE). HAE is also commonly referred to as geometric altitude. GPS receivers can also estimate horizontal velocity within a plane that is tangential to the WGS-84 ellipsoid; vertical velocity is orthogonal to this tangential plane.

Aircraft navigation using GPS is typically performed by a Flight Management System (FMS). An FMS compares estimated horizontal position (latitude, longitude) to desired position along a route and adjusts the aircraft configuration accordingly. It should be noted that despite availability of HAE, most manned aircraft in the ATM environment execute vertical navigation based on pressure altitude. Both FMS and pressure altimetry are discussed in more detail subsequently.

3.2.1.1.1. Advantages of GPS Include:

- Decades of use supporting navigation of civilian and military aircraft in all phases of flight.
- GPS satellite signals are continuously available for position determination globally up to altitudes of 3000 kilometers (km), a region of space also known as the GPS Terrestrial Service Volume (TSV).
- GPS is a key enabler of the NextGen program and PBN.
- Global GPS average horizontal position accuracy is 9 m (95%) and average vertical position accuracy is 15 m (95%). Within the Contiguous United States (CONUS), Alaska, Hawaii, and Puerto Rico, measured horizontal position accuracy is 2.3 m or less (95%) and vertical position accuracy is 4.0 m or less (95%) per the SPS Performance Analysis (PAN) report [49]. However, it should be noted that current FAA procedure approval processes often assume horizontal GPS errors of roughly 100 m [50]. This assumption is based on performance with Selective Availability (SA) on and fewer total satellites in orbit.

3.2.1.1.2. Disadvantages of GPS Include:

- GPS possesses several vulnerabilities. Civilian GPS signals transmitted from MEO are often weak at receiver locations. Because of this characteristic, receivers are vulnerable to jamming (interference) and spoofing (purposeful false signals). Additionally, the constellation is susceptible to powerful solar activity (e.g., flares).
- Many GPS receivers are disabled if they sense they are going faster than 1,000 nautical miles per hour (1,000 knots) or are above 18,000 meters (59,000 ft). This is due to conformance to “COCOM limits.” COCOM (Coordinating Committee for Multilateral Export Controls) was a multi-national group that was created after World War II to embargo military sensitive products from countries associated with the Soviet Union. COCOM was disbanded in 1994, but many receiver manufacturers still adhere to the COCOM restrictions. These limitations were intended to prevent the use of GPS in intercontinental ballistic missile-like applications [41]. Presently the governing organization is the U.S. Department of State (DOS), and the policy is known as the International Traffic in Arms Regulations (ITAR). It dictates limits for when a manufacturer has to register with and abide by the restrictions of the DOS: if the GPS receiver is “specially designed for use with rockets, missiles, SLVs, drones, or unmanned air vehicle systems capable of delivering at least a 500 kg payload to a range of at least 300 km,” and it exceeds the limits above (greater than 1,000 knots or above 18,000 meters). Also, if the receiver is specially designed for military applications or for airborne applications capable of providing navigation information at speeds in excess of 600 m/s,

then it needs to be registered with the DOS [46].[11] While the conditions under which the limits apply have been narrowed, there are still receivers in circulation that use the previous limits (1,000 knots and 18,000 meters) as a cutout point.

3.2.1.1.3. Current GPS Support for ETM:

- GPS is currently being used for navigation and surveillance of Loon HALE telecommunications balloons operating in ETM airspace (e.g., 70,000 ft).
- Although details remain classified, it is reasonable to assume that GPS is being used for surveillance and navigation of high altitude unmanned military vehicles that operate at the boundary between ATM and ETM airspace. These vehicles may also be operating in lower ETM airspace.
- The GPS system as currently configured, and as currently restricted through ITAR, supports all subsonic ETM vehicles envisioned.

3.2.1.1.4. GPS Changes Needed for Greater ETM Support:

- It is unclear if ITAR restrictions apply to supersonic passenger aircraft. If these aircraft are considered military or missile technology per somewhat ambiguous ITAR definitions, they may require an operational waiver in addition to special GPS equipment for navigation in ETM airspace. However, this may only be necessary for vehicles that travel at speeds of 600 m/s or greater (roughly Mach 1.75 or more). Some quiet supersonic transport (SST) concepts are envisioned to travel at speeds below this threshold (e.g., Mach 1.4).

3.2.1.2. Space Based Augmentation System (SBAS)

GPS augmentation systems improve SPS accuracy and integrity. These systems employ GPS receivers that have been installed at precisely surveyed locations. GPS measurements are continuously compared to the known locations, corrections are calculated, and appropriate modifications are transmitted to end users with special receivers. There are two classes of GPS augmentation systems: the space-based augmentation system (SBAS) and ground-based augmentation system (GBAS).

GBAS, previously known as the Local Area Augmentation System (LAAS), is typically installed at an airport and provides extremely accurate position information to aircraft within roughly 25 NM. GBAS is used domestically (e.g., IAH, EWR) and internationally (e.g., Sydney) for precision approaches. Because GBAS is limited to operations in the terminal area, it is not applicable to the ETM environment.

[11] Note that even if the ITAR criteria are not met, there may still be a requirement to register with the Department of Commerce [53].

However, SBAS is applicable to ETM operations and there are multiple implementations. The Wide Area Augmentation System (WAAS), developed by the FAA for civil aviation, provides coverage for CONUS, Alaska, Hawaii, and Puerto Rico. Precisely surveyed Wide Area Reference Stations (WRS) across the NAS receive signals from GPS satellites. WRS sites relay comparative information to WAAS Master Stations (WMS). Each WMS generates messages containing corrective information, sends these messages to uplink stations, which in turn transmit to geostationary orbit (GEO) communications satellites. These satellites broadcast messages on a GPS-like signal. WAAS-enabled receivers within the coverage region process the augmentation message during GPS position estimation.

WAAS Localizer Performance with Vertical guidance (LPV) is an approved navigation source for precision approaches in the NAS. WAAS LPV is used down to Category I approach minima (e.g., 200 ft ceiling).

The European Geostationary Navigation Overlay Service (EGNOS) is an SBAS with coverage across Europe. Similar to WAAS, EGNOS relies on a network of ground stations and geostationary satellites to provide GPS corrections to appropriately enabled receivers. EGNOS was also designed for safety critical systems such as aircraft and ships.

Other operational SBAS implementations include Japan's Multi-functional Satellite Augmentation System (MSAS) and India’s GPS-Aided GEO Augmented Navigation (GAGAN) system. The Quasi-Zenith Satellite System (QZSS) is a Japanese SBAS that is being expanded to provide regional satellite navigation independent of GPS in the 2023 timeframe. In addition to these operational systems, other SBAS implementations are in development for use in Chinese and Russian airspace. Figure 3-Y illustrates global SBAS coverage.

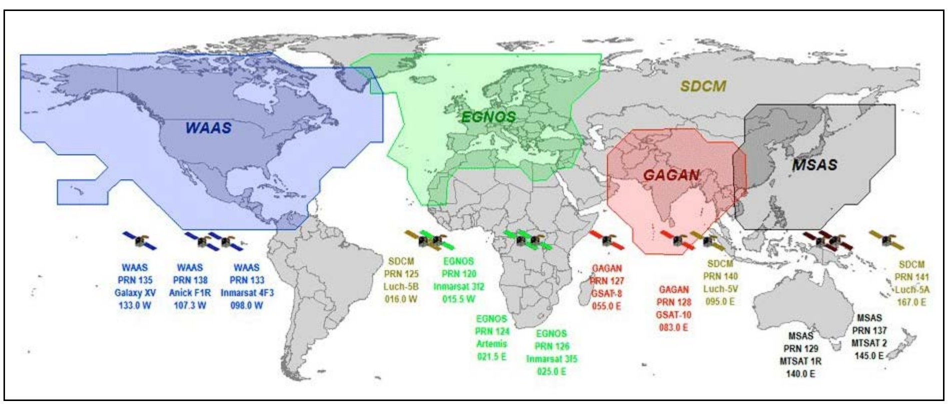


Figure 3-Y. Global SBAS Coverage

3.2.1.2.1. Advantages of SBAS Include:

- Widespread use in civil aviation, including precision approaches.

- Horizontal position accuracy generally around 2 m or less (95%). WAAS LPV accuracy has been measured at 0.8 m (95%) horizontally and 1.4 m (95%) vertically per the WAAS Performance Analysis (PAN) report [51].

3.2.1.2.2. Disadvantages of SBAS Include:

- GPS vulnerabilities (e.g., jamming, spoofing, natural interference) propagate to SBAS. However, it should be noted that SBAS does provide an alerting capability if significant GPS issues are detected (enhanced integrity).
- SBAS (e.g., WAAS) enabled receivers may be subject to ITAR restrictions depending on age, manufacturer, and intended use.
- SBAS avionics are not consistently deployed across the ATM fleet. Large airframe manufacturers (e.g., Boeing, Airbus) provide SBAS enabled GPS receivers as options on some aircraft, but historically have offered GBAS multi-mode receivers (MMRs) in greater numbers. SBAS (WAAS) equipage is more widely deployed across the general aviation fleet. It is unclear how these disparate manufacturer business models will impact ETM.

3.2.1.2.3. Current SBAS Support for ETM:

- The WAAS performance standard [52] specifies coverage up to an altitude of 100,000 ft for the region encompassing CONUS, Alaska, Hawaii, the Caribbean islands, and a large portion of oceanic airspace. All subsonic ETM vehicles operating up to 100,000 ft within an appropriate coverage volume should be able to employ SBAS navigation.
- Supersonic aircraft may require ITAR waivers to employ SBAS enabled receivers, depending on vehicle speed.
- HALE balloons, potentially operating up to 160,000 ft, will be outside of SBAS coverage (e.g., WAAS). The frequency and density of this traffic may not warrant expanded SBAS coverage volumes, however, this could be investigated. GPS SPS may be sufficient in this region of ETM airspace.

3.3. Aircraft-Based Navigation

3.3.1. Inertial Navigation System (INS)

An Inertial Navigation System (INS) is an aircraft-based navigation system that uses accelerometers and gyroscopes for navigation (Figure 3-15). By the process of resolving and integrating the accelerations acquired from the accelerometers, the aircraft’s velocity, distance flown, and direction flown from a reference point can be derived. These can be used to determine the aircraft’s current location and heading. The accelerometers cannot distinguish between the accelerations of the aircraft from the acceleration due to gravity, so it is important the accelerometers are kept level (so gravity is not sensed).

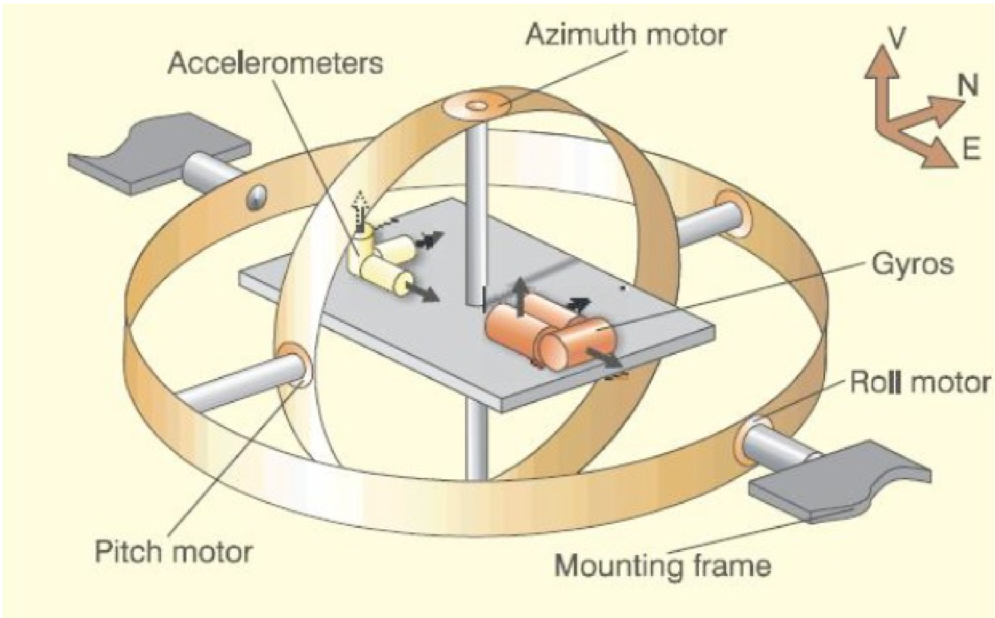


Figure 3-15. Simplified Inertial Navigation System (INS)[12] [19]

Thus, the gyroscopes are needed to keep the accelerometer platform level, since, due to conservation of angular momentum, they have inertia and resist motion. The gyroscopes do not have to be large, rotating devices. For example, modern aircraft use optical gyroscopes such as the "ring laser gyro," which, as the name suggests, use a laser to detect deviations from level [18]. Also, the rotating devices can be microscopic wheels, also known as Microelectro-mechanical Systems (MEMS), which enable the INS to be very small and lightweight, and more easily integrated with other navigation systems (e.g., GNSS). The federal regulations for INS are contained in 14 CFR 121, Appendix G.

3.3.1.1. Advantages of INS Include:

- Completely self-contained. No ground-based or satellite-based signals are necessary for navigation.
- Can operate at any altitude. In fact, INS was used for navigation at different stages of the Apollo spacecraft flights [20].
- Well established technology. The technology has been present since the 1940's and is used in many aircraft and spacecraft today [22].

[12] Does not show the computing unit

3.3.1.2. Disadvantages of INS Include:

There is an error that increases with time. This error, known as ”gyro drift," is due to small errors (e.g., not completely accounting for gravity) accumulating over time and becoming large enough to render the INS-derived position untrustworthy. Different INS’s have different drift rates, depending on their quality, but “the growth in position error after reverting to INS/IRU [Inertial Reference Unit] can be expected to be less than 2 NM per 15 minutes.” [21]

3.3.1.3. Current INS Navigation Support for ETM:

INS is well suited for ETM, especially since there is no upper altitude limit for its use. The biggest obstacle to its use for ETM is the increase in INS error due to gyro drift. In order to use INS in ETM, the amount of accuracy needed in ETM airspace would need to be defined and compared to the possible error due to gyro drift to determine how long the INS output would be valid. In ATM applications, gyro drift is usually mitigated by integrating the output of the INS with another navigation signal (e.g., GNSS or DME) and using the other signal when the INS position is not trustworthy (see section on Sensor Integration).

Note that the equipage requirement for RNP 10 (Oceanic) can be fulfilled by two Inertial Navigation System (INS) systems, with a 2.0 nm /hour drift rate, for up to 6.2 hours of flight time [21].

3.3.2. Other Onboard Navigation Technologies

3.3.2.1. Altitude Equipment

Altitude information is necessary to accomplish three-dimensional navigation. Presently, an altimeter is required of any powered civilian aircraft flying in Class E Airspace under Visual Flight Rules (VFR) or Instrument Flight Rules (IFR) [38]. This has historically been a pressure (or barometric) type of altimeter. There are other types of altimetry, as well:

- GNSS, which gives geometric height above ellipsoid (HAE)
- Radar, which gives height above ground level (AGL)
- INS

3.3.2.1.1. Pressure Altimetry in the ETM Environment

Pressure altimetry uses the concept that ambient air pressure changes with changes in aircraft altitude. Normally, when the aircraft altitude increases, the ambient air pressure decreases. A pressure altimeter senses the outside air pressure and presents the corresponding altitude to the pilot, the autopilot, or to Air Traffic Control (via a Mode-C transponder downlink). A pressure altimeter can be a simple device that in mounted in the airplane dashboard and presents the altitude, via dials, directly to the pilot (Figure 3-16). The altimeter could also be part of an Air Data Computer (ADC), which takes static and dynamic air pressures and temperature, performs calculations on them, and presents to the pilot or autopilot a more accurate representation of altitude and airspeed. Pressure altimetry can also be in the form of an altitude encoder, which senses the outside air pressure and encodes it to a form used by a Mode-C transponder to "squawk" the aircraft's pressure altitude to an air traffic control facility on the ground. Note that the altitude encoder does not present altitude information to the pilot and will not fulfill the requirements for VFR or IFR operation mentioned previously.

A problem with using pressure altimetry devices in the ETM environment is that they likely have not been certified to operate at ETM altitudes of more than 60,000 ft MSL. The standards for dashboard mounted altimeters and ADCs allow the manufacturer to decide the maximum altitude of their device, but the test criteria within those standards go no higher than 50,000 ft [39][42]. If a manufacturer decides to create an altimeter with a maximum height greater than that, there will likely need to be special coordination with the FAA for approval. The same appears to apply to altitude encoders [40][43]. However, the author found an altitude encoder that is qualified for use to 100k ft MSL. The availability of high-altitude (> 60,000 ft) dash-mounted altimeters and ADCs will need to be investigated. If additional work indicates that pressure altitude is required for some ETM operations, it may be necessary to initiate a revision process for altimeter and air data computer standards. Current technology may support development of commercial barometric altimetry systems that accurately function in ETM airspace presently associated with military operations (e.g., 60,000 to 80,000 ft).

Pressure altimetry has increased errors with increased altitude or speed [42][44][45]. The ability to correct for the errors and the implications of this on ETM operations should be studied further, if pressure altimetry is to be selected for ETM operations. Note that since pressure altimetry uses the same aircraft sensors that are used to measure rate-of-climb, angle-of-attack, and airspeed, these measurements can also have increased errors with altitude.

Figure 3-16. Dash-Mounted Pressure (or Barometric) Altimeter

3.3.2.1.2. GNSS Altimetry in the ETM Environment

GNSS altimetry, also known as "geometric altitude," uses the same methodology as is used for GNSS position determination: the travel times of the signals from several satellites to the receiver are used to provide the altitude, as well as the two-dimension location of the receiver.

One significant problem with using GNSS for altimetry is the statement given in AC 20-138D, "Airworthiness Approval of Positioning and Navigation Systems," paragraph 5-7: "GNSS-provided geometric altitude is not adequate for compliance with air traffic control altitude requirements in the national airspace system (NAS) or internationally. The primary barometric altimeter must be used for compliance with all air traffic control altitude regulations, requirements, instructions, and clearances." In fact, there is another paragraph (11-1) in the same AC which states "**The barometric altimeter must always be the primary altitude reference for all flight operations.**" (Bold font in source document.)

The reason for not being able to use GNSS as the primary source would need to be studied further if it is desired to use for altimetry.

Another problem with using GNSS altimetry in the ETM environment is that many GPS receivers are disabled if they sense they are going faster than 1,000 nautical miles per hour (1,000 knots) <u>or</u> are above 18,000 meters (59000 ft), to conform to the outdated COCOM limits, as mentioned previously.

While the conditions under which the limits apply have been narrowed, there are still receivers in circulation that use them as a cutout point. This should also be a consideration if GPS is to be used for altimetry.

3.3.2.1.3. Radar Altimetry

Radar altimeters have been used in aviation for several decades. Essentially, it involves a radar pointed at the ground, and by using the two-way travel time of the radar pulse, it determines the aircraft's elevation. The only TSO in the FAA's inventory having to do with Radar Altimetry is TSO-C87a, entitled "Airborne Low-Range Radio Altimeter." As suggested by the name, the range would not be sufficient to serve the ETM environment. The maximum altitude given in the predecessor edition, TSO-C87 is 500 ft. Thus, radar altimetry is not a promising existing system which can be used for ETM operations.

3.3.2.1.4. INS Altimetry

As mentioned previously, Inertial Navigation Systems (INSs) have errors that increase with time. These errors are even more pronounced in the vertical channel, due to several factors not as significant in the horizontal channels, such as gravity and centrifugal acceleration [18]. These errors need to be compensated for by integrating the INS outputs with another sensor, such as a pressure altimeter or GNSS. Techniques to accomplish INS integration with pressure altimetry have existed for many years [45][48]. The performance of current techniques would need to be studied thoroughly and satisfactorily demonstrated to the regulators before it could be acceptable as a primary altitude reference.

3.3.2.2. Sensor Integration

An on-board system, known as a Flight Management System (FMS) can take the outputs from several sensors or receivers (e.g., GNSS, DME, INS, etc), perform RNAV calculations on those outputs, and present more sophisticated navigation data to the pilot or autopilot (Figure 3-17). "An FMS allows you [the pilot] to enter a series of waypoints and instrument procedures that define a flight route. If these waypoints and procedures are included in the navigation database, the computer calculates the distances and courses between all waypoints in the route. During flight, the FMS provides precise guidance between each pair of waypoints in the route, along with real-time information about aircraft course, groundspeed, distance, estimated time between waypoints, fuel consumed, and fuel/flight time remaining (when equipped with fuel sensors)." [37]

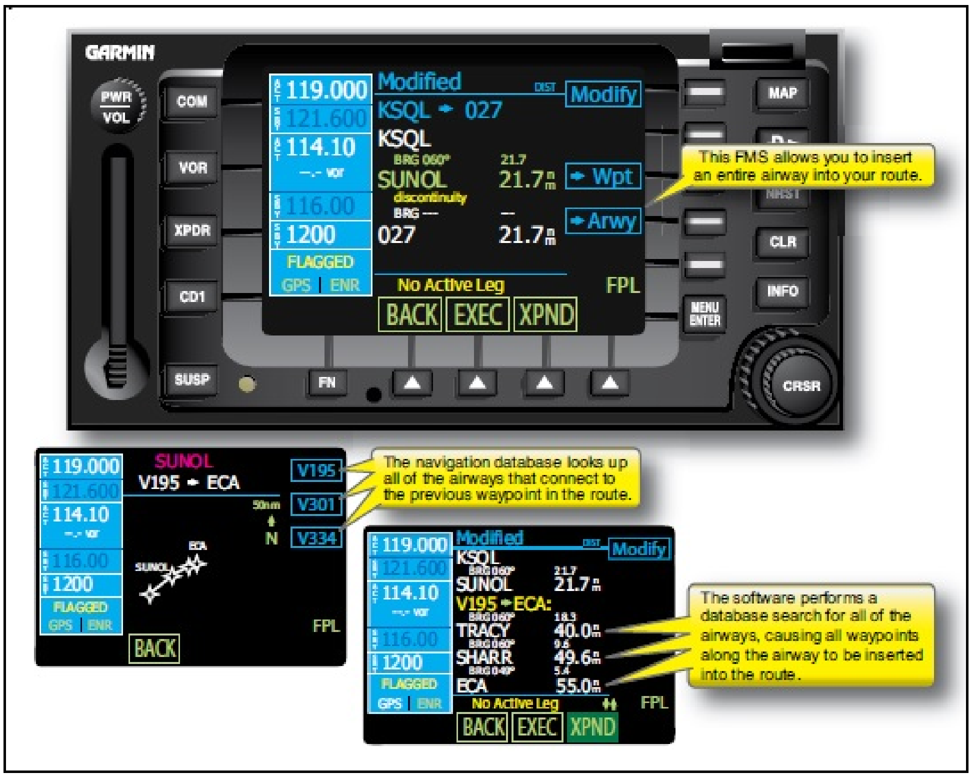


Figure 3-17. A Flight Management System (FMS) [37]

The FAA's Advisor Circular AC 20-138, "Airworthiness Approval of Positioning and Navigation Systems," contains the requirements for FMSs and the sensors themselves for meeting particular RNP/RNAV levels.

FMSs have the ability to prioritize their sensor inputs. A possible prioritization schedule is:

1 GNSS
2 DME/DME
3 INS

With such a schedule, the GNSS is given first preference for navigation. If it does not meet performance requirements, the FMS resorts to using two or more DMEs to determine its position (RNAV DME/DME). If those do not meet performance requirements, then it uses INS.

The FAA's Nextgen DME Program is presently striving to provide coverage by two or more DME's in all Class A Airspace up to FL 450 [33]. This is to attain the PBN NAS Strategy goal of providing RNAV DME/DME capability in the en route environment without the need for INS [9].

4. Conclusions

This document describes the most common systems currently used for navigation in the upper ATM environment, their advantages and disadvantages, their current support for ETM, and what would be necessary of these systems for greater ETM support. One existing system that can be used for (two dimensional) navigation in the ETM environment would be GNSS. However, GNSS Receivers chosen for use at altitudes above 60,000 ft would, of course, need to be operational in that realm. Many GPS receivers in circulation were/are made to be disabled when used beyond the outdated COCOM limits (speeds greater than 1,000 knots and altitudes greater than 59,000 ft). GNSS could be used for the third dimension (altitude) determination also; however, the FAA presently requires that only pressure altimetry be used for operations. Unfortunately, pressure-based altimeter and Air Data Computer standards only provide for testing to 50,000 ft. Thus, for ETM support, qualification of commercial altimeters and ADCs above 50,000 ft would be needed. For resilient, two-dimensional navigation, RNAV DME/DME (an RNAV computing system, using two or more DME inputs to calculate the aircraft's location) could be used at the lower elevations of the ETM environment. An examination of DME power available charts suggest that, in many cases, there is sufficient signal strength available at those elevations. In those areas where the DME signal strength is not sufficient, an INS could be used to "fill in" and provide navigation information. INS integrated with pressure altimetry may also be able to provide altitude data in the ETM environment.

Note that there presently is an effort to identify an alternate Positioning, Navigation, and Timing (PNT) system that would provide resilient navigation in the event of a loss of GPS. The demonstration of candidate systems to decision makers is scheduled to begin Spring of 2020. ELORAN is one such system that is expected to be demonstrated. ELORAN may also be able to be used for ETM operations.

5. Acknowledgments

The authors would like to acknowledge the following aerospace professionals for their invaluable assistance: Pedro Lopez, Nelson Spohnheimer, and Victor Hinton.

6. References

[1] Federal Aviation Administration, 2018, Upper Class E Traffic Management (ETM) Operational Shortfalls Analysis, Washington, D.C., U.S. Department of Transportation.

[2] FAA PPT Presentation: "VOR MON Program Update," December 2018

[3] FAA, "Final Program Requirements Document VOR MON," July 24th, 2015

[4] FAA, AC 00-31A, United States (U.S.) National Aviation Standard for the Very High Frequency Omnidirectional Radio Range (VOR) / Distance Measuring Equipment (DME) / Tactical Air Navigation (TACAN) Systems, FAA, 9/20/82

[5] FAA Order 6050.32B, Spectrum Management Regulations and Procedures Manual, Appendix 2, 11/17/05 (with Change 3, dated 6/11/19)

[8] FAA Academy Text Book, DME Principles, November 1980.

[9] FAA Document, Performance Based Navigation (PBN) NAS Strategy 2016

[10] FAA Power Point Presentation, "VOR MON Program, National Planning Meeting," April, 2018

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

[12] Listing of High VOR, VOR/DME, and VORTAC sites obtained from the FAA intranet website "Technet."

[13] FAA Order 6820.7D, "Maintenance of Navigational Aids Facilities and Equipment – VOR, DVOR, VOR-DME, VORTAC," 3/27/2018

[14] FAA Internet Website, "Navigation Programs - NextGen DME." https://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/transition_programs/nextgen_dme/

[15] FAA Academy Training Manual: "TACAN/DME Principles," November 1992

[16] FAA's Intranet Application: "Facility, Service, and Equipment Profile (FSEP)"

[17] "2017 Federal Radionavigation Plan," Published by the DOD, DHS, and DOT

[18] R.P.G Collinson, "Introduction to Avionics," Chapman and Hall, Microwave Technology Series 11, 1998

[19] Tampere University of Technology "Basic Principles of Inertial Navigation, Seminar on Inertial Navigation Systems."

[20] Draper Laboratory, "Apollo Guidance and Navigation," Volume 1 of 2, June 1965

[21] FAA, AC 20-138D, “Airworthiness Approval of Positioning and Navigation Systems,” 4/7/16

[22] Wikipedia, “Inertial Navigation System.”

[23] U.S. Coast Guard, “LORAN-C User’s Handbook,” November 18th, 1992

[24] Website, U.S.D.H.S, U.S. Coast Guard Navigation Center, “LORAN-C GENERAL INFORMATION,” 6/8/2012 https://www.navcen.uscg.gov/?pageName=loranMain

[25] Federal Register, Vol. 75, No. 4, Thursday, January 7, 2010, pg. 998

[26] U.S. Law, Coast Guard Authorization Act of 2015, Section 681

[27] Website, Federal Register, “Demonstration of Backup and Complementary Positioning, Navigation, and Timing (PNT) Capabilities of Global Positioning System (GPS),” 05/03/2019

https://www.federalregister.gov/documents/2019/05/03/2019-09092/demonstration-of-backup-and-complementary-positioning-navigation-and-timing-pnt-capabilities-of

[28] International LORAN Association, “eLORAN Definitions Document,” Consultation Version, 12 January 2007, pg. 3

[29] FAA AC 90-92 (Cancelled), “Guidelines for the Operational Use of LORAN-C Navigation Systems Outside the U.S. National Airspace System (NAS),” 2/5/93

[30] U.S. Coast Guard Academy, “Loran ASF Variations as a Function of Altitude,” 2006

[31] Keith W. Bose, “Aviation Electronics,” Second Edition, 1976

[32] International Civil Aviation Organization (ICAO), “Performance-based Navigation (PBN) Manual,” Third Edition — 2008

[33] FAA, “Final Program Requirements Document for the NextGen DME Program,” June 2017.

[34] Proceedings of the 33rd annual symposium of the International Loran Association, “Meeting Aviation Requirements for eLoran – An Improved H-field Antenna,” 25-27 October 2004 (Enough?)

[35] Interview by Der Spiegel of David Last, “considered one of the most respected navigation technology professionals in Europe. The 79-year-old was President of the British Royal Institute of Navigation and President of the International Loran Association,” as conveyed by the Resilient Navigation and Timing Foundation, July 30th, 2019.

[36] Informal conversation with Nextgen DME Program Implementation Lead, 8/8/19.

[37] FAA, “Advanced Avionics Handbook,” Document FAA H-8083-6, 2009

[38] Federal Aviation Regulation: 14 CFR § 91.205

[39] FAA Technical Standard Order C-106, which references SAE AS 8002, dated 1981.

[40] FAA TSO-C88b, which references SAE AS 8003, Dated 1974, reaffirmed 2008

[41] Wikipedia, “Coordinating Committee for Multilateral Export Controls,” 16 July 2019

[42] FAA TSO C10C, which references SAE AS 8009, Dated 1975, revised 2016

[43] FAA AC 43-6D, Altitude Reporting Equipment and Transponder System Maintenance and Inspection Practices, 2/15/17

[44] NASA Report, Measurement of Aircraft Speed and Altitude, William Gracy, 1980

[45] NASA Contractor Report, Study of the Concept of Inertially Aided Barometric Altimetry System for Supersonic Aircraft, by J. Ray Rzletenik, John H. Thompson, and Kenneth R. Britting, June 1971

[46] Federal Regulation, CFR 22, Chapter I, Subchapter M, International Traffic in Arms Regulations:

https://www.ecfr.gov/cgi-bin/text-idx?gp=&SID=70e390c181ea17f847fa696c47e3140a&mc=true&tpl=/ecfrbrowse/Title22/22CIsubchapM.tpl

[47] Website,

https://www.gpsworld.com/us-dot-moves-aggressively-on-gps-backup-rfp-this-month/

[48] IFAC Automatic Control in Aerospace, A New Error Compensation Scheme for INS Vertical Channel, Seo, Lee, Park, 2004

[49] Federal Aviation Administration, 2016, Global Positioning System (GPS) Standard Positioning Service (SPS) Performance Analysis Report, Report #93, Atlantic City, NJ, William J. Hughes Technical Center.

[50] Geyer, M. et al., 2014, RNAV (GPS) Total System Error Models for Use in Wake Encounter Risk Analysis of Dependent Paired Approaches to Closely Spaced Parallel Runways, DOT-VNTSC-FAA-14-05, Cambridge, MA, U.S. DOT Volpe National Transportation Systems Center.

[51] Federal Aviation Administration, 2016, Wide Area Augmentation System Performance Analysis Report, Report #55, Atlantic City, NJ, William J. Hughes Technical Center.

[52] Federal Aviation Administration, 2008, Global Positioning System Wide Area Augmentation System (WAAS) Performance Standard, 1st Edition, Washington DC, U.S. Department of Transportation.

[53] Department of Commerce and FAA, “Introduction to U.S. Export Controls for the Commercial Space Industry,” 2nd Edition – November 2017