Emerging Navigation Technologies for Upper Class E Traffic Management (ETM)

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Contents

1. Abstract

Upper Class E Traffic Management (ETM) is the system envisioned to support operations above 60,000 feet (ft). Vehicles expected in this airspace include Unmanned Free Balloons (UFBs), High Altitude Long Endurance (HALE) unmanned systems, and reintroduced supersonic passenger aircraft. This paper discusses emerging navigation technologies and their applicability to aircraft in the ETM environment. These capabilities include surveillance position uplink, navigation with multiple Global Navigation Satellite System (multi-GNSS) inputs, integrated communication, navigation, and surveillance (CNS), implementation of enhanced LORAN (eLORAN) technology, and additional technologies such as inertial reference systems augmented with star tracking. These emerging navigation technologies were assessed in terms of general advantages, disadvantages, current level of support for ETM (if applicable), and changes necessary to enable or enhance ETM support.

2. Introduction

Activity above 60,000 feet (ft) in upper class E airspace is expected to increase. Anticipated vehicles include Unmanned Free Balloons (UFBs), High Altitude Long Endurance (HALE) balloons, HALE fixed wing aircraft, HALE airships, and supersonic passenger aircraft. UFBs with short mission durations are expected to operate up to altitudes of 160,000 ft. HALE balloons, operating up to similar altitudes, will extend mission durations to an average of 100 days. Solar powered, HALE fixed wing aircraft are expected to loiter between Flight Level 600 (FL600) and FL900 for three to six months. HALE airships, currently capable of operating up to 60,000 ft, are also expected to be active in this airspace.

Supersonic passenger aircraft are expected to cruise at speeds between Mach 1.0 and Mach 2.5 at altitudes between FL550 and FL700. Subsequent generations of supersonic aircraft may be capable of even greater speeds. Hypersonic aircraft, while still mostly in the concept phase, should also be considered as potential entrants. Additionally, carrier aircraft for air launched space vehicles are potential ETM candidates. Figure 2-1 depicts (clockwise from left) a Loon HALE telecommunications balloon, a conceptual HALE fixed wing aircraft, and a rendering of the Boom supersonic transport.

Figure 2-1. High Altitude Vehicles

The infrastructure, procedures, and policies 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].

Previous work examined surveillance technologies and potential applications in the ETM environment [2]. A parallel effort [3] examined existing navigation capabilities with a focus on suitability for ETM operations; several shortfalls were identified. Very High Frequency Omni-Directional Range (VOR) and Tactical Air Navigation (TACAN) system installations at elevations above mean sea level (MSL) provide limited navigational coverage in lower ETM airspace. However, the FAA is executing initiatives to reduce both the number of VOR and TACAN sites due to age and cost of the systems. In contrast, the number of Distance Measuring Equipment (DME) sites in the United States (U.S.) is expected to increase through the NextGen DME program. However, DME coverage in ETM airspace is limited to "high" installations with ceilings of 60,000 ft above ground level (AGL); e.g., a ceiling of 65,000 ft MSL for a site with an elevation of 5,000 ft.

Satellite based navigation of aircraft in the U.S. is primarily accomplished using the Global Positioning System (GPS) and Wide Area Augmentation System (WAAS). Many existing GPS receivers were manufactured subject to International Traffic in Arms (ITAR) restrictions that prevent output when altitude is above 59,000 ft or speed is greater than 1000 knots (kts). In 2016, the altitude restriction was removed for civil applications, however, a speed restriction of 600 meters per second (m/s, or 1166 kts) may have been incorporated for all Global Navigation Satellite System (GNSS) receivers. The prevalence of GNSS receivers adhering to the less stringent ITAR requirements is not currently known.

Onboard capabilities such as the Inertial Navigation System (INS) are typically complementary to other navigation sources. An INS position source is subject to drift errors on the order of nautical miles per hour. A flight management system (FMS) would prioritize INS sources last (e.g., behind GPS and DME/DME). Vertical navigation in the ATM environment is primarily performed with information from barometric altimeters. This is due to both convention and FAA requirements for aircraft subject to air traffic control. However, most modern pressure altimetry systems are only required to operate up to 50,000 ft [4]. Generally, it is believed that most barometric altimeters do not provide useful information above 60,000 ft. Cumulatively, these shortfalls form the rationale to examine emerging navigation technologies for application in the ETM environment.

This document addresses multiple emerging navigation technologies, their advantages, disadvantages, level of support for ETM, and potential modifications. These capabilities include surveillance position uplink, multi-GNSS satellite navigation, and integrated communication, navigation, and surveillance (CNS). Additional topics include the potential implementation of enhanced Loran (eLoran), alternate forms of altitude determination, and variations of augmented INS.

3. Emerging Navigation Technologies

3.1. Surveillance Position Uplink

Several technologies are candidates for the cornerstone of an alternate position, navigation, and timing (APNT) capability generically referred to as surveillance position uplink. The system would consist of ground-based surveillance equipment and airborne avionics modified to provide navigation services. Underlying surveillance technologies include multilateration (MLAT) and components of the Surveillance and Broadcast Services (SBS) system.

3.1.1. MLAT Navigation

MLAT systems use aircraft transponder transmissions, e.g., Mode A/C, Mode S, or Automatic Dependent Surveillance – Broadcast (ADS-B), to obtain aircraft identifiers and calculate two-dimensional (2D) or three-dimensional (3D) positions. Time Difference of Arrival (TDOA) at multiple receiving stations establishes vehicle position at the intersection of several hyperboloids. Figure 3-1 depicts a generic architecture for multilateration systems adapted from [5].

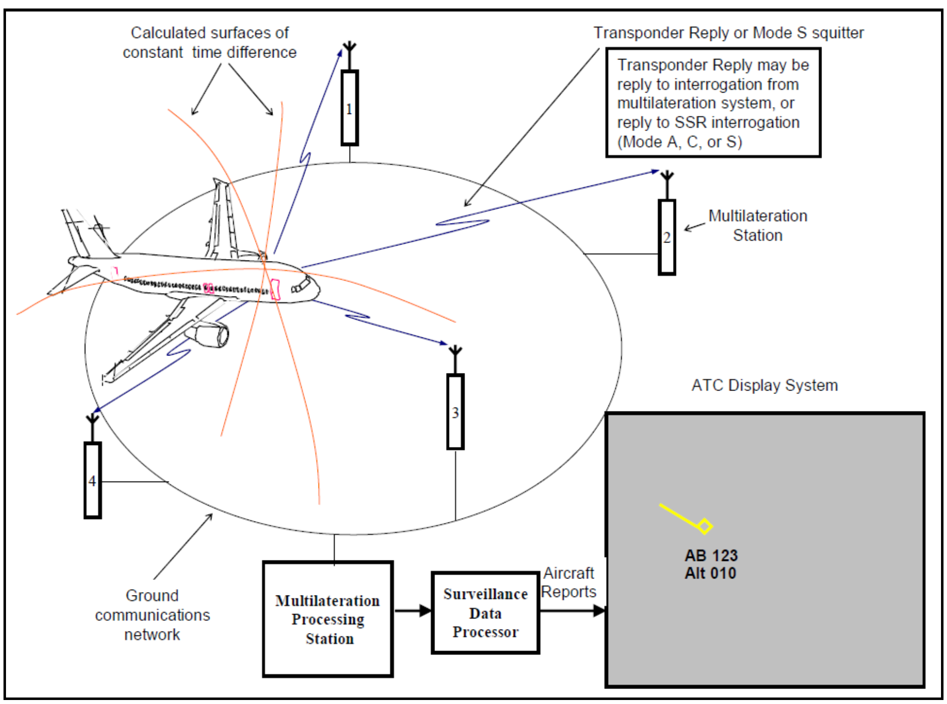

Figure 3-1. Generic Multilateration System Architecture

Triangulation with ADS-B Ground Stations (TAGS) [6] is an APNT concept that envisions aircraft position and timing determination using the SBS ADS-B radio station network. TAGS is being considered as a potential backup to GPS satellite navigation. As such, position calculation is based on multilateration of transmissions (e.g., ADS-B broadcasts) that contain identifying information such as 24-bit address, but do not necessarily contain position (e.g., during a GPS disruption). Timing information would be determined by the ground system through specialized clocks and synchronization between antennas.

The number of radio sites required for TAGS to calculate position of an individual aircraft is dependent on the availability of pressure altitude in the source transmissions (i.e., 2D position calculation plus altitude or 3D position computation) and system integrity level (fault detection and isolation). Calculated position and the corresponding time stamp would be uplinked to "ownship." In other words, the aircraft being surveilled would receive a transmission containing its own position and corresponding timestamp. This could be accomplished using either the Traffic Information Service – Broadcast (TIS-B) or Automatic Dependent Surveillance – Rebroadcast (ADS-R) component of the SBS system.

Aircraft in U.S. airspace equipped with ADS-B "In" technology may only receive vehicle-to-vehicle (V2V) transmissions from other aircraft using a frequency identical to their ADS-B "Out" broadcasts (1090 megahertz (MHz) or 978 MHz). ADS-R fills a situational awareness gap by converting downlinks on one frequency to uplinks on the other frequency. Similarly, TIS-B uplinks radar and/or MLAT derived data for aircraft not equipped with (not transmitting) ADS-B. Combined, V2V ADS-B transmissions, ADS-R uplinks, and TIS-B uplinks provide nearly complete airspace surveillance to aircraft equipped with ADS-B In.

To achieve coverage comparable to existing navigation aids, TAGS may require multiple MLAT servers interfaced to the SBS network of radios that provide ADS-B, ADS-R, and TIS-B services. Airborne avionics will also require potentially significant changes. Standards for ADS-B receivers [7][8] may need to be altered to accommodate reception and forwarding of messages uplinked from TAGS that contain the same identifier (24-bit address) as messages being transmitted from the aircraft.

Similarly, requirements for ADS-B In traffic computers [9] may need to be modified to enable appropriate processing of TAGS uplinks. For example, existing architectures have mechanisms in place to detect and suppress uplinked ownship information. However, these mechanisms could be adapted to serve a role in the TAGS concept.

The SBS system employs multi-sensor trackers (MSTs) to determine information that should be uplinked as TIS-B. MSTs typically receive MLAT (e.g., airport vicinity) and secondary surveillance radar (SSR) data for TIS-B processing. MLAT data may contain International Civil Aviation Organization (ICAO) identifiers, however, relayed SSR data does not. MSTs routinely generate radar-based TIS-B tracks with identifiers assigned by the SBS system. MSTs also produce tracks for ADS-B equipped aircraft containing ICAO addresses obtained from downlinks. In order to prevent the uplink of TIS-B for ADS-B equipped aircraft, MSTs constantly attempt to spatially correlate TIS-B type "A" (pre-uplink) tracks with those formed by ADS-B downlinks. If correlation is not achieved, a TIS-B type A track is determined to be valid for uplink (i.e., not an ADS-B equipped aircraft) and its most recent state is transmitted as TIS-B type "B." This process fails occasionally and results in what is known as a "TIS-B shadow," i.e., a ground-to-air uplink of data that is also being transmitted V2V through ADS-B.

During ADS-B In standards development, it was determined that the sudden appearance of an ownship TIS-B shadow on a Cockpit Display of Traffic Information (CDTI) may cause flight crews to take evasive actions when none are necessary. To mitigate this, ADS-B In surveillance processors are required to perform a function known as ownship shadow detection. One logic path in sample algorithms for this function identify an ownship shadow as a TIS-B track that meets the following criteria: an ICAO address identical to that in ownship ADS-B broadcasts, ADS-B and TIS-B horizontal position agreement of 1 nautical mile (NM) or less, and ADS-B and TIS-B vertical position agreement of 500 ft or less. An existing sample architecture for this function in ADS-B traffic processors is illustrated in Figure 3-2.

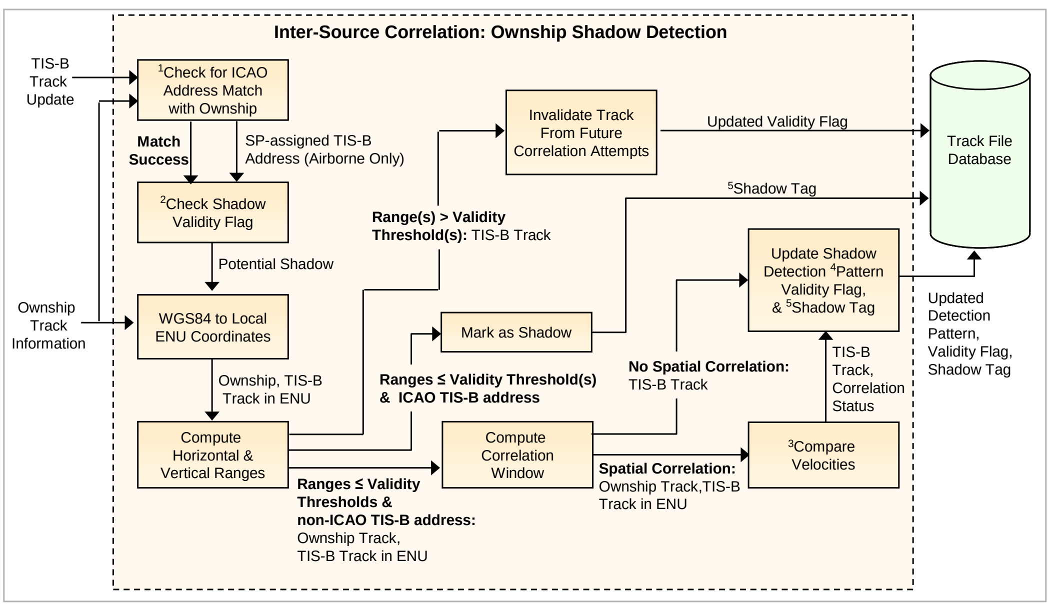

Figure 3-2. Ownship Shadow Detection

An adaptation of the ownship shadow detection mechanism could be used to support TAGS. For example, an ICAO address in a TIS-B track uplinked in a geographically targeted fashion, combined with message bits set to indicate the intent of the message, may be adequate to flag the information as a navigational message. The uplinked data could be stored in a unique track object. The type of navigational support will dictate whether an interface is required between the airborne surveillance processor and other avionics. For manual navigation, flight crew guidance provided through a new CDTI application may be adequate. For autopiloted flight or unmanned vehicles, an interface may be necessary between the surveillance processor and FMS. Because ADS-B/ADS-R/TIS-B position consists of latitude, longitude, and pressure altitude, an appropriate interface should allow these coordinates to be input to the FMS as if they were originating from typical onboard systems (e.g., GPS receiver and barometric altimeter). Depending on the desired level of sophistication, it may also be possible to rely on complementary navigation sources such as INS in between TAGS updates.

A similar, but distinct surveillance position uplink system could consist of expanded and modified Phase 2 Wide Area Multilateration (WAM). Phase 2 WAM installations in Charlotte, North Carolina, and Los Angeles, California, provide surveillance of terminal area traffic due to irregularities in SSR coverage. These implementations, owned and operated by L3Harris Technologies, Inc., consist of MLAT servers interfaced to the SBS system (ADS-B radios). Phase 2 WAM uses barometric altitude to adjust and complement 2D position determined through TDOA. Deployment of additional WAM servers, combined with necessary position uplink mechanisms and avionics modifications, could provide a navigational capability similar to the TAGS concept.

3.1.1.1. Advantages of MLAT Navigation

Analysis of the TAGS concept indicates that the system, based on the current network of ADS-B radios, could provide navigational accuracy of 1 NM or less and integrity of 2 NM or less for a significant portion of U.S. airspace. This is illustrated by Figure 3-3 from [6].

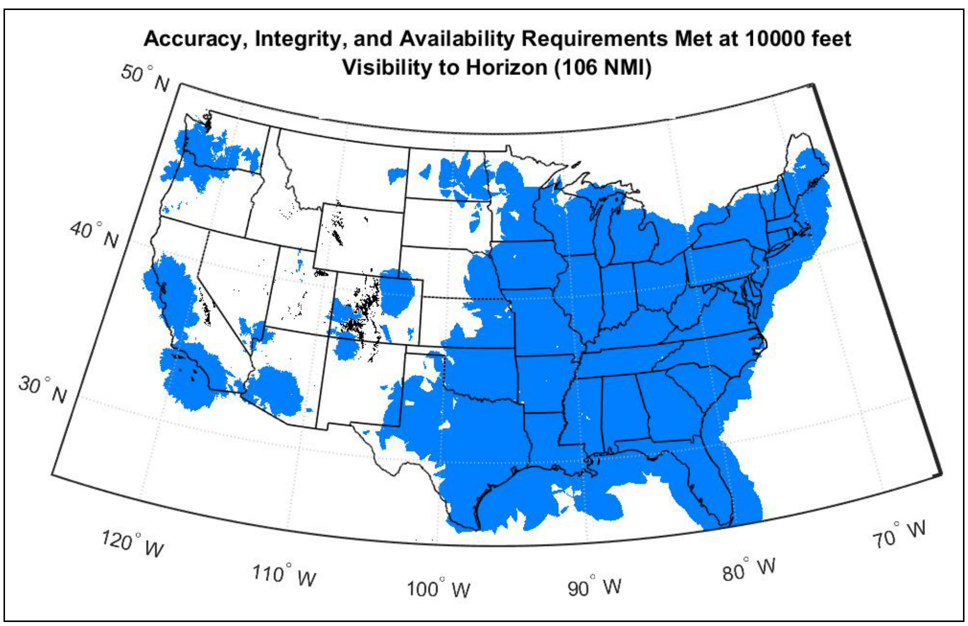

Figure 3-3. TAGS Coverage at 10,000 ft

A WAM based navigation system could conceivably provide accuracy similar to that offered by existing surveillance implementations. The WAM critical services specification requires position accuracy of 420 ft or less (95%) [10]. Phase 2 installations at Charlotte and Los Angeles have demonstrated position accuracy of roughly 100 ft (95%). WAM or TAGS, relying on pressure altitude provided by aircraft transponders, could provide barometric altitude accuracy of 200 ft (99.7%) for commercial aircraft currently operating in the ATM environment. This value is derived from an Altimetry System Error (ASE) model validated against all Boeing, Airbus, Embraer, and Bombardier aircraft [11].

WAM is required to provide an update interval of 3.0 seconds (95%) for the terminal domain. Phase 2 WAM installations typically provide update intervals between 1 and 2 seconds. TAGS, employing a similar MLAT capability across the same network of ADS-B radio stations, should be capable of position determination at a similar update rate.

3.1.1.2. Disadvantages of MLAT Navigation

A key disadvantage of TAGS is its vertical coverage limit. TAGS was primarily designed for use by general aviation (GA) aircraft without supplemental navigation sources (e.g., INS) during a GPS disruption. Because GA aircraft typically fly in lower altitude bands in comparison to air transport category vehicles, TAGS was designed to accommodate navigational support up to 10,000 to 12,000 ft. Phase 2 WAM supports surveillance at higher altitudes, however, it is not configured for coverage above 60,000 ft.

TAGS or WAM navigation would also rely on pressure altimeters, combining barometric altitude with 2D position computed through TDOA. However, many commercial pressure altimeters do not provide useful information above 60,000 ft. 3D MLAT, if implemented as an alternative, suffers in accuracy due to increased geometric dilution of precision (GDOP) in the vertical dimension. This also spills over into the horizontal plane. Additionally, MLAT accuracy may not be adequate for some ETM applications. For example, TAGS accuracy on the order of 1 NM may be insufficient for a constellation of HALE vehicles that employ a laser data link for telecommunication services.

Phase 2 WAM, as currently implemented, relies on GPS for timing. To qualify for an APNT system, this dependency would have to be addressed. The TAGS concept describes the use of Cesium or Rubidium clocks as a potential solution.

Another potential disadvantage of MLAT navigation is the possibility that navigational accuracy and update rate may be significantly worse than the characteristics of the underlying surveillance mechanism. Because of issues such as frequency congestion (notably in the 1030 to 1090 MHz range), transmissions between the ground component and a vehicle may be latent or disrupted by interference. Full characterization of this would require further study.

3.1.1.3. Current MLAT Navigation Support for ETM

TAGS or a navigation system based on Phase 2 WAM are conceptual and do not currently exist.

3.1.1.4. MLAT Navigation Changes for Greater ETM Support

Development and deployment of an MLAT navigation capability with ETM coverage would be dependent on several changes to, and integration of, existing systems. 2D MLAT envisioned by TAGS and currently implemented in Phase 2 WAM may require the use of high altitude pressure altimeters to cover ETM vehicles (e.g., altimeters built to new requirements or cancelled military standards). This may effectively increase coverage ceilings to 80,000 ft. However, Phase 2 WAM also relies on weather forecast data to correct barometric altitude. If this forecast data is unavailable for high altitudes, or a coverage ceiling greater than 80,000 ft is desired, a different approach may be required. 3D multilateration may be necessary and its performance will need to be studied further to determine the level of support it can provide to ETM operations.

Regardless of how aircraft positions are calculated, multiple MLAT servers will have to be deployed and interfaced to SBS system equipment. If geographical coverage provided by the current ADS-B radio network (as illustrated in Figure 3-3) is determined to be insufficient, additional radios may be necessary. Phase 2 WAM software would be modified to remove a filter that excludes targets above 60,000 ft. An additional software mechanism known as ADS-B Flow Control (AFC) may also require modification to enable optimal high altitude position calculation. TAGS would presumably require development of similar software capabilities.

To enable position uplinks, requirements for multiple systems may need to be revised. The first set of such standards would be the critical services specification for TIS-B (and/or potentially ADS-R) that dictates data contained in uplinks. The TAGS concept addresses the notion of selective or targeted uplink in which only a radio or radios closest to the target aircraft transmit the navigation message. If the system is intended to be used during nominal conditions (e.g., no GPS issues), uplink messages will be need to be formatted and transmitted in a way that does not interfere with normal surveillance functions. One way to accomplish this would be to set bits used by surveillance, but not by navigation, in a manner that would cause the messages to be discarded by legacy avionics. For example, if certain data quality parameters are purposely set lower than acceptable surveillance application thresholds, the information will be discarded if received and processed by current equipment. ADS-B receiver standards may need to be modified to enable aircraft reception of messages containing the same identifier as transmissions. ADS-B processor standards would need to be revised to enable detection, tracking, and storage of ownship position uplinks. If navigation information is intended to be displayed to flight crews via CDTI, the requirements for that component of the ADS-B In system would also need modification. For autopiloted flight, an interface between ADS-B In avionics and the FMS would likely be required. Depending on the level of sophistication, standards for multiple aircraft systems may be subject to revision.

Research, development, infrastructure, software, and service provider bandwidth/access costs could be significant for an MLAT navigation system. Additional topics that may require consideration include frequency/spectrum congestion and latency (data age).

3.1.2. TIS-B Navigation

A TIS-B navigation capability would be similar to an MLAT navigation system. The primary difference is that the underlying surveillance mechanism employs SSR data fusion. TIS-B navigation would rely on SBS MSTs that produce type A tracks for all traffic within SSR coverage. A TIS-B navigation capability could selectively uplink ownship information using specially formatted messages, or, in a wider APNT application could uplink all type A tracks under certain conditions (e.g., GPS disruption). Airborne avionics would be agnostic to the position source and therefore could be identical to those previously described for MLAT navigation.

3.1.2.1. Advantages of TIS-B Navigation

A key advantage of TIS-B navigation is that the necessary infrastructure and interfaces exist (SSR surveillance sources, MSTs, and uplink radios). Another advantage of this notional system is the SSR capability to track most types of vehicles, including supersonic aircraft, unmanned fixed wing vehicles, and balloons, when equipped with appropriate technology (e.g., transponders). Excluding several relatively small volumes of airspace over mountainous terrain, most of the contiguous U.S. (CONUS) is covered by radar surveillance at an altitude of 18,000 ft. This is illustrated by Figure 3-4, adapted from [12].

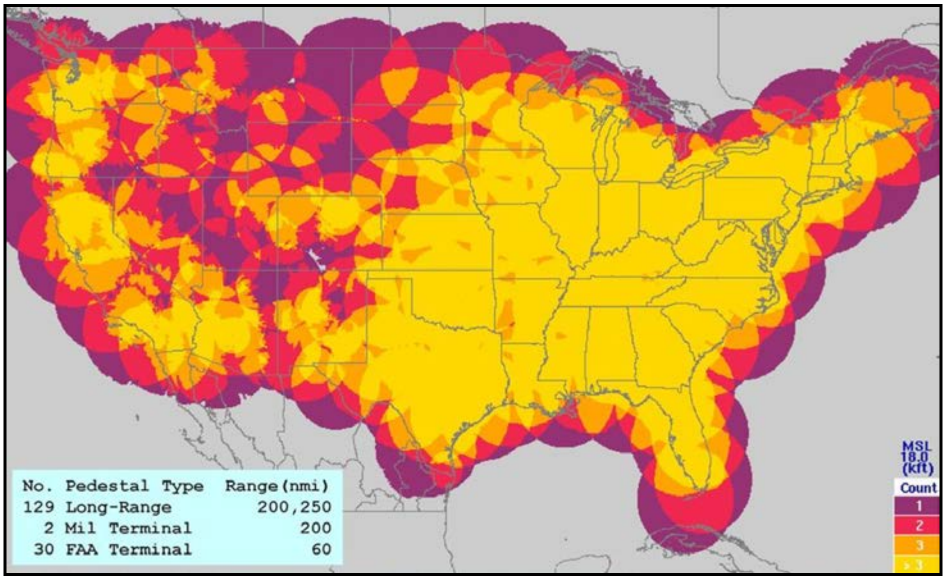

Figure 3-4. CONUS Radar Coverage at 18,000 ft

TIS-B horizontal position accuracy is typically between 92.6 meters (m) and 185.2 m (95%) in terminal areas. Similar to TAGS or Phase 2 WAM, pressure altitude transmitted to SSR systems (and ultimately TIS-B) is accurate to 200 ft (99.7%) for commercial aircraft currently operating in the ATM environment [11].

Because TIS-B employs multi-sensor tracking, update intervals as low as 3 seconds are common in terminal areas. An additional benefit of TIS-B is SSR data source independence from GPS.

3.1.2.2. Disadvantages of TIS-B Navigation

TIS-B is limited to U.S. domestic use; it is not implemented internationally. Because of the dependency on SSR surveillance, coverage of oceanic airspace is extremely limited. Where TIS-B coverage does exist, service is limited to a ceiling of 18,000 ft. Additionally, depending on the number and type of SSR feeds, TIS-B accuracy and update rates may be poor. For example, in the en route domain, update intervals can be as great as 12 seconds. Similar to 2D MLAT, TIS-B (via SSR) relies on pressure altitude; barometric altimeters may not provide useful information above 60,000 ft.

3.1.2.3. Current TIS-B Navigation Support for ETM

TIS-B navigation is conceptual and does not currently exist.

3.1.2.4. TIS-B Navigation Changes for Greater ETM Support

Development and deployment of TIS-B navigation would involve steps similar to those necessary for an MLAT navigation capability. Software filters in the ground system would have to be modified to enable coverage above the current ceiling of 18,000 ft. An appropriate uplink mechanism that doesn't interfere with surveillance functions would also be necessary. Necessary changes to avionics are envisioned to be identical to those needed for an MLAT navigation capability and would accommodate reception, processing, display and/or automated utilization of transmitted positions.

Because SSR surveillance is dependent on pressure altitude and current commercial equipment may be incapable of providing this in ETM airspace, a workaround may be required to enable TIS-B navigation. One approach would be the use of high altitude pressure altimeters that operate up to 80,000 ft (e.g., military specifications). Another alternative would be the combination of uplinked 2D position (latitude and longitude) with geometric altitude determined onboard aircraft (e.g., through unrestricted GPS receivers). However, this would only be useful in nominal GPS operating conditions. It may be possible to uplink geometric elevation determined by Air Route Surveillance Radars (ARSRs) with stacked beam technology; this could require significant software upgrades to TIS-B and would be geographically limited to areas with specific ARSR installations.

Because the TIS-B system was not intended for long term use, extending its lifecycle could be programmatically challenging. A potential dependency on GPS timing may also require examination and change. Additionally, the Spectrum Efficient National Surveillance Radar (SENSR) program is currently working to consolidate functions of certain existing surveillance radars. Some systems would be replaced by a surveillance solution that addresses requirements of multiple U.S. government agencies. ETM and SENSR stakeholder collaboration may be necessary to ensure adequate radar coverage of some vehicles operating above FL600.

3.2. Multi-GNSS Navigation

Fully operational GNSS constellations that provide worldwide satellite navigation (satnav) capability include GPS, operated by the U.S. Air Force (USAF), and GLONASS, operated by the Russian state corporation Roscosmos. Two additional GNSS constellations are being implemented: Galileo developed by the European Union, and BeiDou developed by China. Regional satnav systems will include the Navigation

Indian Constellation (NavIC) and Japanese Quasi-Zenith Satellite System (QZSS). Stakeholders for these global and regional systems form the United Nations (UN) International Committee on GNSS (ICG). The ICG is actively working toward development of interoperable equipment (e.g., receivers) primarily for space missions.

An alternative GNSS technology is the Satellite Location and Timing (STL) service. STL receivers employ Doppler positioning using signals from the Iridium satellite constellation in low Earth orbit (LEO).

Multi-GNSS navigation in the ETM environment could be performed with interoperable receivers or a processor/tracker interfaced to multiple independent receivers. This navigation capability would primarily benefit HALE operations that require consistent, accurate positioning for long durations (e.g., months). Figure 3-5 depicts GNSS satellites that will ultimately be available to such a system; it should be noted that space based augmentation system (SBAS) satellites are included in the graphic.

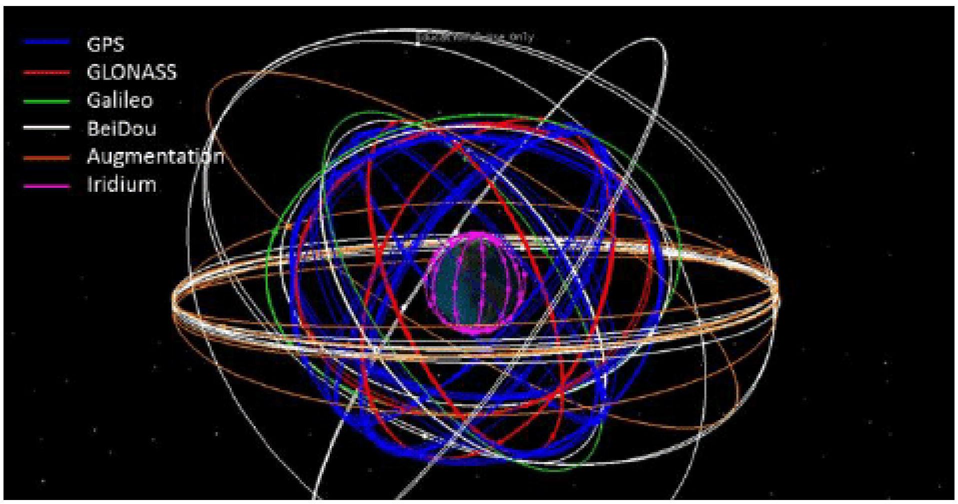

Figure 3-5. GNSS Satellites

3.2.1. Advantages of Multi-GNSS Navigation

The primary advantages of multi-GNSS navigation are increased availability and redundancy. At any given time, a significantly greater number of satellites would be available for navigation. HALE 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 [3]). 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 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. Disadvantages of Multi-GNSS Navigation

Traditional GNSS (e.g.,, GPS, GLONASS) signals 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.

Revised ITAR restrictions published in 2016 removed previous speed and altitude limits placed on GPS receivers. However, the following characteristic is now restricted: GNSS receiving equipment specially designed for military applications (missile technology if designed or modified for airborne applications and capable of providing navigation information at speeds in excess of 600 m/s). This would not impact UFBs or HALE vehicles. However, depending on the interpretation of this requirement, supersonic passenger aircraft traveling in excess of 600 m/s (1166 kts) may be considered missile technology and therefore ineligible for GNSS navigation from any source.

A disadvantage of STL is a dependency 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.

3.2.3. Current Multi-GNSS Navigation Support for ETM

Loon HALE telecommunications balloons currently operating in ETM airspace (e.g., 70,000 ft) around the world employ a multi-GNSS capability. Per [13], these vehicles are equipped with redundant GPS receivers and Iridium positioning technology.

3.2.4. Multi-GNSS Navigation Changes Necessary for Greater ETM Support

Receivers compatible with both GPS and GLONASS are currently available. Availability of fully interoperable receivers (i.e., GPS, GLONASS, Galileo, and BeiDou capable) could be subject to continued work by the ICG and market demand. Proprietary systems that produce vehicle state estimates using multiple independent GNSS position sources may be currently available.

If supersonic passenger aircraft are considered military or missile technology per ITAR definitions, they may require an operational waiver in addition to special GNSS 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).

3.3. Integrated CNS

At least two forms of integrated communication, navigation, and surveillance (CNS) are currently operational. One type is illustrated by the unmanned, HALE, fixed wing RQ-4 Global Hawk operated by the U.S. military. Global Hawk aircraft can be programmed with mission trajectories (e.g., a series of waypoints) that an autopilot will execute/track once the vehicle is airborne. However, at any time, based on surveillance or other data (e.g., video feeds), a remote pilot in command (RPIC) can take control of the vehicle and issue trajectory changes via a communications mechanism. While specific details remain classified, it is known the Global Hawk employs GPS and INS navigation capabilities. Publicly available information indicates that these unmanned systems are capable of flying up to altitudes of 60,000 ft.

Loon HALE telecommunications balloons illustrate a second type of integrated CNS. While specific technical details of the Loon navigation system remain proprietary, several elements are described or implied in published material [13][14]. For example, processors in a mission control center ingest wind forecast data to model trajectories that the vehicles will track if an internal bladder enables altitude changes (and therefore wind field changes) at specifics points. HALE balloons are believed to be capable of altitude changes on the order of 10,000 ft. ADS-B surveillance, likely the space-based ADS-B (SBA) variant provided by Aireon, is relayed to the Loon mission control center and used to track vehicle locations. When a vehicle is appropriately positioned, a communications mechanism transmits bladder commands to induce altitude changes. As depicted by Figure 3-6 (excerpted from [14]), this is performed across a constellation of Loon vehicles and is operational in various locations around the world. Depending on the level of sophistication, comparisons of modeled and surveilled (actual) trajectories may also enable computation of differential corrections to wind forecasts.

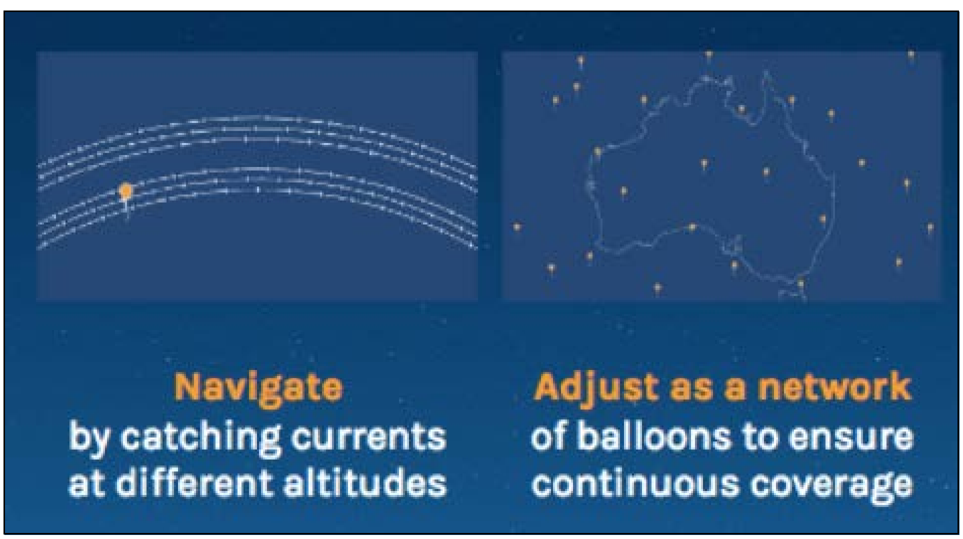

Figure 3-6. Loon Navigation

As previously discussed, Loon vehicles employ multi-GNSS (GPS and Iridium) positioning. Additionally, the aviation tracking service Flightradar24 indicates that Loon HALE balloons determine and transmit both GNSS height above ellipsoid (HAE) and calibrated pressure altitude. As shown in Figure 3-7, this functionality is operational in lower ETM airspace (e.g., 66,000 ft). This is notable because of concerns regarding pressure altimeter accuracy above 60,000 ft. It is unclear if the Loon system adheres to current standards for civilian equipment.

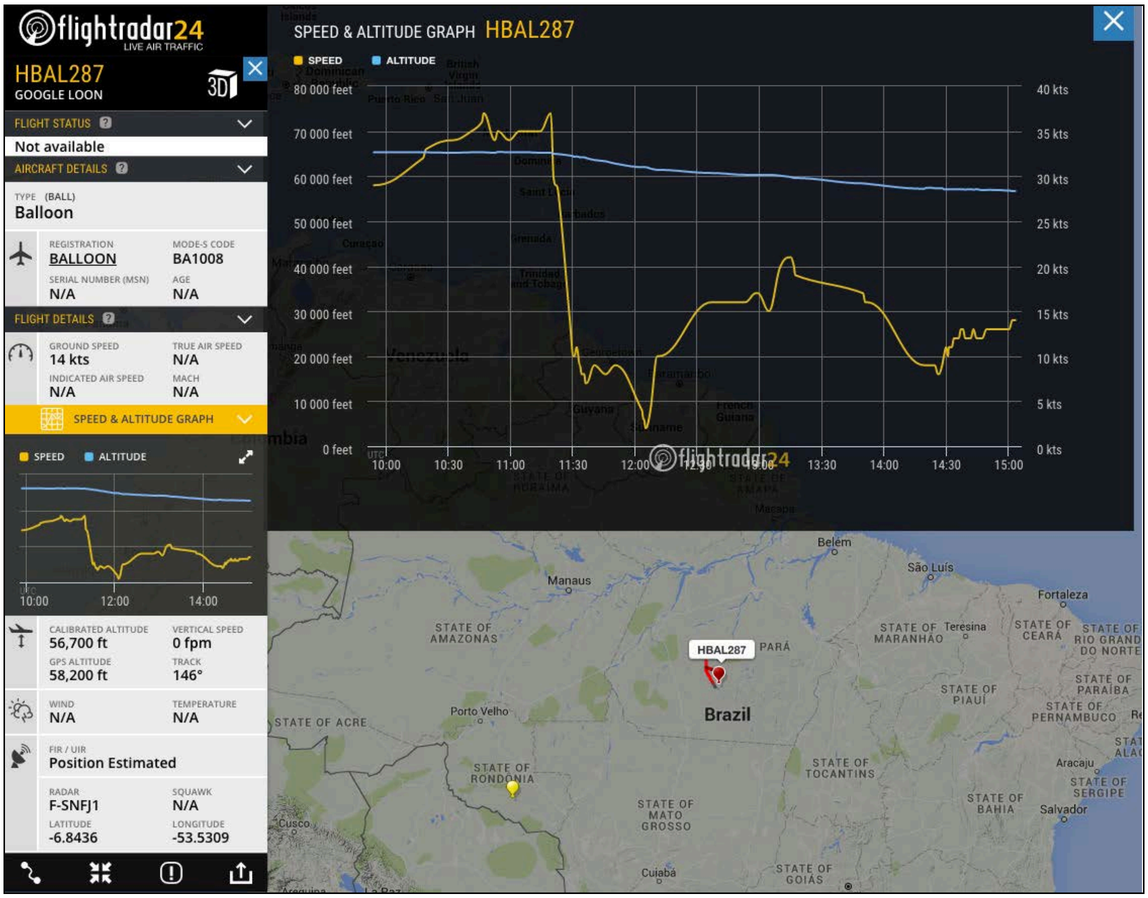

Figure 3-7. Flightradar24 Loon Surveillance Data

Global Hawk and Loon operations demonstrate the feasibility of integrated CNS in upper ATM and lower ETM environments.

3.3.1. Advantages of Integrated CNS

One advantage of integrated CNS is support for at least one aspect of the cooperative separation paradigm. Loon has demonstrated that safe ETM operations can be achieved with corporate operators and service providers (e.g., Iridium and Aireon). Government entities maintain regulatory and air traffic control roles, but do not necessarily provide CNS services as is done in the ATM environment.

An additional advantage of integrated CNS is the potential for global coverage. This is illustrated by geographically disperse Loon operations that have taken place in Puerto Rico and New Zealand.

A potential benefit of integrated CNS is common accuracy between navigation and surveillance systems. For example, GNSS navigation and ADS-B surveillance would presumably rely on positions with similar, if not identical, errors. This in contrast to the ATM environment in which an aircraft may be navigating based a variety of inputs with different error characteristics (e.g., GNSS, DME, VOR) and surveilled by an independent system such as SSR with its own unique inaccuracies.

3.3.2. Disadvantages of Integrated CNS

On the other hand, a potential disadvantage of integrated CNS systems is a common point of failure (depending on the implementation). For example, a vehicle relying on a single GNSS for both navigation and surveillance could lose both functions in the event of a significant disruption to the source GNSS. However, redundancy (e.g., use of multi-GNSS) may mitigate this. Even with resiliency, an integrated CNS system may be susceptible to the failure of one component. For example, if surveillance is relied upon for positioning that determines vehicle navigation commands, and the surveillance mechanism fails, navigation will be impacted. Similarly, failure of a communications mechanism that enables transmission and reception of vehicle commands would negatively impact navigation.

Another potential disadvantage of integrated CNS is complexity. Communication, navigation, and surveillance systems are traditionally separate entities with personnel responsible for the specific role of the system. Integrated CNS may be more susceptible to human and machine errors, depending on the implementation. Service provider cost is also a consideration. Depending on the fleet size and factors such as CNS update rate, services such as SBA, Iridium positioning, and commercially available communication links may be associated with significant costs when used in combination.

3.3.3. Current Integrated CNS Support for ETM

Loon HALE telecommunications balloons are currently using integrated CNS for operations in the lower ETM airspace band of 60,000 to 70,000 ft. Based on known Global Hawk characteristics, it is also possible that military operations employing integrated CNS are also taking place in the ETM environment.

3.3.4. Integrated CNS Changes Necessary for Greater ETM Support

Because the technical details of integrated CNS systems are proprietary and/or classified, potential changes for greater ETM support can only be postulated. For example, a combination of elements from Loon and Global Hawk systems could support constellations of HALE fixed wing aircraft. These unmanned vehicles could be controlled by an autopilot or RPIC with monitoring performed at mission control centers. A similar paradigm could be used for airship operations. Supersonic passenger aircraft, because of safety criticality, may be poor candidates for integrated CNS. However, if a track route structure similar to the one used by Concorde were implemented and published, other ETM vehicles could employ integrated CNS to avoid this airspace.

If barometric altitude is required for ETM operations, integrated CNS may have to rely on pressure altimeters that adhere to cancelled military standards and function up to 80,000 ft. It is unclear what specifications Loon barometric altimeters were built to. Alternatively, GNSS HAE could be sufficient for slow moving vehicles. Depending on manufacturer interpretation of current ITAR requirements, all GNSS receiver outputs may be restricted at speeds greater than 600 m/s (1166 kts). Waivers would be required for unrestricted systems.

Traditonal ATM communication links may need to be modified to support ETM operations. Some Very High Frequency (VHF) equipment currently used for ATM operations may not function properly above 45,000 ft. Extending functionality to ETM airspace could require significant effort. Alternative communication technologies may be required.

3.4. Implementation of eLORAN

Long Range Navigation version C (LORAN-C) was a hyperbolic radio navigation system for maritime and aviation applications. LORAN-C receivers determined vehicle positions with low frequency radio signals transmitted by fixed land-based radio beacons. In 2010, U.S. LORAN-C service was terminated because of cost considerations and increased reliance on GPS navigation. Before LORAN-C was decommissioned, significant work on its successor, enhanced LORAN (eLORAN), had been completed.

The eLORAN system was envisioned to provide improved accuracy, reliability, integrity, and availability in comparison to LORAN-C. Notable design upgrades included changes to transmission equipment (e.g., control and Cesium clocks) and a data channel to improve accuracy with differential corrections. The susceptibility of GPS (or any GNSS) to events such as solar storms and potential anti-satellite attacks has renewed interest in eLORAN as a navigation capability.

3.4.1. Advantages of eLORAN

LORAN technology supported navigation of civilian and military aircraft for decades. The primary advantage of an eLORAN implementation would be horizontal position accuracy comparable to GPS/GNSS (e.g., on the order of 10 m [15]). An additional benefit of eLORAN, if implemented at all LORAN-C stations, is coverage throughout most of the U.S. and Europe, in addition to a significant portion of Asia. LORAN-C global coverage prior to decommissioning is illustrated by Figure 3-8, excerpted from [15].

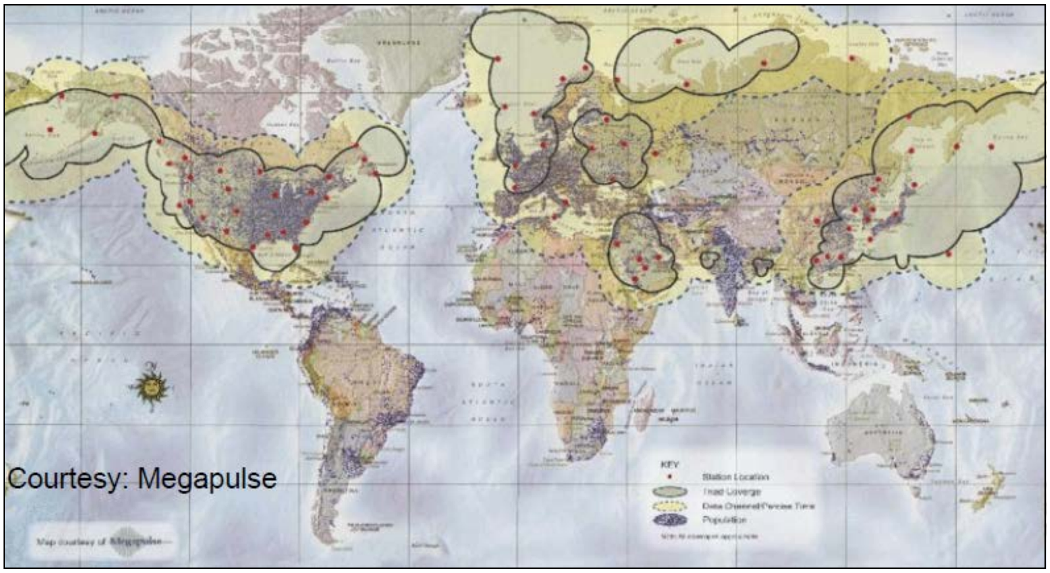

Figure 3-8. LORAN-C Coverage Prior to 2010

It is also significantly more challenging to jam or spoof low frequency eLORAN signals in comparison to traditional GNSS. Lastly, operational and maintenance costs of eLORAN would be substantially less than those associated with a satellite navigation capability. Anecdotally, a U.S. LORAN system could run for 20 years for the same cost as one GPS satellite.

3.4.2. Disadvantages of eLORAN

A significant limitation of LORAN-C that could be carried over to eLORAN is a coverage ceiling of 60,000 ft. Additionally, even with global adoption and implementation of eLORAN, total airspace covered by the capability would be a fraction of that covered by GNSS. The dependence of eLORAN on land-based radios limits oceanic coverage. Another significant limitation of eLORAN is a lack of vertical positioning. Airborne avionics would require a different position source for the vertical dimension.

3.4.3. Current eLORAN Support for ETM

Although eLORAN has been tested, it is not deployed. Previous LORAN-C stations did not provide coverage in the ETM environment.

3.4.4. eLORAN Changes Necessary for Greater ETM Support

An assessment performed by the Stanford GPS Lab [15] prior to LORAN-C decommissioning highlighted several elements that would be necessary to upgrade LORAN-C to eLORAN. These include but are not limited to: transmitter control and clock changes, implementation of a data channel for integrity and differential corrections, and new user equipment (e.g., “all in view” receivers with H field antennas). Some of these elements (e.g., eLORAN receivers) had been manufactured prior to termination of LORAN-C. Deactivated radio stations would also have to be recommissioned; in the U.S. this would likely be performed by the Coast Guard.

To enable eLORAN coverage of ETM airspace, performance of the system would require further study and characterization above FL600. Airborne avionics would require an altitude source to combine with horizontal position provided by eLORAN. Candidate vertical position sources could include high altitude pressure altimeters that function up to 80,000 ft or GNSS. However, it should be noted that reliance on the latter conflicts with a goal of GNSS independence. The cost necessary for further research, development, recommissioning of infrastructure, and deployment could be significant.

3.5. Additional Navigation Technologies

For completeness, additional technologies that could potentially function as ETM navigation mechanisms are briefly discussed, but not assessed in detail. One technology would add time information to frequency modulation (FM) radio signals at specific locations. This information alone could not be used for navigation. However, if combined with position, for example, determined with an expanded DME network, the two components could provide an APNT capability. Based on the number of FM and DME sites, both in the U.S. and internationally, this type of capability could conceivably support a large geographic area.

Alternatively, a previous APNT study [16] proposed transmission of timing information directly from DME stations. This capability, referred to as DME-Sync could include synchronized DME transponders. However, it should be noted that position and time information produced with DME-Sync was envisioned to be integrated with INS data.

Vertical navigation in the ATM environment primarily relies on altitude provided by barometric altimeters. A recurring theme in ETM concept work [2][3] is the potential inadequacy of these systems above FL600. Potential solutions include the use of pressure altimeters adhering to cancelled military standards (operation to 80,000 ft) or a transition to vertical navigation based on GNSS HAE. An alternate solution for vehicles operating in lower ETM airspace (e.g., supersonic transports) may be an inertially aided barometric altimeter [17]. It may also be possible for aircraft to estimate geometric elevation based on signals from DME stations in an expanded network, however, this would require further study to characterize or assess feasibility.

Lastly, an intriguing APNT capability that has been proposed [18] is an INS augmented with a star tracker for high altitude unmanned operations. The concept envisions a camera (or cameras) that captures imagery of the sky and references a star atlas to determine position. This would be combined with INS output to provide optimal location estimates.

4. Conclusions

Operations above 60,000 ft are expected to increase significantly in the near future. A diverse range of vehicles are anticipated to be active in this airspace, including but not limited to: Unmanned Free Balloons, High Altitude Long Endurance aircraft (fixed wing, balloons, and airships), reintroduced supersonic passenger flights, air launched space vehicle carriers, and potentially hypersonic aircraft. The policies, infrastructure, and procedures in place for current operations may not accommodate the diversity expected in this airspace. The ETM concept addresses these shortfalls with principles drawn from ATM, UTM, and operations currently performed above FL600. This paper discussed emerging navigation technologies and their applicability to aircraft in the ETM environment.

One potential capability is a system that employs surveillance position uplinks. The underlying surveillance mechanism could be comprised of MLAT or SSR TIS-B. Potential MLAT variants include the TAGS concept or expanded Phase 2 WAM; either possibility would be deployed within the SBS network of ADS-B radio stations. Positions determined with TAGS or Phase 2 WAM would be uplinked to aircraft via ADS-R or TIS-B links. It would be necessary for avionics to recognize the uplinks and display navigation information to crews in a manned application, or forward the data to onboard systems (e.g., an FMS) in an autopilot or unmanned application. A surveillance position uplink system based on TIS-B would rely on SSR position determination and would use similar uplink, processing, display, and piloting mechanisms.

Another emerging navigation capability is the use of multiple Global Navigation Satellite System (multi-GNSS) inputs. Multi-GNSS navigation would offer resilience in the event that a single GNSS is disrupted and greater availability of navigation satellites in nominal conditions. Loon HALE operations currently use multi-GNSS positioning with signals from GPS and Iridium satellites.

Integrated communication, navigation, and surveillance is illustrated by Global Hawk and Loon unmanned HALE operations. Operators, monitoring personnel, and processors at mission control centers rely on surveillance to determine vehicle conformance to mission trajectories. Flight path (i.e., navigation) changes are achieved by transmitting appropriate commands to vehicles with proprietary communication links.

An APNT system gaining renewed interest is eLORAN. The hyperbolic navigation system was a planned upgrade to LORAN-C and would provide horizontal position accuracy similar to GPS. However, LORAN-C sites were decommissioned in the U.S. in 2010. If radio stations were to be reactivated and coverage was determined to be sufficient, eLORAN may be a feasible navigation source for aircraft in lower ETM airspace. One limitation that will need to be overcome is a lack of vertical positioning.

Additional technologies include FM time broadcasts and the DME-Sync concept that envisions an expanded DME network providing both time and location signals. Potential vertical positioning solutions for ETM include high altitude pressure altimeters, GNSS HAE, inertially aided barometric altimeters, and geometric elevation determined with DME transmissions. Lastly, an INS augmented with a star tracker was examined for high altitude unmanned operations. This system would employ cameras that determine position by cross-referencing imagery with a star atlas, and combine this information with data output from an INS.

This intention of this work was to survey operational and hypothetical navigation technologies. No effort was made to promote one alternative over another.

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