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# Existing Navigation Technologies for Upper Class E Traffic Management (ETM)

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# 1 Abstract

Upper Class E Traffic Management (ETM) is the system envisioned to support an increasing number of operations above 60,000 feet (ft). This paper discusses existing ground, satellite, and aircraft-based navigation technologies and their 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. Additionally, aircraft-based technologies, such as Inertial Navigation Systems (INS), are discussed. These navigation capabilities are assessed in terms of general advantages, disadvantages, and current level of support for ETM.

# 2 Introduction

### 2.1 Overview of ETM

Operations above Flight Level (FL) 600 are expected to increase in the future. Multiple vehicle types are anticipated to be active in this airspace. Uncrewed Free Balloons (UFBs) with minimal flight path control and short mission durations may operate up to altitudes of 160,000 ft. High Altitude Long Endurance (HALE) balloons could potentially operate up to altitudes of 100,000 ft with mission durations up to several to months. Solar-powered, HALE fixed-wing aircraft are expected to loiter between FL600 and FL900 for several months with daily climbs during daylight and minimally powered descents at night to maintain air speed. HALE airships, controllable in both direction and altitude, are also expected in this airspace with current designs capable of operating up to 60,000 ft. Additional entrants potentially include stratospheric "space" tourism balloons.

Multiple airframe manufacturers are developing Supersonic Transports (SSTs), including both larger (e.g., 65 passenger) and smaller business jet models. SSTs are expected to initially cruise at speeds between Mach 1.0 and Mach 2.5, at altitudes between FL500 and FL600. Subsequently developed SSTs may be capable of even greater speeds at higher altitudes. Hypersonic aircraft, while still mostly in the concept phase, are also vehicles that should be considered. Carrier aircraft for air-launched space vehicles may also operate in this environment. Figure 1 depicts renderings of a HALE telecommunications balloon, a HALE fixed-wing aircraft, and an SST.



Figure 1: High-Altitude Vehicles

The policies, regulatory framework, infrastructure, and procedures in place today may not costeffectively scale to accommodate the disparate vehicle performance characteristics and operational diversity expected in this environment. The ETM concept addresses these shortfalls with principles drawn from traditional Air Traffic Management (ATM), Uncrewed Aircraft System (UAS) Traffic Management (UTM), and operations currently performed above FL600 [1]. Figure 2 contains a notional depiction of the ETM environment, including Cooperative Areas (CAs), where many operations are expected to occur. This document focuses on the navigation component of the ETM concept.



Figure 2: Notional Depiction of the ETM Environment

### 2.2 Aircraft Navigation

As described in the 2019 Federal Radionavigation Plan, aircraft navigation "includes determining position, orientation, course and distance to the desired destination, and deviation from the desired track" [2]. This has been accomplished for many years in the traditional ATM environment using a variety of systems, some based solely in the aircraft, and some using ground or satellite-based components in combination with aircraft components.

Aircraft-based systems were the first instruments used for navigation beyond visual acquisition of landmarks. Initially, these included compasses, altitude indicators, and gyroscope-driven attitude and turn-and-slip indicators. Later, more sophisticated gyroscopic systems such as the INS were developed.

Ground-based systems requiring communication with an aircraft component via radio waves began with the Low Frequency (LF) ranges installed by the United States (U.S.) government in the 1920s. Transmitting systems on the ground sent signals to receivers on the aircraft. Each signal was modulated with Morse Code and conveyed to the pilot whether or not the aircraft was flying on a

course toward a particular 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 VORs in the 1940s [3]. VORs are still being used today, as further described in Section 3.1.1. Other ground-based Navigation Aids (NAVAIDs) 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 in the 1950s 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 the U.S. 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. GPS is currently available to all users on a continuous, worldwide basis, free of any direct user charges.

With the proliferation of different navigation systems and the introduction of Area Navigation (RNAV) equipment, which integrates data from multiple navigation systems to provide directroute 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 [4].

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" [5].

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, as shown in Figure 3.

	Approact	Arrival	En Route	Departure	
(GPS), P)	RNAV 1, RNP 1, RNAV A-RNP, RNAV (R	RNAV 1, RNP 1, A-RNP	RNAV 2 and A-RNP, Oceanic: RNP 2, RNP 4, and RNP 10	RNAV 1, RNP 1, A-RNP	
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Figure 3: RNAV/RNP Specifications for Different Operations [5]

Figure 4 shows the values of performance requirements for different phases of flight/operations. For example, under the en route phase of flight in Figure 3, oceanic operations can use an RNP 4 specification. This corresponds to a performance requirement for lateral and along-track accuracies within  $\pm$ 4 Nautical Miles (NM) for at least 95% of the total flight time.

	MEASURES OF MINIMUM PERFORMANCE CRITERIA TO MEET REQUIREMENTS						
REQUIREMENTS	ACCURACY (95%)			CONTINUETY	INTEODITY	TIME TO	COVERAGE
	Horizontal	Vertical		CONTINUITY	INTEGRIT	ALERT	COVERAGE
Oceanic	10 or 4 nmi***	N/A	0.99 - 0.99999		1-1x10-7//hr	N/A	N/A
Enroute	2 nmi	N/A	0.99 - 0.99999	1-1x10≄/hr to 1-1x10⁴/hr	1-1x10ग/hr	5 min	N/A
Terminal	1 nmi	N/A	0.99 - 0.99999	1-1x10⊀/hr to 1-1x10-∜hr	1-1x10 <sup>-7</sup> /hr	15 s	N/A
Non Precision Approach	220 m	N/A	0.99 - 0.99999	1-1x10+/hr to 1-1x10⁵/hr	1-1x10-7/hr	10 s	N/A
APV-I	16 m	20 m	0.99 - 0.99999	1-8x10-∜15 s	1-2x10-7 in any approach	10 s	N/A
APV-II	16 m	8 m	0.99 – 0.99999	1-8x10∿/15 s	1-2x10-7 in any approach	6 s	N/A
CATI	16 m	6 – 4 m	0.99 - 0.99999	1-8x10⁵/15 s	1-2x10 <sup>-7</sup> in any approach	6 s	N/A
<ul> <li>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.</li> <li>** Not Specified by ICAO, Annex 10, Vol. 1, Table 3.7.2.4-1, Signal-in-Space Performance Requirements.</li> </ul>							

\*\*\* Depends on the navigation specification (RNP 10 or RNP 4) employed in the oceanic area.

Figure 4: RNP Performance Requirements for Different Airspaces/Operations

Accuracy, in the context of RNAV and RNP, defines the 95% Total System Error (TSE). TSE is a composite mainly made up of three types of errors (Figure 5) [4].

• **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 accuracy of the electronics or signal-in-space.

- Flight Technical Error (FTE) has to do with pilot or autopilot capability to maintain (i.e., 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 system's ability to correctly define the desired path. Errors here could be due to inaccuracies in the system's database of fix, waypoint, and NAVAID locations.



Figure 5: TSE Components

# **3** Navigation Technologies

This section describes the most common systems currently used for navigation and PBN in the traditional ATM environment, their advantages and disadvantages, and current support for ETM.

### 3.1 Ground-Based Navigation

#### 3.1.1 Very High Frequency (VHF) Omni-Directional Range (VOR)

A VOR is a ground-based navigation system (shown in Figure 6) that provides azimuth information to a receiver on an aircraft.



Figure 6: 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 AM signal has a modulation phase that varies depending on the azimuth of the aircraft with respect to the ground station and magnetic north (illustrated by Figure 7). The VOR receiver on the aircraft detects the phase relationship between the FM reference and AM variable signals, driving an indicator that 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. (Figure 8).



Figure 7: Phase Relationships Between VOR FM and AM Signals [6]



Figure 8: VOR and Victor Airways

Most VOR ground systems are co-located with one of two systems that provide distance information to other instruments in aircraft: DME or a TACAN system. The combination provides the pilot (or autopilot) with a two-dimensional location of the aircraft, 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 co-located with a DME, it is known as a VOR-DME. The DME and TACAN systems are discussed in-depth in Sections 3.1.2 and 3.1.3, respectively. The VOR receiver can also feed an 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 aircraft to follow paths that do not terminate on a VOR, allowing more direct flights.

#### 3.1.1.1 VOR Advantages

Advantages of VORs include:

- Decades of use supporting navigation of civilian and military aircraft in all phases of flight.
- Wide ranging coverage (shown in Figure 9).



Figure 9: 2016 VOR Network 40 NM Service Volume at 5,000 ft [7]

• The capability 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, the VOR Minimum Operational Network (MON) program [8] has been established to serve as an Alternate Positioning, Navigation, and Timing (APNT) method in the event that GPS is disrupted. One objective of the MON 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 5,000 ft and higher (Figure 10).



Figure 10: Planned VOR MON 70 NM Service Volume at 5,000 ft [7]

- An established infrastructure supported by Federal Aviation Administration (FAA) logistics and maintenance programs.
- The ability to provide a signal to at least 60,000 ft Above Transmitter Height (ATH). When differences between transmitter height and ground level are negligible, ATH and Above Ground Level (AGL) values are comparable. As shown in Figure 11, the current Frequency Protected Service Volumes (FPSVs) of some VORs (i.e., High class) reach a maximum elevation of 60,000 ft ATH [9]. An FPSV is a volume protected from frequency interference by adjacent facilities. It is essentially the same as the operational service volume, which is the coverage area advertised to be available and have sufficient signal strength.



Figure 11: VOR FPSVs [9]

#### 3.1.1.2 VOR Disadvantages

Disadvantages of VOR navigation include the following.

- VORs typically have a TSE of ±4.5 degrees (i.e., 95% probability) [10]. Cross-track accuracy worsens with distance from the station (e.g., 4.5 degrees at 130 NM from a VOR station corresponds to a cross-track accuracy of 10.21 NM). Navigation TSE achieved with VORs is significantly greater than that provided by other means such as GPS.
- The normal range of operation for a VOR is only up to roughly 60 degrees in elevation angle [10]. Aircraft above this elevation angle can encounter unreliable and erratic indicator outputs.
- VORs only provide azimuth information. Altitude and distance information are still needed for complete navigation.
- Structures, foliage, or other objects near a VOR facility can cause reflections (or multipath) of the signal that interfere with the directly propagated signal. This can cause unreliable and erratic indicator outputs. To mitigate this, restrictive easements are usually constructed around facilities, contributing to increased costs.
- VOR equipment and infrastructure are aging as many were installed in the 1980s, causing the need for expensive refurbishments.

#### 3.1.1.3 Current VOR Navigation Support for ETM

The main factor limiting VOR navigational support for ETM is the elevation of FPSV ceilings. It is possible that some FPSVs exist above FL600 for VORs with a ground elevation greater than zero ft above Mean Sea Level (MSL). The VOR in the Contiguous U.S. (CONUS) with the greatest elevation is Red Table (DBL) near Eagle, Colorado; it has a High FPSV with a ground elevation of 11,800 MSL, potentially placing the FPSV ceiling well above FL600.

Additionally, High VOR installations may provide sufficient signal strength above FL600 for some operations. Figure 12 shows it is possible to have more than the required level of signal strength (-123 decibel watts, or dBW) above 60,000 ft AGL [9]. However, it should be noted that only roughly 45% of all VORs are presently in the High category.



Figure 12: VOR Power Available Curves [9]

#### 3.1.2 Distance Measuring Equipment (DME)

DME is a ground-based navigation system (shown in Figure 13) that uses the two-way travel time of pulse pairs to provide distance information to a pilot (or autopilot).



Figure 13: DME Ground Installation

Determination of distance is initiated by an interrogator on an aircraft transmitting two pulses, separated by a specific time interval of 12 microseconds (Figure 14). These pulses are received by a 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.<sup>1</sup> The interrogator determines the overall time elapsed from initial pulse transmission and, by using the speed of light, the slant range between the aircraft and the ground station can be determined. The processing time of the transponder is accounted for by the interrogator [11]. The distance can be presented to the pilot as a digital display and/or sent to a Flight Management System (FMS) for integration with other NAVAID (e.g., VOR) data.



Figure 14: Block Diagram of DME [11]

Nearly all DMEs are presently co-located with a facility that provides azimuth data (e.g., a VOR), to enable determination of two-dimensional position in both distance and azimuth. This is changing, however, with the VOR MON and NextGen DME programs. The VOR MON program, as mentioned earlier, is reducing the number of VORs, leaving standalone DMEs. The NextGen DME 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" [5]. This will result in an increase in DME-only coverage at higher elevations in Class A airspace.

#### 3.1.2.1 DME Advantages

Advantages of DME include:

<sup>&</sup>lt;sup>1</sup> 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. The fixed processing time of the transponder for the "Y" mode is 56 microseconds.

- Decades of use supporting navigation of civilian and military aircraft in all phases of flight.
- Wide ranging coverage in CONUS, above 24,000 ft in the U.S. Western Mountainous Area (USWMA), and 18,000 ft elsewhere (illustrated by Figure 15); this coverage is expected to increase due to the NextGen DME program (shown in Figure 16).



Figure 15: Existing DME Coverage



Figure 16: Planned DME Coverage

- The capability to withstand jamming and spoofing, as with VOR, due to relatively high signal strength.
- An established infrastructure supported by FAA logistics and maintenance programs, with continued support.

#### 3.1.2.2 DME Disadvantages

Disadvantages of DME include the following.

- DME has a required NSE of ±0.5 NM (926 meters (m)) or 3% of the slant range distance, whichever is greater (95% probability). This is required when the airborne system error and the ground system error (considered no greater than 0.1 NM) are combined by the root-sum-square method [10]. Accuracy decreases with increased distance to the DME station. For example, at 130 NM, the required accuracy is 3.9 NM. This is significantly greater than that provided by other means such as GPS.
- DME FPSVs possess the same dimensions as those for a co-located VOR (Figure 11), unless the DME is used for RNAV operations. In that case, it will have the dimensions shown in Figure 17 [9]. In either case, like VORs, DME signals are only protected up to a maximum elevation of 60,000 ft ATH.



Figure 17: DME FPSVs for RNAV Operations [9]

- A single DME only provides distance information; altitude and azimuth information are still needed for complete navigation. However, two-dimensional location information can be derived by performing RNAV calculations on information from two or more DMEs (known as DME/DME RNAV).
- Ground distance is not equivalent to slant range calculated by a DME receiver. With greater elevation angles, there is less of a correspondence between slant range and ground distance to the DME station.

#### 3.1.2.3 Current DME Navigation Support for ETM

As with VOR, it is possible that a DME FPSV exists above FL600 for a transmitter with an elevation above zero ft MSL. Also, it is possible that sufficient signal strength is present above defined FPSVs. As shown in Figure 18 and Figure 19, the theoretical power available exceeds the lower limit (-114.5 dBW) above 60,000 ft AGL for some DMEs [9]. Considering both of these factors, it may be possible to use DMEs for some expected ETM operations. As with VORs, only roughly 45% of all DMEs are presently in the High category [12]; FPSVs that exist above FL600 are dependent on the ground elevations of respective DMEs. The number of High DMEs will be increasing with the NextGen DME program.



Figure 18: FAA dBS5100A DME Power Available Curves [9]



Figure 19: Cardion DME Power Available Curves [9]

#### 3.1.3 Tactical Air Navigation System (TACAN)

TACAN is a ground-based navigation system that builds upon DME to provide azimuth and distance information to an aircraft; however, use of the azimuth information is limited 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 co-located with a VOR, and the two together are known as a VORTAC (shown Figure 20, with a TACAN antenna indicated).



Figure 20: VORTAC Station

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 [13].

#### 3.1.3.1 TACAN Advantages

Advantages of TACAN include:

- Decades of use supporting navigation of civilian aircraft (distance) and military aircraft (azimuth and distance) in all phases of flight.
- Wide ranging coverage in the U.S.; approximately 440 stations are presently commissioned.
- Low susceptibility to jamming and spoofing, as with the VOR and DME, due to the relatively high signal strength.
- An established infrastructure supported by FAA logistics and maintenance programs. "The Department of Defense (DoD) requirement for land-based TACAN will continue until military aircraft are properly certified for RNAV/RNP operations" [2].

#### 3.1.3.2 TACAN Disadvantages

Disadvantages of TACAN include the following.

- The azimuth TSE requirement for TACAN is the same as for VOR: +4.5 degrees (95% probability). The distance NSE requirement for TACAN is the same as for DME: 0.5 NM (926 m) or 3% of the slant range distance, whichever is greater (95% probability) [10]. There is the same decrease in accuracy as with the VOR and DME, with an increase in distance from the TACAN. These navigation errors are significantly larger than those associated with other systems such as GPS.
- As with VORs and DMEs, TACAN FPSVs are only defined to a maximum altitude of 60,000 ft ATH. TACANs have the same FPSVs as the VORs they are co-located with (Figure 11), unless they are used for RNAV operations, in which case FPSVs are identical to those shown in Figure 17 [9].
- TACAN only provides azimuth information to military aircraft. Generally, civilian aircraft cannot use TACAN receivers for azimuth information.
- Within the FAA, the TACAN Reduction Initiative aims to reduce the number of TACANs in inventory by either eliminating them or converting them to DME only [7]. Many TACANs have already been identified for elimination or conversion.
- TACANs only provide azimuth and distance information. Altitude information is still needed for complete navigation.

#### 3.1.3.3 Current TACAN Navigation Support for ETM

As with the DME, it is possible that TACAN FPSVs exist above FL600 for stations with a ground elevation greater than zero ft MSL. Also, it is possible that sufficient signal strength is present

above some FPSVs. In Figure 21, the limit of coverage (the curve indicating -114.5 dBW) extends above 60,000 ft AGL. It may be possible to use TACANs for some ETM operations.



Figure 21: TACAN Power Available Curves [9]

### 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 (i.e., 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 center of gravity of the Earth. Figure 22 illustrates satellite-based trilateration using four signals.



Figure 22: Satellite Based Trilateration

A constellation of navigation satellites that provides global coverage is referred to as GNSS. Four GNSS constellations are fully operational: GPS operated by the U.S. Air Force, GLONASS operated by the Russian state corporation Roscosmos, Galileo operated by the European Union, and the Chinese BeiDou system. 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 an FMS. An FMS compares estimated horizontal position (i.e., latitude, longitude) to desired position along a route and adjusts the aircraft configuration accordingly. It should be noted that, despite availability of HAE, most crewed aircraft in the traditional ATM environment execute vertical navigation based on pressure altitude. Both FMS and pressure altimetry are discussed in more detail in Section 3.3.

#### 3.2.1.1.1 GPS Advantages

Advantages of GPS include the following.

- 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 3,000 kilometers (km), a region of space also known as the GPS Terrestrial Service Volume (TSV).

- GPS is a key enabler of the FAA NextGen program and PBN.
- Global GPS average horizontal position accuracy is roughly 9 m (95%) and average vertical position accuracy is 15 m (95%). Within CONUS, Alaska, Hawaii, and Puerto Rico, horizontal position accuracy has been measured at 2.3 m or less (95%) and vertical position accuracy has been measured at 4.0 m or less (95%) per the Standard Positioning Service (SPS) Performance Analysis (PAN) report [14]. However, it should be noted that current FAA procedure approval processes often assume horizontal GPS errors of roughly 100 m [15]. This assumption is based on past performance with SA on and fewer total satellites in orbit.

#### **3.2.1.1.2 GPS Disadvantages**

Disadvantages of GPS include the following.

- 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., solar flares).
- Presently, the governing organization for GPS receivers is the U.S. Department of State (DOS) and the policy is known as the International Traffic in Arms Regulations (ITAR). If a GNSS receiver is specially designed for military applications or airborne applications capable of providing navigation information at speeds in excess of 600 m/s, then it needs to be registered with the DOS and may be disabled once that condition is triggered [16]. These ITAR restrictions have relaxed previous requirements that indicated GNSS receivers would be disabled if they sensed vehicle speeds faster than 1,000 knots (kts) or were above altitudes of 18,000 m (roughly 59,000 ft). The limitations were intended to prevent the use of GNSS in intercontinental ballistic missile-like applications.

#### 3.2.1.1.3 Current GPS Support for ETM

The GPS system, as currently configured and restricted through ITAR, supports all subsonic ETM vehicles envisioned. GPS receivers have been employed for operations above FL600 by former and current operators; examples include:

- HALE telecommunications balloons employed GPS for navigation and surveillance when operating up to FL700.
- GPS used for surveillance and navigation of high-altitude UAS that operate up to 65,000 ft MSL.

The 600 m/s ITAR speed limit for GPS receivers equates to roughly Mach 2.03 at FL600, assuming the International Standard Atmosphere (ISA) and no wind. Initial SST deployments operating below Mach 2.03 (e.g., at Mach 1.7) would, in theory, be capable of employing GPS for navigation, as well as surveillance inputs. Subsequently developed SSTs capable of greater speeds, as well as hypersonic vehicles, would cruise above the ITAR limit; however, it is unclear if conceptual passenger aircraft would be classified as military or missile technology per current policy.

#### **3.2.1.2** Space-Based Augmentation System (SBAS)

GPS augmentation systems improve both 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 in the U.S. and internationally for precision approaches. However, because GBAS is limited to operations in the terminal area, it is not applicable to the expected ETM environment.

SBAS is potentially 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 (WRSs) across the U.S. National Airspace System (NAS) receive signals from GPS satellites. WRS sites relay comparative information to WAAS Master Stations (WMSs). Each WMS generates messages containing corrective information and 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 (LPV) guidance 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. EGNOS support for Galileo GNSS augmentation is in development.

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 addition to these operational systems, other SBAS implementations are in development for use in Chinese and Russian airspace. Figure 23 illustrates global SBAS coverage.



Figure 23: Global SBAS Coverage

#### 3.2.1.2.1 SBAS Advantages

Advantages of SBAS include:

- Widespread use in civil aviation for precision navigation.
- Horizontal position accuracy generally near 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 PAN report [17].

#### 3.2.1.2.2 SBAS Disadvantages

Disadvantages of SBAS include the following.

- GNSS vulnerabilities (e.g., jamming, spoofing, natural interference) propagate to SBAS. However, it should be noted that WAAS provides an alerting capability if significant GPS issues are detected for enhanced integrity.
- SBAS (e.g., WAAS) enabled receivers may be subject to ITAR restrictions, depending on intended use and vehicle performance.

#### 3.2.1.2.3 Current SBAS Support for ETM

The WAAS performance standard [18] 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 horizontal SBAS navigation.

Initial SST deployments operating below Mach 2.03 (e.g., at Mach 1.7) would, in theory, be capable of employing SBAS for navigation, as well as surveillance inputs. Subsequently developed SSTs capable of greater speeds, as well as hypersonic vehicles, would cruise above the ITAR limit; however, it is unclear if conceptual passenger aircraft would be classified as military or missile technology per current policy.

Some balloons, potentially operating up to 160,000 ft, will be outside of SBAS coverage (e.g., WAAS). However, the GPS SPS alone may be sufficient in this region of expected ETM airspace.

#### 3.2.2 Multiple Global Navigation Satellite System (Multi-GNSS) Navigation

Stakeholders for global and regional satnav systems form the United Nations (UN) International Committee on GNSS (ICG). The ICG is actively working toward development of interoperable equipment (e.g., receivers). An alternate GNSS capability not previously discussed is the Satellite Time and Location (STL) service. STL receivers employ Doppler positioning using signals from the Iridium satellite constellation in Low Earth Orbit (LEO).

Multi-GNSS navigation could be performed with interoperable receivers or a processor/tracker interfaced to multiple independent receivers. Figure 24 depicts available GNSS constellations; SBAS satellites are included in the graphic.



Figure 24: GNSS Satellites

#### 3.2.2.1 Multi-GNSS Navigation Advantages

The primary advantages of multi-GNSS navigation are the following.

- Multi-GNSS navigation provides increased availability and redundancy; at any given time, a significantly greater number of satellites would be available for navigation. Aircraft employing this capability could continue to operate in the event of disruption to a single GNSS.
- Multi-GNSS position accuracy is expected to be similar to that provided by a single constellation (e.g., GPS). However, position errors that currently occur due to a change in visible satellites from a single constellation may be reduced; this would require further characterization. STL has been advertised to provide position accuracy of roughly 30 to 50 m, however, typical performance may be on the order of 100 m.
- STL signals are also encrypted and are significantly more powerful than traditional GNSS signals due to origination in lower orbits. These characteristics make STL more resilient to

both jamming and spoofing. In theory, multi-GNSS navigation would be resilient to spoofing by virtue of the fact that many different signals would need to be falsified to produce a desired result.

#### 3.2.2.2 Multi-GNSS Navigation Disadvantages

Key disadvantages of multi-GNSS navigation include the following.

- Traditional GNSS signals (e.g., originating in MEO) are relatively weak. Interoperable receivers or multi-input processors/trackers may be as susceptible to jamming as a single source system; this vulnerability would require further study to fully characterize.
- Similarly, multiple GNSS constellations may also be vulnerable to natural phenomena such as solar storms.
- STL is dependent on GPS for time synchronization. In the event of a GPS failure, the system is designed to use Rubidium-disciplined timing receivers at ground stations around the world. However, it is reasonable to assume that performance would be degraded.
- Multi-GNSS receivers would likely still be subject to ITAR speed restrictions.

#### 3.2.2.3 Current Multi-GNSS Navigation Support for ETM

HALE telecommunications balloons that operated up to FL700 around the world employed a multi-GNSS capability; however, the effort has since concluded. These vehicles were equipped with redundant GPS receivers and Iridium positioning technology.

#### **3.3** Aircraft-Based Navigation

#### 3.3.1 Inertial Navigation System (INS)

An INS is an aircraft-based navigation system that uses accelerometers and gyroscopes for navigation (illustrated in Figure 25). By the process of resolving and integrating acquired accelerations, aircraft velocity, distance flown, and direction flown from a reference point can be derived. These can be used to determine aircraft location and heading. Accelerometers cannot distinguish between the accelerations of the aircraft and those due to gravity, so it is important that the units are kept level (to ensure gravity is not sensed).



Figure 25: Simplified INS [19]

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 ring laser gyros, which use a laser to detect deviations from a level position [20]. Additionally, the rotating devices can be microscopic wheels, also known as Microelectro-Mechanical Systems (MEMS), which enable an INS to be small and lightweight, and more easily integrated with other navigation systems (e.g., GNSS). The federal regulations for INS are contained in the Code of Federal Regulations (CFR) Title 14, Part 121, Appendix G.

#### 3.3.1.1 INS Advantages

Advantages of INS include the following.

- INS devices are completely self-contained. No ground-based or satellite-based signals are necessary for navigation.
- INS can operate at any altitude. INS was used for navigation at different stages of the Apollo spacecraft flights [21].
- INS technology has been present since the 1940s and is used in many aircraft and spacecraft applications.

#### **3.3.1.2 INS Disadvantages**

Disadvantages of INS include the following.

• Errors, known as gyro drift, increase with time. This occurs due to small errors (e.g., not completely accounting for gravity) accumulating over time and becoming large enough to render the INS-derived position inaccurate. Different INS types have different drift rates, depending on their quality, but the growth in position error can typically be expected to be less than 2 NM per 15 minutes [22].

#### 3.3.1.3 Current INS Navigation Support for ETM

INS is well suited for ETM operations as there is no upper altitude limit for its use. The biggest obstacle to its use for ETM operations is the increase in error due to gyro drift. In traditional 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. The equipage requirement for RNP 10 (oceanic flights) can be fulfilled by two INS systems, with a 2.0 NM/hour drift rate, for up to 6.2 hours of flight time [22].

#### 3.3.2 Altitude Equipment

Altitude information is necessary to accomplish three-dimensional navigation. Presently, an altimeter is required for any powered civilian aircraft flying in Class E airspace under Visual Flight Rules (VFR) or Instrument Flight Rules (IFR) [23]. This has historically been a pressure (or barometric) altimeter. Other types of altimetry include GNSS, which provides geometric HAE, and INS. Radar altimeters that provide geometric elevation AGL, typically used for precision approaches, generally work up to altitudes of 500 ft and are therefore not expected to be used for ETM operations.

#### **3.3.2.1 Pressure Altimeters**

A pressure altimeter determines aircraft altitude above MSL based on ambient air pressure changes. Normally, when 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 (ATC) (via a Mode C transponder downlink). A pressure altimeter can be a simple device that is mounted in the airplane dashboard and presents the altitude, via dials, directly to the pilot (Figure 26). 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 provides a more accurate representation of altitude and airspeed. Pressure altitude can also be encoded by a Mode-C transponder to transmit the information to an ATC facility on the ground. An altitude encoder does not present altitude information to the pilot and will not fulfill the requirements for VFR or IFR operations.



Figure 26: Dash-Mounted Pressure (or Barometric) Altimeter

The standards for dashboard-mounted altimeters and ADCs allow manufacturers to decide the maximum altitude of their devices, but the test criteria within those standards go no higher than 50,000 ft [24]. While some commercial barometric altimeters have been approved for use between 50,000 ft and 60,000 ft (e.g., business jets and Concorde), it is generally believed that most traditional civilian systems do not provide useful information above 60,000 ft. At least one modern system has been approved for use up to 70,000 ft based on extrapolation of requirements defined to 50,000 ft. One manufacturer/operator employed these units in HALE telecommunication balloons that operated in various locations around the world up to FL700. Some military barometric altimeters were required to indicate pressure altitude up to 80,000 ft per MIL-STD-843. Above FL800, it is possible that atmospheric density is too low to support accurate pressure altimetry measurements with commercial systems.

Similar limitations appear to apply to most commercial altitude encoders. However, at least one altitude encoder qualified for use to 100,000 ft was identified. Pressure altimeters produce increased errors at greater altitudes or speeds. Because pressure altimeters use the same aircraft sensors that are used to measure rate-of-climb, angle-of-attack, and airspeed, these measurements can also have increased errors at greater altitudes.

#### 3.3.2.2 GNSS Altimeters

GNSS altimetry uses the same methodology as is used for GNSS position determination. The travel times of the signals from several satellites to a receiver are used to provide geometric altitude (i.e., HAE), as well as the horizontal location of the receiver.

One significant problem with using GNSS for altimetry is the statement given in the FAA Advisory Circular (AC) 20-138D, Airworthiness Approval of Positioning and Navigation Systems [22], paragraph 5-7: "GNSS-provided geometric altitude is not adequate for compliance with ATC altitude requirements in the NAS or internationally. The primary barometric altimeter must be used for compliance with all ATC altitude regulations, requirements, instructions, and clearances." 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." This is possibly due to large discrepancies that can exist between barometric and GNSS altitude measurements for a single aircraft. GNSS and pressure altitude measurements produced by equipment in the same aircraft may differ by thousands of feet. This is caused by different references (i.e., MSL and the WGS84 ellipsoid) as well as factors such as pressure gradients.

Another potential problem with using GNSS altimetry in the ETM environment is that ITAR restrictions limit GPS receiver functionality to vehicles operating slower than 600 m/s, as mentioned previously. Horizontal speed in excess of this threshold could potentially trigger all output to be suppressed, including geometric altitude.

#### 3.3.2.3 INS Altimeters

As mentioned previously, INS units produce 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 [20]. These errors need to be compensated for by integrating INS outputs with another sensor, such as a pressure altimeter or GNSS receiver.

Techniques to accomplish INS integration with pressure altimetry have existed for many years [25].

#### 3.3.3 Sensor Integration

An onboard 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 27). "An FMS allows [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)" [26].



Figure 27: FMS [26]

The FAA's AC 20-138D, Airworthiness Approval of Positioning and Navigation Systems [22], contains the requirements for FMS units and sensors for meeting particular RNP/RNAV levels. FMS units have the ability to prioritize sensor inputs. A possible prioritization schedule is:

- 1. GNSS
- 2. DME/DME
- 3. INS

With such a schedule, 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 focusing on providing coverage by two or more DMEs in all Class A airspace up to FL450 [27]. 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 [5].

# 4 Conclusions

This document described the most common systems currently used for navigation, associated advantages and disadvantages, and current level of support for ETM. One existing system that could be used for (two-dimensional) navigation in the ETM environment would be GNSS. However, GNSS receivers for aircraft operating at speeds in excess of 600 m/s (equivalent to Mach 2.03 for ISA at FL600) need to be registered with the DOS and may be disabled if that condition is triggered. GNSS could also potentially be used for altitude determination; however, the FAA presently requires that only pressure altimetry be used for operations.

Most commercial pressure altimeters may not provide useful barometric altitude information in upper Class E airspace, although it is known that at least one system has been approved for use up to 70,000 ft. 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 potentially be used at lower elevations of the ETM environment. An examination of DME power available charts suggests that, in many cases, there is sufficient signal strength available at those elevations. In those areas where the DME signal strength is insufficient, an INS could potentially be used to provide navigation information. INS integrated with pressure altimetry may also be able to provide altitude data in the ETM environment. However, INS implementations would be subject to drift errors that increase with time.

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# **Appendix B** Acronyms

All acronyms used throughout the document are provided in Table 1.

Acronym	Definition
AC	Advisory Circular
ADC	Air Data Computer
AFSPC	Air Force Space Command
AGL	Above Ground Level
AM	Amplitude Modulated
APNT	Alternate Positioning, Navigation, and Timing
ATC	Air Traffic Control
ATH	Above Transmitter Height
ATM	Air Traffic Management
СА	Cooperative Area
CFR	Code of Federal Regulations
CONUS	Contiguous U.S.
DBL	Red Table
dBW	Decibel Referenced to One Watt
DME	Distance Measuring Equipment
DoD	Department of Defense
DOS	Department of State
EGNOS	European Geostationary Navigation Overlay Service
ETM	Upper Class E Traffic Management
FAA	Federal Aviation Administration
FL	Flight Level
FM	Frequency Modulated
FMS	Flight Management System
FOC	Full Operational Capability
FPSV	Frequency Protected Service Volume
ft	Feet
FTE	Flight Technical Error
GAGAN	GPS-Aided GEO Augmented Navigation

#### Table 1: Acronyms

Acronym	Definition
GBAS	Ground-Based Augmentation System
GEO	Geostationary Orbit
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HAE	Height Above Ellipsoid
HALE	High Altitude Long Endurance
ICG	International Committee on GNSS
IFR	Instrument Flight Rules
ILS	Instrument Landing System
INS	Inertial Navigation System
IOC	Initial Operational Capability
ISA	International Standard Atmosphere
ITAR	International Traffic in Arms Regulations
KAL	Korean Airlines
km	Kilometers
LAAS	Local Area Augmentation System
LEO	Low Earth Orbit
LF	Low Frequency
LORAN	Long Range Navigation
LPV	Localizer Performance with Vertical
m	Meter
m/s	Meter per Second
MEMS	Microelectro-Mechanical Systems
MEO	Medium Earth Orbit
MON	Minimum Operational Network
MSAS	Multi-Functional Satellite Augmentation System
MSL	Mean Sea Level
NAS	National Airspace System
NAVAID	Navigation Aid
NAVSTAR	Navigation System with Timing and Ranging
NDB	Non-Directional Beacon
NM	Nautical Miles

Acronym	Definition
NSE	Navigation System Error
PAN	Performance Analysis
PBN	Performance Based Navigation
PDE	Path Definition Error
QZSS	Quasi-Zenith Satellite System
RNAV	Area Navigation
RNP	Required Navigation Performance
SA	Selective Availability
SBAS	Space-Based Augmentation System
SPS	Standard Positioning Service
SST	Supersonic Transport
STL	Satellite Time and Location
TACAN	Tactical Air Navigation
TSE	Total System Error
TSV	Terrestrial Service Volume
UAS	Uncrewed Aircraft System
UFB	Uncrewed Free Balloon
UN	United Nations
USWMA	U.S. Western Mountainous Area
UTM	UAS Traffic Management
VFR	Visual Flight Rules
VHF	Very High Frequency
VOR	VHF Omni-Directional Range
VORTAC	VOR and TACAN
WAAS	Wide Area Augmentation System
WGS84	World Geodetic System 1984
WMS	WAAS Master Station
WRS	Wide Area Reference Station