Preliminary Assessment of Surveillance Alternatives for Upper Class E Traffic Management (ETM)

Robert Eftekari

Regulus Group

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1. Abstract

Expected activity above Flight Level 600 (FL600) includes expanded use of Unmanned Free Balloons (UFBs), High Altitude Long Endurance (HALE) missions, the reintroduction of supersonic passenger flights, and more frequent space operations. Upper Class E Traffic Management (ETM) is the system envisioned to support these operations. Surveillance options include ground based and aircraft provided alternatives: radar, Wide Area Multilateration (WAM), Automatic Dependent Surveillance – Broadcast (ADS-B), and Automatic Dependent Surveillance – Contract (ADS-C). These four surveillance technologies were assessed in terms of general advantages, disadvantages, current level of support for ETM, and changes necessary to enhance ETM support. Two potential constructs for the surveillance component of the ETM system were developed. One construct is a low resiliency, ADS-B based option designed for simplicity and lower cost, while the other construct is a high resiliency alternative containing multiple, independent surveillance sources.

2. Introduction

Operations above 60,000 feet (ft) in upper class E airspace are expected to increase significantly in the near future. Multiple vehicle types are anticipated to be active in this volume. Unmanned Free Balloons (UFBs) with minimal flight path control and short mission durations are expected to operate up to altitudes of 160,000 ft. High Altitude Long Endurance (HALE) balloons, operating up to similar altitudes, will extend mission durations to an average of 100 days and employ some degree of altitude control allowing changes on the order of 10,000 ft [1]. Loon, a subsidiary of Alphabet Inc., currently operates HALE telecommunication balloons in various locations around the world up to altitudes of 70,000 ft. Solar powered, HALE fixed wing aircraft are expected to loiter between Flight Level 600 (FL600) and FL900 for three to six months with daily climbs during daylight and minimally powered descents at night to maintain airspeed. HALE airships, controllable in both direction and altitude, are also expected in this airspace. Current HALE airship designs are capable of operating up to 60,000 ft.

Multiple airframe manufacturers are developing Supersonic Transports (SSTs) and Supersonic Business Jets (SSBJs). These passenger aircraft are expected to cruise at speeds between Mach 1.0 and Mach 2.5 at altitudes between FL550 and FL700. Subsequently developed aircraft may be capable of even greater speeds. Traditional space launch, newer forms of launch and recovery, air launch, and reentry operations are already increasing in frequency. Hypersonic aircraft, while still mostly in the concept phase, are also vehicles that will potentially operate in this airspace. Figure 2-1 depicts several high altitude vehicles, including, clockwise from top: a rendering of the Boom SST concept, Loon HALE telecommunications balloon, and the air launched Virgin Galactic SpaceShipTwo.

Figure 2-1. High Altitude Vehicles

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

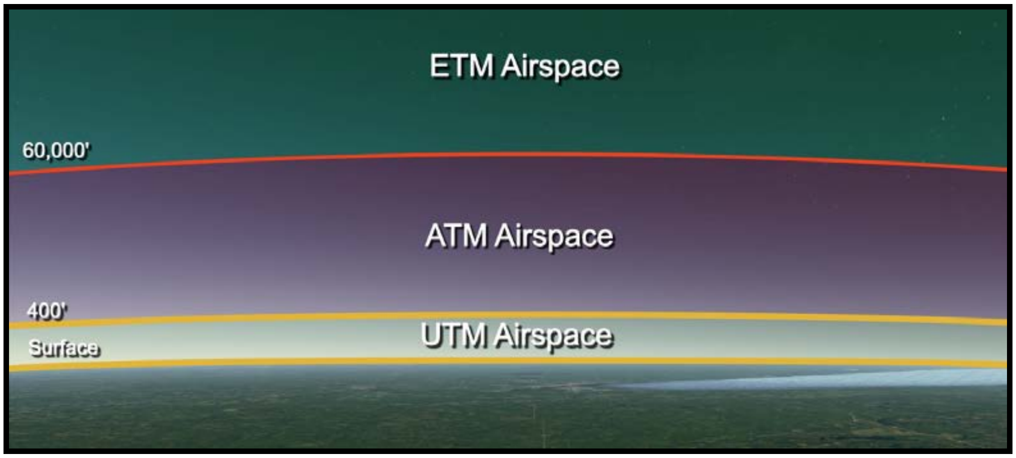

Figure 2-2. Notional Depiction of UTM, ATM, and ETM Environments

The traffic separation methodology for the ETM environment is comprised of managed separation, cooperative separation, and due regard. Managed separation in ETM will be similar to positive separation applied today in the ATM environment, however, it will likely be limited to specific operations (e.g., supersonic passenger flights). Cooperative separation in this context refers to operator data exchanges (e.g., trajectory sharing), strategic deconfliction in the flight planning phase, shared situational awareness, collaborative traffic management, and sense and avoid (SAA) or detect and avoid (DAA) mechanisms that combine to enable safe and efficient operations. It should be noted that cooperative surveillance technologies should be distinguished from the notion of cooperative separation. Cooperative surveillance is traditionally associated with transponder-based managed separation. Due regard involves the safe accommodation of civilian operations in the ETM environment by participating states.

This document focuses on the surveillance component of the ETM concept. This work does not address alternatives to surveillance, e.g., a system in which safe separation and efficiency are solely achieved with trajectory sharing and flight plan deconfliction.

3. Surveillance Alternatives

Four surveillance alternatives were considered in this assessment. Two of these alternatives, radar and Wide Area Multilateration (WAM), are categorized as ground based solutions because aircraft states (i.e., position, velocity, and time of applicability) are calculated within ground infrastructure. The remaining two options, Automatic Dependent Surveillance – Broadcast (ADS-B) and Automatic Dependent Surveillance – Contract (ADS-C), are considered to be forms of aircraft provided surveillance because states are computed within airborne avionics. However, the end to end systems that provide all of these surveillance services are comprised of both ground and airborne components.

3.1. Ground Based Surveillance

Radar and WAM both operate under a similar overarching principle. Ground infrastructure is used to determine aircraft states and this information is provided to Air Traffic Control (ATC).

3.1.1. Radar

Primary Surveillance Radar (PSR) uses reflected electromagnetic energy to measure the position of aircraft in range and azimuth. Secondary Surveillance Radar (SSR) sends interrogations to aircraft transponders, determines range and azimuth based on reply timing within a narrow beam, and receives coded identification and pressure altitude information. ATC radars are typically standalone SSR installations or co-located PSR and SSR arrays. Radar data feeds are critical inputs to data fusion and automation systems used by Terminal Radar Approach Control (TRACON) and Air Route Traffic Control Center (ARTCC) facilities.

ATC radars are generally divided into two categories: Airport Surveillance Radar (ASR) and Air Route Surveillance Radar (ARSR). ASRs typically support surveillance of airport traffic within a 60 nautical mile (NM) radius at altitudes up to roughly 25,000 ft. Depending on the implementation, ASR vertical coverage may be limited by software as opposed to hardware capabilities. For example, automation filters may limit ASR coverage provided to end users to a local sector ceiling (e.g., 23,000 ft) plus a conservative buffer. ARSRs are capable of surveilling en route traffic with ranges up to 250 NM and altitudes up to 100,000 ft (e.g., ARSR-4). Similarly, software filters may limit ARSR data provided to end users. Some ARSRs are capable of determining three-dimensional (3D) aircraft position, independent of altitude reporting mechanisms, by transmitting and receiving multiple beams of radio waves at two or more elevation angles.

3.1.1.1. Radar Advantages

Radar has been used for decades to support managed separation of civilian and military aircraft. 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 3-1, adapted from [2].

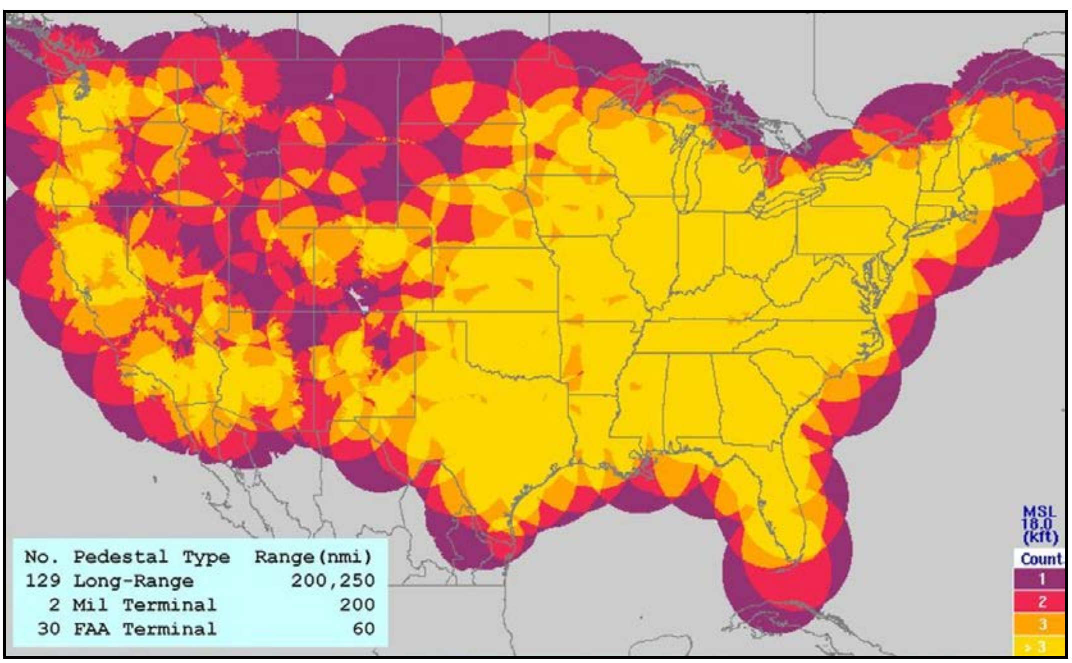

Figure 3-1. CONUS Radar Coverage at 18,000 ft

Non-monopulse, Monopulse Secondary Surveillance Radar (MSSR), and Mode S implementations have varying performance characteristics, however, these are not elaborated for the purposes of this paper. A general, internationally applicable characterization of all current SSR technologies is range accuracy of 0.03 NM root-mean-square (RMS) and azimuth accuracy of 0.07 degrees (deg) RMS or 0.14 deg (95%) for random errors [3]. Pressure altitude accuracy in SSR systems is 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 [4]. The ASE model produces an error of roughly 186 ft (99.7%). A radar specific value of 200 ft is obtained through Mode C quantization. This is consistent with the Reduced Vertical Separation Minimum (RVSM) basic envelope ASE requirement of 200 ft (99.7%) [5].

Radar is less susceptible to jamming or spoofing in comparison to Global Navigation Satellite System (GNSS) based surveillance. SSR also provides critical inputs to ATC automation systems, e.g., Standard Terminal Automation Replacement System (STARS) and En Route Automation Modernization (ERAM). Radar independently validates ADS-B downlinks to the Surveillance and Broadcast Services (SBS) system. Radar data are spatially and temporally correlated with ADS-B, substantiating ADS-B for use in STARS and ERAM. Radar data are also input to systems that support traffic flow management and collaborative decision making, e.g., Traffic Flow Management System (TFMS). Radar based Traffic Information Service – Broadcast (TIS-B) uplinks to ADS-B In avionics improve airborne situational awareness. TIS-B also generates see and avoid enhancing alerts in the Traffic Situation Awareness with Alerts (TSAA) application, also known as the ADS-B Traffic Advisory System (ATAS). Note, however, that TIS-B is intended for altitudes up to 18,000 ft.

3.1.1.2. Radar Disadvantages

Radar position errors increase with range and can be significantly greater than those associated with GNSS based surveillance sources. For example, a radar track for a target at a range of 100 NM may contain a position error up to 0.24 NM (444 meters) [3]. ADS-B installations are required to provide position accuracy of 92.6 meters (95%) throughout the U.S. National Airspace System (NAS), independent of proximity to ground based transceivers [6]. Velocity errors produced by radar trackers can be significant, notably when aircraft are turning. This phenomenon is commonly referred to as radar lag.

Limitations of commercial barometric altimeter systems may constrain useful radar surveillance of many aircraft. Air data computers that calculate pressure altitude based on static port inputs are not required to operate above 50,000 ft [7]. Many of these systems continue to function at greater altitudes, however, required performance is uncharacterized. Certification pathways for high altitude commercial installations do exist. Concorde was certified to operate at 60,000 ft and multiple business jet models are currently certified to cruise at altitudes up to 51,000 ft. It is generally believed that barometric altitude provided by most commercial systems is no longer useful above 60,000 ft. Some military altimeter systems were required to indicate pressure altitude up to 80,000 ft per MIL-STD-

843, however, these requirements were subsequently cancelled. F-15s were certified to fly at FL800 with restrictions and F-22s routinely operate at FL600 to improve supersonic cruise performance [8]. Typical military barometric altimeter systems are now consistent with civil standards with most platforms tested to and operating up to 50,000 ft. For systems that do operate at higher altitudes, the error band increases significantly (e.g., ± 850 ft at 80,000 ft). Degraded or invalid pressure altitude values will impact derivation of two-dimensional (2D) range from SSR measured slant range. 3D radar installations that measure geometric elevation are available in some instances, however, these measurements are not necessarily useful for current civil operational support with separation based on barometric altitude.

SSR update intervals are typically between 4.8 seconds (ASR) and 12 seconds (ARSR). Some airborne applications that employ TIS-B compensate for potential update intervals of 24 seconds due to missed sweeps [9]. However, it should be noted that data fusion systems are capable of providing significantly lower update intervals (e.g., 3.0 seconds) in some locations.

Classical (non-monopulse) SSR and MSSR are subject to several potential errors, including: resolution failures (inability to distinguish separate aircraft in close proximity), false target or position reports caused by reflections or multipath, and false altitude or identity code reports. Additionally, Mode C altitude is quantized in 100 ft increments. Mode S radar can resolve two aircraft at the same location. Mode S altitude (quantized to 25 ft) and identity downlinks are typically error free.

Radar coverage of oceanic airspace is limited to coastal regions and areas surrounding select islands. Coverage of an individual radar is defined by a rotating, titled signal. The region directly above an array, within which traffic is not surveilled, is commonly referred to as the cone of silence. These volumes expand with altitude. Radar installations have also been associated with high procurement and maintenance costs.

3.1.1.3. Current Radar Support for ETM

Of all surveillance alternatives presented in this paper, radar has been used the most for surveillance of vehicles in ETM airspace. However, there are several significant limitations. This is described through historical use cases based on vehicle type.

Radar provides limited surveillance of UFB operations above 60,000 ft standard pressure altitude. Equipage with radar reflective devices is required per 14 CFR Section 101.35. Some operators voluntarily equip with Secondary Surveillance Radar (SSR) transponders, however, these are typically operated intermittently at cruise altitude to conserve power [10] and are subject to pressure altimeter limitations above FL600. Operators are required to notify ATC of position and intended cruise altitude prior to launch, and current position and altitude prior to descent. Radar surveillance of UFBs in ETM airspace may be characterized as measured range when available (i.e., PSR or SSR acquired over land or coastal areas), potentially combined with and modified by intermittent and/or degraded pressure altitude (SSR). In some cases, geometric elevation may be available, but it is not currently useful. ATC does not actively separate aircraft from UFBs, however, it does provide traffic advisories to potentially affected flights. Traffic advisory contents include known or estimated UFB position, and unknown or reported altitude.

Radar also provides limited surveillance for High Altitude Long Endurance (HALE) aircraft. This includes fixed wing, balloon, and airship vehicles. Military HALE aircraft equipped with appropriate altimetry systems and transponders, operating over land or coastal regions, in the lower ETM airspace band of 60,000 to 80,000 ft may be adequately surveilled by long range radars. Radar surveillance of civilian HALE vehicles equipped with commercial altimetry systems and transponders is comparable to coverage of transponder equipped UFBs. HALE aircraft without SSR transponders may only be tracked by PSR, where available, assuming an appropriate radar reflective surface and cross section.

Radar is capable of tracking supersonic vehicles up to altitudes supported by onboard altimetry systems. Military aircraft operating at supersonic speeds in ETM airspace are visible to some radar systems. However, limitations do exist. For example, it is not uncommon for ATC radar trackers to experience issues when military aircraft execute high speed horizontal or vertical maneuvers. Radar has also been used historically for surveillance of Concorde SST aircraft that operated at the boundary of ETM airspace. Concorde achieved speeds of Mach 2.0 in oceanic airspace inside of long range radar coverage. Figure 3-2 depicts the North Atlantic Track SM used by Concorde flights into New York and the descent/deceleration region near Nantucket, MA. ATC typically provided Concorde flights with altitude blocks (e.g., FL550 to FL600) to accommodate cruise climb trajectories. Radar based surveillance systems were typically configured to allow monitoring of conformance to the assigned altitude block. However, there was a capability to indicate pressure altitude up to 60,000 ft. Occasionally, pressure altitude was temporarily unavailable during descents due to the rate of change and tracking system limitations. Radar surveillance of supersonic vehicles in ETM airspace may be summarized as available over land or coastal areas up to altitudes supported by onboard altimetry systems (e.g., 80,000 ft in some military applications), stable during level flight, with limitations during high speed horizontal or vertical maneuvers.

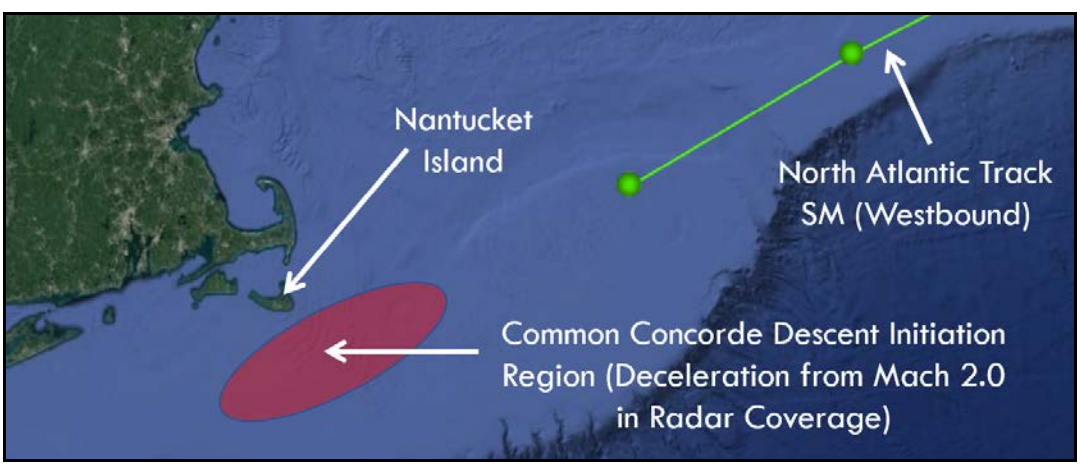

Figure 3-2. Concorde Supersonic Flight Segment

Radar tracking of current space launch, recovery, and reentry operations is extremely limited. Commercial systems are not required to equip with SSR transponders. The primary method of surveillance for commercial space procedures is operator proprietary telemetry. Some vehicles equipped with special transponders are tracked by military radar.

Because hypersonic operations are still in the concept phase, radar tracking of these vehicles cannot be fully characterized. Issues present in radar tracking of supersonic vehicles may be indicative of potential performance limitations in the hypersonic domain.

3.1.1.4. Radar Changes Necessary to Enhance ETM Support

Radar changes to enhance ETM support are expected to be minimal due to cost considerations and current capabilities, e.g., coverage up to 100,000 ft in some instances. However, several systems and processes that support radar based surveillance may require significant changes, pending further study of ETM needs.

If additional work indicates that pressure altitude provided by SSR transponders is required for some ETM operations, it may be necessary to initiate a revision process for air data computer standards [7]. Advances in technology may support development of commercial barometric altimetry systems that accurately function in ETM airspace typically associated with military operations (e.g., 60,000 to 80,000 ft). SSR transponder pressure altitude transmission codes are currently defined to 126,750 ft [11]. Appropriately developed requirements, performance characterizations, system tests, and expanded certification pathways may pave the way for such systems to routinely operate above 60,000 ft in both civilian and military applications. High altitude civilian separation standards would also need to be developed in this scenario.

Data fusion and automation platforms (e.g., ERAM) may require software changes to adequately process radar data for ETM traffic (e.g., supersonic SSTs). ETM traffic may also necessitate software changes to systems such as TFMS that are considered to be critical to NAS efficiency. ERAM provided flight data is a primary input to TFMS.

In areas with fewer overlapping radar coverage regions, high altitude surveillance may be limited because of upwardly expanding cones of silence. If radar surveillance is required for ETM activity in these areas, it may be necessary to impose operational limits based on coverage constraints.

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 government agencies. These requirements may impose additional limitations on radar support for ETM operations. ETM and SENSR stakeholder collaboration may be necessary to ensure adequate radar coverage of some vehicles operating above FL600.

3.1.2. Wide Area Multilateration (WAM)

Multilateration systems use transponder transmissions (Mode A/C, Mode S, or ADS-B) to obtain aircraft identification and calculate 2D or 3D positions. Time Difference of Arrival (TDOA) at multiple receiving stations establishes aircraft position at the intersection of several hyperboloids. The accuracy of a multilateration system is dependent on the geometry of the target in relation to the receiving stations and the relative time of reception of the signal at each station. Figure 3-3 depicts a generic architecture for multilateration systems adapted from [3].

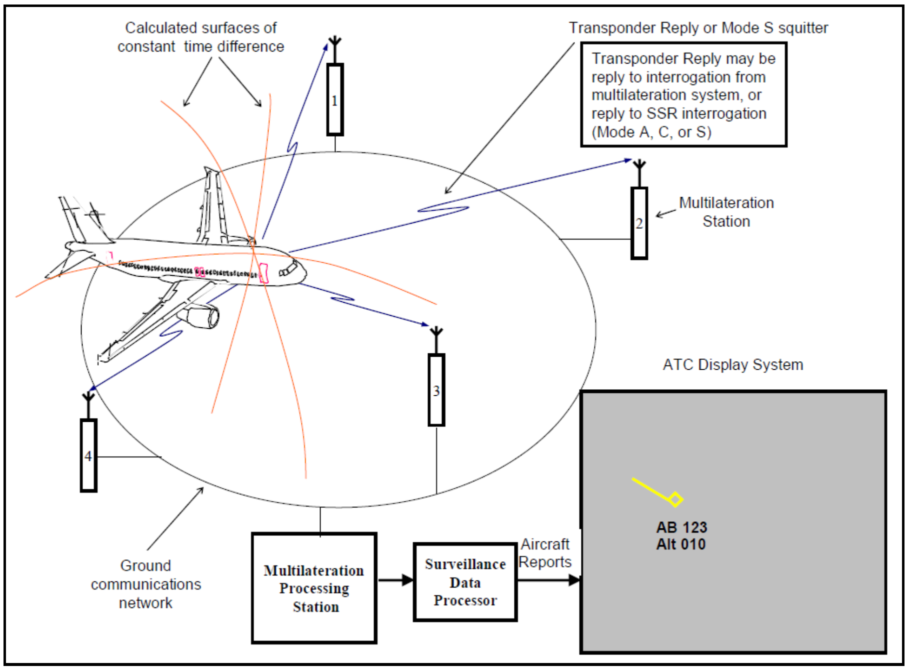

Figure 3-3. Generic Multilateration System Architecture

Multilateration systems designed for airport surface surveillance, e.g., Airport Surface Detection Equipment Model X (ASDE-X) or Airport Surface Surveillance Capability (ASSC), are not expected to support any ETM operations and are considered to be out of scope. WAM, however, is a candidate for ETM surveillance. WAM is operational at multiple locations in the U.S., including: several airports in the Colorado mountains, Juneau, Alaska, and Charlotte, North Carolina. A WAM installation in Los Angeles is currently under development to correct radar anomalies. Phase 1 installations (Juneau and Colorado) were designed by Saab Sensis Corporation, but are owned and operated by the Federal Aviation Administration (FAA). Phase 2 installations (Charlotte and Los Angeles) are designed, owned, and operated by Harris Corporation. Phase 2 systems employ SBS system radios also used for ADS-B services. Another key difference in operation between Phase 1 and 2 systems is the use of reported barometric altitude versus corrected pressure altitude (respectively). Phase 2 systems correct pressure altitude with weather forecast data. In both cases, barometric altitude is used to adjust 2D position determined through TDOA. Phase 1 installations are slated to be replaced with Phase 2 service hosted within SBS in the 2021 timeframe.

3.1.2.1. WAM Advantages

A key advantage of WAM is that it provides accurate surveillance in regions that preclude radar deployment (e.g., mountainous terrain). WAM supports both terminal and en route domains. The WAM critical services specification requires position accuracy of 420 ft or less (95%) [12]. However, Phase 2 installations at Charlotte and Los Angeles have demonstrated position accuracy of roughly 100 ft (95%). Because WAM relies on pressure altitude provided by aircraft transponders, barometric altitude accuracy is 200 ft (99.7%) for commercial aircraft currently operating in the ATM environment [4].

WAM provides an update interval of 3.0 seconds (95%) for the terminal domain. Phase 2 installations typically provide update intervals between 1 and 2 seconds. Virtual radar configurations are available with established inputs to ATC data fusion and automation systems. Phase 2 WAM systems offer the benefit of deployment using existing infrastructure.

3.1.2.2. WAM Disadvantages

Many commercial pressure altimeters do not provide useful information above 60,000 ft. This supporting system limitation impacts vertical and horizontal position estimates provided by WAM as barometric altitude errors will propagate to 2D position calculations. 3D multilateration, if implemented, suffers in accuracy due to increased geometric dilution of precision (GDOP) in the vertical dimension. This also spills over into the horizontal plane.

Phase 1 system requirements specify a coverage ceiling of 20,000 ft. However, accurate surveillance is limited to a ceiling of roughly 16,000 ft because targeted horizontal position accuracy values could not be guaranteed at higher altitudes. Phase 2 systems are not configured to provide surveillance above 60,000 ft. Cumulative WAM coverage is only a fraction of the total area surveilled by radar and ADS-B. Coverage of oceanic airspace is extremely limited as WAM is dependent on land based remote units.

Update intervals between 6.0 and 12.0 seconds are typical in en route coverage regions, however, similar to ASR coverage constraints, this limitation is imposed by software. Additionally, because WAM relies on Global Positioning System (GPS) timing, it is currently susceptible to GPS disruptions.

3.1.2.3. Current WAM Support for ETM

Phase 1 WAM surveillance is not applicable to ETM operations because of its low coverage ceiling. Phase 2 WAM surveillance of commercial vehicles in ETM airspace may be characterized as extremely limited due to system configurations and pressure altimeter constraints. System filters prevent appropriate acquisition of targets above 60,000 ft. If position can be determined, potential pressure altitude errors may negatively impact calculations.

3.1.2.4. WAM Changes Necessary to Enhance ETM Support

To enable Phase 2 WAM surveillance of ETM airspace, several SBS system changes are necessary, including: deployment of additional multilateration servers, removal of a filter that excludes WAM targets above 60,000 ft, and opening gates from ADS-B Flow Control (AFC) to allow more than eight radios to report a detection.

Additionally, multilateration performance on targets above 60,000 ft will require characterization. If high altitude pressure altimeters are available (e.g., built to new requirements or cancelled military standards) and adequate weather forecast data is provided, 2D multilateration may be a viable option with increased coverage ceilings (e.g., 80,000 ft). Otherwise, 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. Another potential option is the use of geometric altitude provided by ADS-B transmissions instead of pressure altitude in a 2D WAM implementation. WAM performance with geometric altitude has been characterized in some cases, however, this would also require further study for ETM applications.

With appropriate system changes to enable ETM coverage, update rates at altitudes above 60,000 ft should be similar to those achieved at lower altitudes. In addition to research and development costs, funding for additional service provider bandwidth should be considered. Automation and other peripheral systems will also likely require software changes to enable WAM inputs for ETM traffic.

3.2. Aircraft Provided Surveillance

Two aircraft provided surveillance alternatives are candidates for the ETM environment. Both options are variations of Automatic Dependent Surveillance (ADS). These technologies are not mutually exclusive.

3.2.1. Automatic Dependent Surveillance – Broadcast (ADS-B)

ADS-B, as initially designed and implemented in the U.S., consists of airborne avionics and SBS system ground infrastructure. ADS-B avionics generate and transmit messages containing aircraft identification (24 bit address), GPS derived position and velocity, time of applicability, data quality metrics (e.g., position and velocity accuracy), and additional information such as aircraft type (emitter category). In the U.S., ADS-B equipped aircraft transmit information on one of two frequencies. Universal Access Transceiver (UAT) operates on the 978 MHz frequency and is typically associated with general aviation (GA) aircraft. 1090 MHz Extended Squitter (1090ES) systems extend standard transponder message sets with additional ADS-B information and are associated with both GA and air transport category vehicles. 1090ES is the ICAO international ADS-B link. The transmission of ADS-B information from an aircraft is known as ADS-B Out. On January 1, 2020, all aircraft operating in U.S. airspace will be required to possess ADS-B Out installations [6]. In general, operators flying at 18,000 ft and above will require 1090ES equipment. Those that fly below 18,000 ft may use either UAT or 1090ES equipment.

The SBS system consists of a network of radio stations and multi-sensor trackers (MSTs) throughout the U.S. The SBS system receives ADS-B messages from equipped aircraft, reformats ADS-B and uplinks it as Automatic Dependent Surveillance – Rebroadcast (ADS-R) to accommodate otherwise incompatible airborne transactions (e.g., UAT messages received by 1090ES equipment), and is also responsible for transmitting radar or multilateration data for unequipped aircraft in the form of TIS-B. ADS-B data independently validated through radar and TDOA position comparisons in the SBS system are input to STARS and ERAM data fusion and automation used for ATC. SBS system infrastructure supports ADS-B coverage of airspace above CONUS, Alaska, Hawaii, Puerto Rico, and Guam. Similar to radar, surveillance of oceanic regions is limited. Radio installations on oil platforms do, however, provide significant coverage in the Gulf of Mexico (GOMEX). Figure 3-4 depicts ADS-B coverage provided by the SBS system.

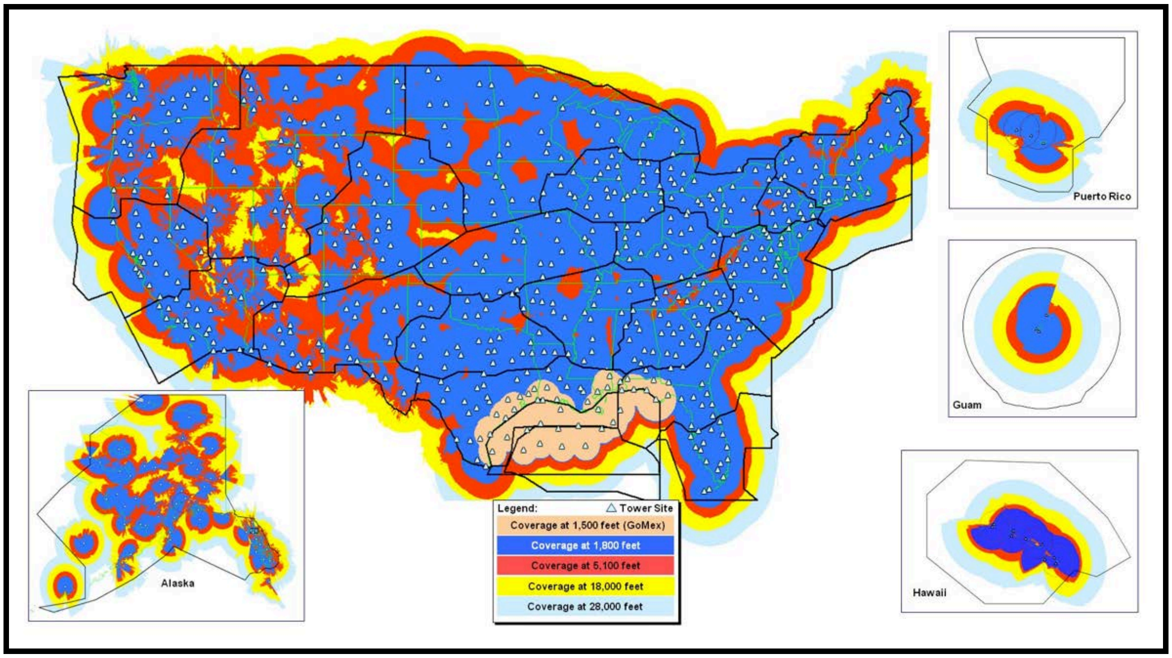

Figure 3-4. ADS-B Coverage Provided by the SBS System

Space-based ADS-B complements surveillance provided by the SBS system. 1090ES receiver payloads installed in Iridium NEXT satellites enable ADS-B surveillance in oceanic and remote continental airspace. The FAA has not made a final investment decision regarding space-based ADS-B.

The reception and processing of ADS-B information by an aircraft is known as ADS-B In. The Aircraft Surveillance Applications (ASA) system is comprised of an Airborne Surveillance and Separation Assurance Processor (ASSAP) and Cockpit Display of Traffic Information (CDTI). ASA system standards [9] support multiple ADS-B In applications. A subset of these applications includes:

a. Basic Airborne Situation Awareness (AIRB): ADS-B, ADS-R, Traffic alert and Collision Avoidance System (TCAS), and (optionally) TIS-B traffic situational awareness; AIRB is typically implemented in air transport category aircraft.

b. Traffic Situation Awareness with Alerts (TSAA), also known as the ADS-B Traffic Advisory System (ATAS): ADS-B, ADS-R, and TIS-B based conflict detection and see and avoid enhancing alerts.

c. In-Trail Procedure (ITP): ADS-B based traffic situational awareness and controller authorized altitude changes in oceanic airspace.

3.2.1.1. ADS-B Advantages

A key advantage of ADS-B is international adoption of 1090ES technology. Mandates or proposals exist in the U.S., Canada, Europe, Australia, Mexico, Indonesia, Singapore, Sri Lanka, Taiwan, Hong Kong, and Vietnam. Local surveillance networks, complemented by space-based ADS-B, offer the potential for worldwide surveillance with a common technology.

In the U.S., ADS-B is required to possess position accuracy of 92.6 meters (m) or less (95%) and velocity accuracy of 10 meters per second (m/s) or less (95%) throughout the NAS, independent of proximity to ground based transceivers. ADS-B avionics interfaced with Wide Area Augmentation System (WAAS) receivers often provide position accuracy of 10 m or less (95%) and velocity accuracy of 3 m/s or less (95%) [13][14]. Comparable to radar and WAM, barometric altitude provided by ADS-B has an accuracy of 200 ft (99.7%) for commercial aircraft currently operating in the ATM environment [4]. In contrast to Mode C, ADS-B provides altitude quantization to 25 ft increments.

Position and velocity are broadcast at a rate of 2 Hz with 1090ES and 1 Hz with UAT equipment. ADS-B can resolve two aircraft at the same location. ADS-B is also an established input to ATC data fusion and automation systems (e.g., STARS, ERAM). However, for ADS-B information to be used in these applications it is subject to independent validation.

The emitter category field in ADS-B messages indicates a wide range of vehicle types, including: light, small, large, high vortex (e.g., B757), heavy, and high performance fixed wing aircraft. Also included are: rotorcraft, gliders/sailplanes, lighter-than-air vehicles, UAS, and space/trans-atmospheric vehicles.

In addition to ground user support, ADS-B supports enhanced situational awareness for flight crews. ADS-B, ADS-R, and TIS-B provide a nearly complete picture of surrounding traffic. This is contrast to the limited information traditionally conveyed by TCAS and ATC advisories.

3.2.1.2. ADS-B Disadvantages

1090ES equipment is capable of 2 Hz update rates, but because it operates on the same frequency as standard transponders, achieved update rates are reduced in high 1090 MHz interference environments that occur in dense airspace such as the Northeastern corridor and LA basin, even with short range transmissions (e.g., less than 40 NM) [13]. UAT equipment does not currently share this limitation.

GPS satellite signals are continuously available for position and velocity determination up to altitudes of 3000 kilometers (km), a region of space also known as the GPS Terrestrial Service Volume (TSV) [15]. However, the Coordinating Committee for Multilateral Export Controls (COCOM) has placed restrictions on many GPS receivers. Two conditions can trigger significant limitations: an altitude greater than 59,000 ft or velocity greater than 1000 knots (kts). Depending on the manufacturer, COCOM restrictions may be interpreted loosely or conservatively. For example, some receivers will function above 59,000 ft as long as the velocity condition is not triggered. Other receivers will cease to output GPS state solutions if either condition is triggered. This constraint was put into place to prevent foreign adversaries from using GPS for weapon system navigation. These limitations impact both 1090ES and UAT ADS-B installations. Unrestricted GPS receivers do exist and have been used to test prototype ADS-B installations for ETM operations [16].

Commercial pressure altimeters may not provide useful barometric altitude information above 60,000 ft. This limitation impacts pressure altitude reported in 1090ES and UAT messages. Additionally, this constraint impacts geometric altitude information provided by 1090ES systems. In current version 2 1090ES installations, geometric altitude is reported as a difference relative to pressure altitude (e.g., +500 ft relative to 30,000 ft). If pressure altitude is unavailable and data integrity is greater than required per [6], absolute geometric altitude can be substituted for pressure altitude in 1090ES messages. However, this case is an exception. One advantage of version 3 1090ES ADS-B will be availability of absolute geometric altitude.

Current version 2 ADS-B requirements limit position and altitude reporting, independent of GPS receiver and pressure altimeter constraints. The horizontal position information in 1090ES messages is encoded in a compact position reporting (CPR) format. CPR reduces the number of bits needed to encode WGS-84 latitude and longitude data. Consistent decoding of CPR position messages is algorithmically dependent on aircraft traveling 1000 kts or less. The current 1090ES format also limits altitude to 126,750 ft, horizontal velocity to 4,086 kts, and vertical rate to 32,608 feet per minute (fpm). The UAT format as currently defined limits altitude to 101,337 ft and vertical rate to 32,608 fpm.

ADS-B is also susceptible to jamming and spoofing. ADS-B jamming is most likely to occur as interference with GPS signals. Spoofing is possible through creation of false GPS signals or transmission of false ADS-B messages. Current ADS-B avionics standards do not address mitigations for these vulnerabilities. Radar and other techniques provide validation of ADS-B messages in the SBS system to mitigate such vulnerability. Additionally, ADS-B is susceptible to GPS disruptions from solar storms or human action (e.g., anti-satellite, or ASAT, weapons). In the event of a significant GPS outage, 1090ES equipment will continue to broadcast ADS-B messages lacking GPS specific parameters (e.g., horizontal position and velocity), but containing independently derived data such as pressure altitude. UAT equipment will cease broadcasts if a GPS outage lasts more than 20 minutes.

WAAS avionics are not consistently deployed across the air transport fleet. Large airframe manufacturers (e.g., Boeing, Airbus) provide WAAS enabled GPS receivers as options on some aircraft, but historically have offered Ground Based Augmentation System (GBAS) multi-mode receivers (MMRs) in greater numbers.

WAAS equipage is more widely available in the GA fleet. Because of these equipage trends, the availability of extremely accurate ADS-B (e.g., position errors less than 10 m) is inconsistent.

Another significant disadvantage of ADS-B is that UAT technology is not consistently deployed internationally. Oceanic airspace coverage will also be limited if space-based ADS-B is not formally adopted.

3.2.1.3. Current ADS-B Support for ETM

ADS-B surveillance of commercial vehicles in ETM airspace may be characterized as extremely limited due to COCOM restrictions on many GPS receivers and pressure altimeter limitations. Depending on the implementation, GPS calculated horizontal position, horizontal velocity, and geometric altitude may be unavailable above 59,000 ft. Pressure altitude may be present in messages transmitted above FL600, however, it may not be useful. Military aircraft with unrestricted GPS receivers and appropriately integrated ADS-B equipment may be adequately surveilled up to pressure altitudes supported by their onboard systems.

Despite the significant limitations noted above, multiple experiments indicate that ADS-B is a viable surveillance alternative for ETM vehicles. Embry-Riddle Aeronautical University and the MITRE Corporation successfully designed and operated a prototype UAT transmitter on a UFB up to an altitude of 94,000 ft [17]. Transmissions to the SBS system included both geometric and pressure altitude. This case illustrates that at least some commercial barometric altimeters can continue to operate at altitudes significantly greater than 60,000 ft. More recently, NASA successfully designed and tested a prototype 1090ES transmitter at supersonic speeds in an F-18 aircraft [16]. The NASA system contained an unrestricted GPS receiver. Maneuvers included a 10,000 ft military power climb and supersonic dive at Mach 1.4 to simulate space launch and reentry procedures (respectively). The study concluded that with unrestricted GPS and appropriate antenna diversity (e.g., upper and lower antennas), the SBS system adequately tracked the aircraft during supersonic segments. An experiment conducted by the Royal Military College of Canada (RMCC) found that a 1090ES receiver successfully detected ADS-B messages emanating from the ATM environment at an altitude of 92,850 ft [18]. These observations indicate that vehicle to vehicle transmissions and receptions are feasible in the ETM environment.

Additionally, 1090ES and UAT signal characteristics do not preclude support for high speed operations. 1090ES equipment employs pulse modulation and is reasonably immune to doppler shift issues associated with high velocity transmissions. UAT signals are phase modulated and should not encounter issues at high speeds.

3.2.1.4. ADS-B Changes Necessary to Enhance ETM Support

A key change needed to enable adequate ADS-B surveillance of ETM operations is a revision to COCOM GPS receiver restrictions. Two GNSS constellations are operational (GPS, GLONASS) and two constellations are in development (Galileo, BeiDou). The availability of multiple navigation solutions may warrant a reassessment of the risk posed by potential foreign adversary use of GPS. Additionally, mitigating this risk should be weighed against the impact it has on U.S. national advancement in the aerospace domain.

Consistent with radar and WAM surveillance, several peripheral systems may require changes to enhance ADS-B support of ETM operations. These may include modifications to air data computer standards and commercial barometric altimeter technology if pressure altitude is a necessary parameter above FL600. Additionally, data fusion, automation, and traffic flow management systems may require software changes to enable additional inputs and operational use of this information.

Lastly, and perhaps most critically, increased ADS-B support for ETM operations is dependent on continued development of version 3 standards. ICAO and FAA Air Traffic Organization (ATO) stakeholders have initiated this process in the RTCA Combined Surveillance Committee (CSC). This effort is initially focused on 1090ES support for supersonic, hypersonic, and commercial space vehicles. Proposed requirements [19] include the following coverage limits requested by stakeholders: geometric altitude up to 330,000 ft, vertical rate up to 131,400 fpm, and horizontal velocity up to 14,200 kts. New (alternate) airborne position and velocity message formats have also been proposed for vehicles in high altitude airspace and/or traveling at high velocities. Changes to these messages include: position encoding in the clear (not employing CPR) to enable functionality at greater speeds, consistently available absolute geometric altitude, and transmission rates of 2 Hz unless studies show a need for more frequent updates. Additionally, a speed-based transition between current and alternate formats has been proposed. Current proposals have the transition initiating at speeds of 1000 kts and may include the broadcast of both current and alternate messages to facilitate reception by aircraft operating in both ATM and ETM environments. Currently specified position messages broadcast during the transition would require modified transmission timing that should prevent CPR decoding issues. Table 3-1 summarizes the proposed speed-based transitions between 1090ES message formats. UAT equipment changes to support ETM vehicles are expected to be developed in parallel to 1090ES work.

Table 3-1. Standard and Alternate 1090ES ADS-B Transmissions vs. Airspeed

Speed Condition	Transmitted Messages				
	Standard Position Message	Standard Position with Modified Rate	Standard Velocity Message	High Velocity Position Message	High Velocity Velocity Message
Increasing Speed					
< 1000 kts	X		X		
1000-1800 kts		X	X	X	
> 1800 kts				X	X
Decreasing Speed					
> 1600 kts				X	X
1600-800 kts		X	X	X	
< 800 kts	X		X		

3.2.2. Automatic Dependent Surveillance – Contract (ADS-C)

ADS-C is typically comprised of aircraft avionics, satellite communication (satcom) links, and ground infrastructure. Onboard avionics automatically provide ADS-C reports in accordance with contracts established between aircraft and Air Navigation Service Providers (ANSPs). Reports can be sent at specific time intervals or whenever particular events occur. This technology is widely used in oceanic and remote continental airspace. ADS-C and Controller Pilot Data Link Communications (CPDLC) are required for flights assigned to the most efficient routes in the North Atlantic Organized Track System (NAT-OTS) [20]. ADS-C and CPDLC enable lateral separation of 23 NM, longitudinal separation of 30 NM, and a 15 NM Climb/Descend Procedure [21] in oceanic airspace.

Periodic ADS-C reports sent at regular intervals contain aircraft identification, GPS and inertial reference unit (IRU) based position, time of applicability, altitude, speed, and positional accuracy. It is not uncommon for this information to be sent in accordance with multiple simultaneous contracts (e.g., current ANSP, following ANSP, and airline operations center). ADS-C messages are typically transmitted by satcom equipment to a service provider constellation (Inmarsat Classic Aero, Inmarsat SB-S, or Iridium) [21], forwarded to Ground Earth Stations (GES), and relayed to the Aircraft Communications Addressing and Reporting System (ACARS) network. This architecture is depicted by Figure 3-5. ADS-C also supports traditional VHF transmissions, however, with reduced performance.

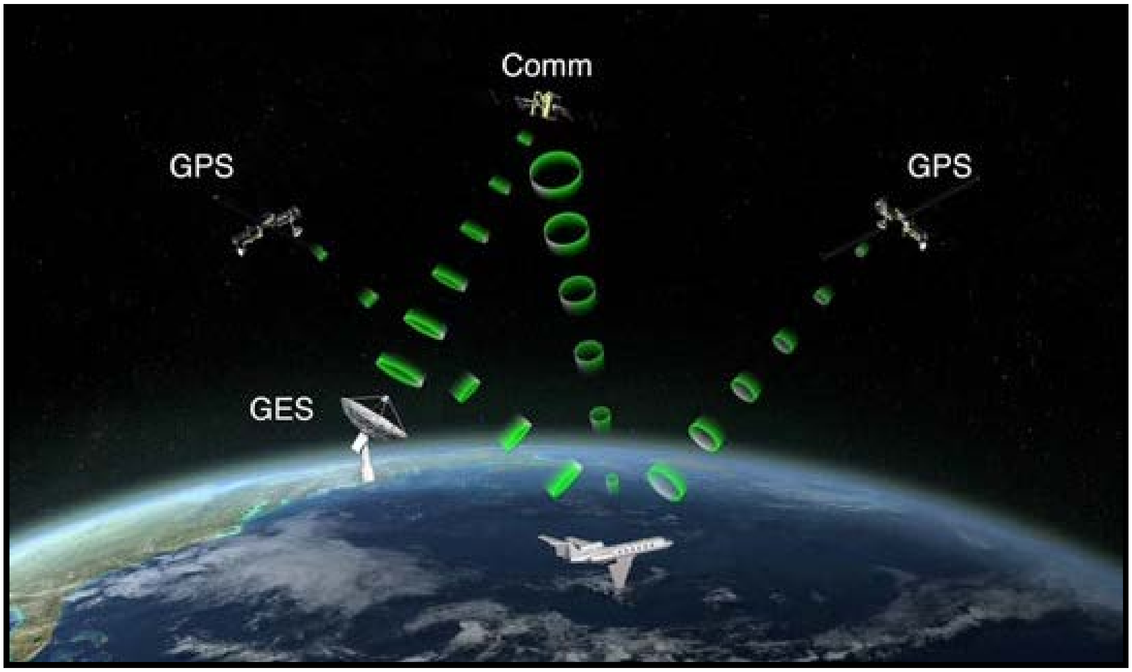

Figure 3-5. ADS-C Architecture

3.2.2.1. ADS-C Advantages

The primary benefit that ADS-C provides is surveillance in oceanic and remote continental regions. This technology is a key enabler of reduced separation minima in oceanic airspace. ADS-C provides barometric altitude accuracy of 200 ft (99.7%) for commercial aircraft currently operating in the ATM vertical band [4]. ADS-C is an established input to the Advanced Technologies & Operating Procedures (ATOP) automation system.

3.2.2.2. ADS-C Disadvantages

ADS-C is not used or approved for tactical separation of aircraft. It is only used for non-radar procedural separation or to manage procedural separation. The ICAO Surveillance Panel does not consider ADS-C to be a formal surveillance system due to its limitations and lack of fully defined performance requirements. Additionally, despite the coverage ADS-C provides in remote airspace, it does not provide coverage over the poles.

Existing standards set the lowest achievable ADS-C update interval to 64 seconds [22]. The lowest update interval required for minimum separation in oceanic airspace is currently 12 minutes. Typical position accuracy is consistent with a Figure of Merit (FOM) of 6, which equates to 0.25 NM (95%). Position accuracies significantly less than 92.6 m (95%) are not indicated by ADS-C. Additionally, velocity accuracy and state data integrity indicators are not provided. Pressure altitude in ADS-C messages, supplied by commercial barometric altimetry systems, may not be useful above 60,000 ft.

ADS-C end to end latency averages 4.5 seconds with the newer Inmarsat SB-S broadband constellation [21]. This is significantly greater than ADS-B and WAM latencies which are often characterized in hundreds of milliseconds. ADS-C reliance on GPS increases susceptibility to jamming, spoofing, and other disruptions. However, the use of ADS-C primarily in oceanic and remote continental airspace may reduce this risk.

Fees are typically charged for the transmission of each ADS-C message. Because most of these costs are incurred by airlines, there is reluctance to use ADS-C at higher update rates. Additionally, ADS-C does not provide enhanced situational awareness to flight crews. It is primarily used by ANSPs for monitoring of procedural separation.

3.2.2.3. Current ADS-C Support for ETM

ADS-C surveillance of commercial vehicles in ETM airspace may be characterized as extremely limited due to COCOM restrictions on GPS receivers and pressure altimeter constraints. GPS provided horizontal position and velocity may be unavailable above 59,000 ft. Pressure altitude may be present in messages transmitted above FL600, however, it may not be useful.

3.2.2.4. ADS-C Changes Necessary to Enhance ETM Support

Unrestricted GPS receivers are a key enabler of ADS-C surveillance for ETM traffic. If pressure altitude is a necessary parameter above FL600, modifications to air data computer standards and commercial barometric altimeter technology may also be necessary. Continuous availability of absolute geometric altitude may also be required.

The ICAO Separation and Airspace Safety Panel (SASP) is currently developing further reduced oceanic separation minima supported by ADS-C surveillance. Potential changes to standards include required update rates between 64 seconds and 5 minutes, aircraft route conformance monitoring revisions, and alert modifications. ETM stakeholders may need to participate in this process for ADS-C to provide adequate surveillance of operations above FL600.

Satcom service providers (Inmarsat, Iridium) may have to reconfigure systems to accommodate ADS-C support for ETM, e.g., implementing software changes such as filter modifications. Tracking and automation systems used by ANSPs (e.g., ATOP) may also require software changes to process any ADS-C information specific to ETM vehicles. ADS-C is not integrated with STARS, ERAM, or Micro En Route Automated Radar Tracking System (MEARTS). If integration with these automation systems is necessary, costs could be substantial (e.g., greater than $200M). Lastly, operators may have to consider greater service provider fees associated with faster update rates.

3.3. Additional Surveillance Technologies

For completeness, additional technologies that could potentially function as ETM surveillance mechanisms are briefly discussed, but not assessed in detail. One alternative may involve aircraft self-reporting on a communications link to be determined through future work. Long range, active

Radio Frequency Identification (RFID) is another emerging technology. However, it should be noted that current long range RFID systems are not capable of acquisition beyond roughly one mile.

4. Potential ETM Surveillance Constructs

Potential constructs for the surveillance component of the ETM system were identified by first examining altitude reporting limitations that impact all assessed technologies. There is a general consensus that most modern commercial barometric altimeters do not provide useful information above 60,000 ft. Geometric altitude is capable of filling this gap, however, measurements provided by many GPS receivers are currently restricted above 59,000 ft. Geometric elevation measurements could be available through other means, e.g., 3D long range radar and 3D WAM, however, accuracy may be reduced in comparison to GPS. Alternatively, systems adhering to cancelled military standards do provide pressure altitude up to 80,000 ft. Assuming that geometric altitude for ETM vehicles will be available (e.g., regulatory changes that allow unrestricted GPS receivers), there are at least two potential options for surveillance in the vertical dimension. One option is simply that surveillance relies on pressure altitude for most vehicles below 60,000 ft and geometric altitude for most vehicles above 60,000 ft. Benefits of this option include a simple demarcation with similarities to the transition altitude of 18,000 ft and extension of the ATM paradigm of reliance on one altitude type into ETM airspace. Because differences between barometric and geometric altitudes may be significant, additional vertical separation may be necessary between vehicles operating near this boundary (e.g. one below and one above). Another option consists of the following:

a. Surveillance system reliance on pressure altitude for most vehicles below 60,000 ft.

b. Some vehicles, likely of higher criticality (e.g., SSTs or SSBJs with passengers), equip with special pressure altimeters built to cancelled military standards or a similar new specification, enabling surveillance of these aircraft to rely on barometric altitude up to roughly 80,000 ft. Geometric altitude will be available as a secondary measurement between FL600 and FL800.

c. Surveillance system reliance on geometric altitude for all other relevant vehicles between FL600 and FL800.

d. Geometric altitude for most vehicles above 80,000 ft.

Benefits of the second option may include reduced vertical separation between vehicles reporting pressure altitude near FL600 and availability of independent altitude measurements for some vehicles between FL600 and FL800. Figure 4-1 depicts vertical dimension options across ATM and ETM environments.

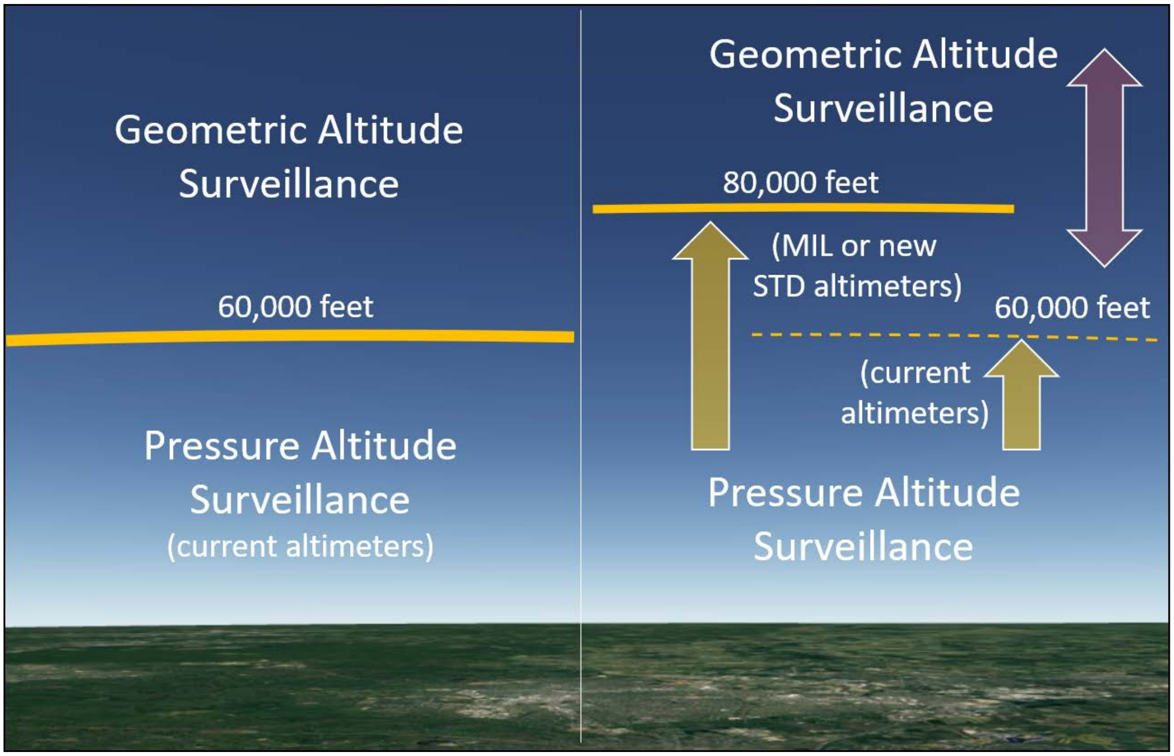

Figure 4-1. Vertical Dimension Options

To enable these vertical options, several changes to candidate surveillance systems will be necessary. 1090ES ADS-B typically indicates geometric altitude as a difference relative to pressure altitude, propagating barometric altimeter errors to geometric values. Other ADS-B limitations include maximum altitude values of 126,750 ft and 101,337 ft for 1090ES and UAT implementations (respectively). Version 3 ADS-B is expected to resolve these (and other) constraints. Phase 2 WAM algorithms may need to change from 2D positioning plus modified pressure altitude to 2D positioning combined with geometric altitude from version 3 ADS-B transmissions. Alternatively, 3D WAM with ground system determination of geometric elevation may be an option if accuracy is determined to be sufficient. If needed, ADS-C may require changes similar to ADS-B to enable continuous absolute geometric altitude reporting in ETM airspace. Pending additional study, ADS-C may also require modified update intervals to accommodate vertical changes of ETM vehicles (e.g., supersonic passenger flights) in oceanic airspace. Lastly, automation systems (e.g., ERAM, ATOP) would likely require changes to enable processing and display of geometric altitude from any of these sources. Additional inputs may be provided by long range radars capable of measuring geometric elevation if accuracy is sufficient. With these system modifications, numerous ETM surveillance constructs are possible. For the purposes of this assessment, two alternatives have been developed.

4.1. Low Resiliency Surveillance Construct

One alternative is essentially an upward extension of current SBS ADS-B. If further study indicates an appropriate need, this could be complemented by enhanced ADS-C for some vehicles in oceanic regions. In this construct, most vehicles in ETM airspace over land and coastal areas of the NAS will be surveilled with version 3 ADS-B. This is expected to be enabled by unrestricted GPS receivers and removal of relevant filters in the SBS system (e.g., current range and altitude limits). Below FL600, ATM requirements are expected to apply to most ETM aircraft (excluding some UFBs): mandatory equipage with SSR and ADS-B transponders. Figure 4-2 depicts the low resiliency surveillance construct for the ETM environment. The coverage volumes shown are for illustration purposes only and do not represent actual boundaries.

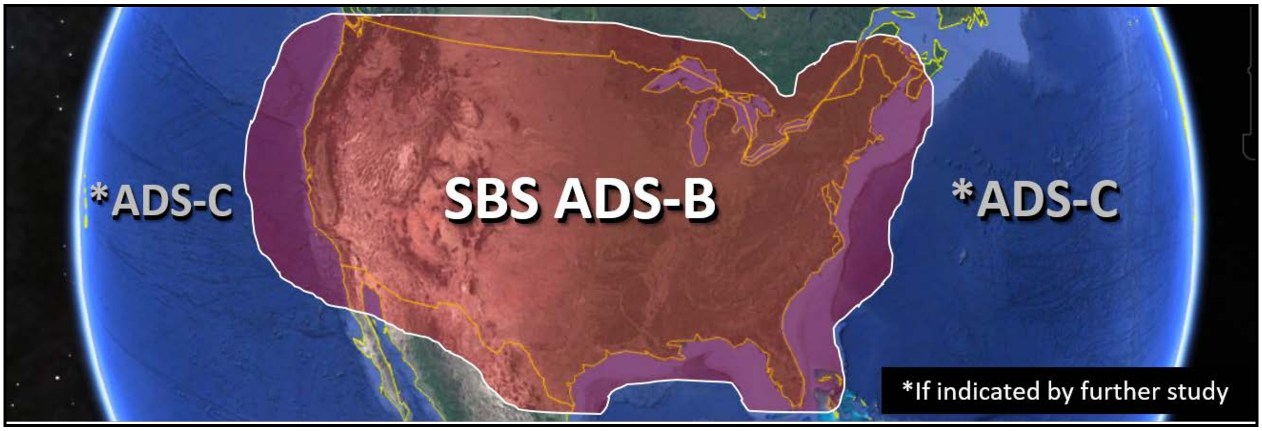

Figure 4-2. Low Resiliency ETM Surveillance Construct

Light UFB vehicles may continue to adhere to 14 CFR Section 101.35 requirements for reflective material and lighting, with optional equipage of SSR (or potentially ADS-B) transponders at the discretion of operators. However, if further work indicates that light UFBs pose a significant risk to ATM and/or ETM operations, more stringent requirements may be necessary.

Heavy UFBs, along with HALE aircraft (fixed wing, balloons, and airships), should adhere to a modified version of ICAO Annex 2 Appendix 4 standards that call for SSR and ADS-B transponders in airspace above corresponding ground infrastructure. An additional requirement for version 3 ADS-B would be necessary to enable geometric altitude surveillance in ETM airspace. Operators would hold several responsibilities drawn from the cooperative separation concept, potentially including but not limited to: trajectory sharing, pre-flight deconfliction, shared situational awareness, conformance monitoring, regular communication with ANSPs, and flight path adjustments if instructed and applicable.

SST and SSBJ aircraft could traverse oceanic airspace using a system similar to Concorde. This would employ special use tracks and procedural separation. If further work (e.g. analysis, consultation of ANSPs) indicates that procedural separation alone is inadequate because of expected traffic density, conflicts with subsonic aircraft, or other factors, an enhanced version of ADS-C could be used by these aircraft in oceanic regions. ADS-C modifications may include a faster update rate and consistently available geometric altitude referenced to the WGS-84 ellipsoid. RTCA DO-258A/EUROCAE ED-100A limits the minimum update interval to 64 seconds. However, the range and resolution of the time interval parameter in the periodic contract allows for an interval to be specified between 1 second and 4,096 seconds. When in range of ground based transceivers, surveillance for these vehicles would be provided by SBS ADS-B. It may be necessary for supersonic aircraft to adhere to more stringent antenna requirements (e.g., placement diversity) to enable adequate tracking when traveling at high velocities. Because the supersonic aircraft being considered are intended for passenger flights, some form of managed separation is expected for these vehicles. Additionally, since supersonic aircraft are expected to be the most maneuverable in potential ETM vehicle-to-vehicle pairings, some form of DAA mechanism may also be required. This could be accomplished with an enhancement to TSAA, or potentially with an active ranging system that computes range and bearing and combines those parameters with geometric altitude reported by version 3 ADS-B. Analysis of a TSAA system enhanced with lateral resolutions demonstrated that the 2015 collision between a Cessna and F-16 over Moncks Corner, SC, could have been detected 30 seconds in advance and was most likely preventable. This experimental system also showed that it is feasible to detect conflicts between vehicles with disparate performance characteristics.

Space launch, recovery, and reentry procedures are envisioned to be surveilled with two sources: operator provided telemetry routed to the Space Data Integrator (SDI) and SBS ADS-B extended to hardware limits, i.e., beyond current boundaries set by software filters. Multiple surveillance sources for these vehicles may increase the likelihood of continuous surveillance during phases in which telemetry alone may be limited. Space vehicles may require antenna diversity similar to experimental supersonic applications. Additionally, high power transmitters may be needed to enable adequate extended SBS system surveillance. Identification of exact coverage boundaries will require additional study, but it is believed that potential coverage will encompass significant portions of airspace currently subject to temporary closures during space operations. However, it should be noted that even extended SBS system coverage will be limited in oceanic airspace compared to space based surveillance. Additionally, the use of multiple ADS-B transponders in some operations could significantly improve NAS efficiency. For example, separate transponders on recovery and payload delivery stages of space systems may enable smaller temporary airspace closures and more expedient reopening of these volumes. Pressure altimeters and SSR transponders are not envisioned for space vehicles. Rapid changes in external pressure due to flight dynamics (e.g., acceleration) are known to cause significant issues with barometric altitude reporting (e.g., non-trivial lag). Automation and decision support systems (e.g., TFMS) will also likely require changes to accommodate information provided by version 3 ADS-B. Space operators are also envisioned to hold the same responsibilities as heavy UFB and HALE operators. These responsibilities may include collaborative flight planning, pre-flight deconfliction, shared situational awareness, conformance monitoring, and regular communication with ANSPs.

The level of support that this surveillance construct can provide for hypersonic operations is currently unknown because these vehicles are still in the concept phase. The same is true for other potential entrants not discussed in this assessment. To enable this construct, an additional potential requirement for some ETM vehicle is equipage with more robust GPS receiver chipsets. Current designs are known to experience issues when they encounter more than four times gravitational acceleration (4g). This could occur through events such as acceleration to achieve escape velocity and parachute deployment.

The primary weakness of this construct is a lack of resiliency due to a limited number of surveillance sources and a common point of failure in GPS state determination. The primary benefit of this construct is that it is mostly an extension of current capabilities and should be implemented at lower cost than other options.

4.2. High Resiliency Surveillance Construct

The second potential ETM surveillance construct is built upon the first alternative. The second option would include all elements of the first system, with additional surveillance sources for added resiliency. SSR surveillance of some vehicles in ETM airspace (e.g., supersonic aircraft, balloons in lower altitude bands) could be enabled by barometric altimeters built to cancelled military standards, or similar, new commercial standards with functionality up to FL800. Some vehicles (e.g., most HALE applications) could be surveilled with 3D long range radars that calculate geometric elevation using typical SSR transponder replies, depending on availability and accuracy. These mechanisms could provide an additional surveillance source, independent of GPS, capable of tracking a significant portion of ETM operations. However, this functionality may be outside the scope of radar consolidation planned through the SENSR program. Expansion of another surveillance source could compensate for this uncertainty.

Phase 2 WAM, implemented within the SBS network, could be expanded with deployment of additional multilateration servers, removal of current software limits (e.g., altitude caps, simultaneous radio contact constraints), and changes to positioning algorithms. Position calculations could employ 2D positioning combined with geometric altitude from version 3 ADS-B transmissions or 3D WAM with ground system determination of geometric elevation. It should be noted that Phase 2 WAM currently relies on GPS timing. 3D WAM with an independent timing source would likely be required to remove all dependencies on GPS. Both potential WAM implementations require additional study to fully characterize, however, it is expected that either option will cover significant portions of ETM airspace with update rates comparable to those provided by current installations.

The last component of the high resiliency ETM surveillance construct is space-based ADS-B. This surveillance source, modified to accommodate version 3 1090ES standards, would provide a mechanism to surveil trans-continental supersonic passenger flights. Update rates would be significantly faster than those achieved today with ADS-C in oceanic operations. Additionally, space-based ADS-B would extend coverage of space operations beyond the limits of a modified SBS system. If additional work indicates that ADS-C is needed for some ETM vehicles in oceanic regions, space-based ADS-B and ADS-C would share a common point of failure with GPS state determination. However, hybrid GPS/IRU positioning systems may allow ADS-C to provide some form of position estimate in the event of GPS disruptions; characterizing this may require further work.

The primary benefit of this surveillance construct is resiliency achieved with multiple, independent technologies. Weaknesses of this construct include a high level of complexity, potential reliance on GPS positioning in oceanic airspace, and potentially significant costs. Figure 4-3 depicts the high resiliency surveillance construct for the ETM environment. The coverage volumes shown are for illustration purposes only and do not represent actual boundaries.

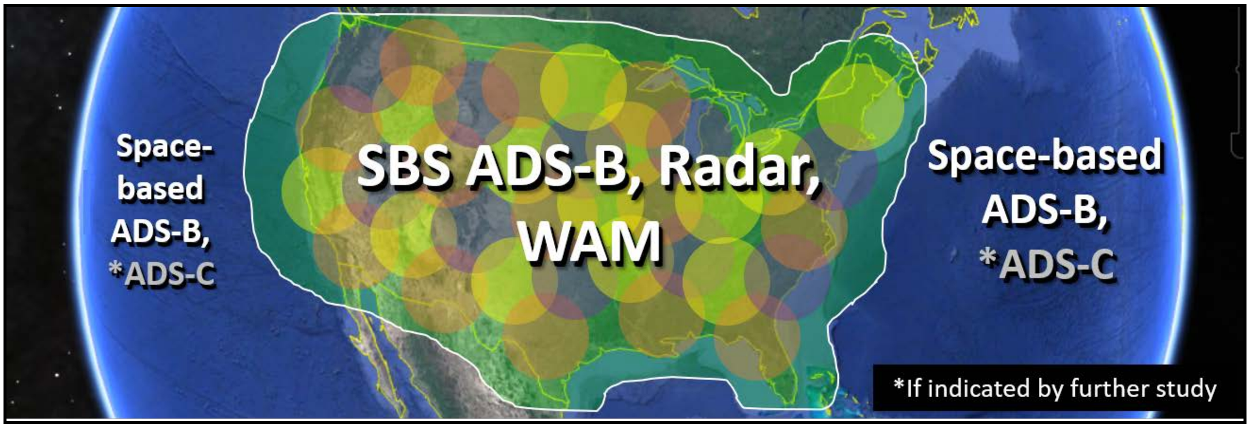

Figure 4-3. High Resiliency ETM Surveillance Construct

5. 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, space vehicles, and potentially hypersonic aircraft. The regulatory framework, policies, infrastructure, and procedures in place for current operations may not cost-effectively scale to 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.

Four surveillance alternatives were assessed for ETM operations: radar, WAM, ADS-B, and ADS-C. Each technology was characterized in terms of general advantages, disadvantages, current level of support for ETM, and changes necessary for enhanced ETM support. Limitations of peripheral systems (e.g., pressure altimeters and GPS receivers) that impact these surveillance sources were also discussed.

Two vertical dimension options were formulated for surveillance of ETM airspace. One option consists of a transition from pressure altitude to geometric altitude surveillance at 60,000 ft. The second option consists of pressure altitude reporting to 60,000 ft, a mixture of pressure and geometric altitude surveillance between FL600 and FL800, and reliance on geometric altitude above 80,000 ft. Two potential surveillance constructs for ETM that satisfy these criteria were formulated.

In a low resiliency construct, surveillance for most ETM vehicles over land and coastal areas would be provided by version 3 ADS-B transmitted to an extended SBS network. Enhanced ADS-C could provide surveillance for supersonic passenger flights in oceanic airspace if a need is indicated by additional work. Space operations would be surveilled with operator provided telemetry routed to the SDI and version 3 ADS-B. Space and HALE operators would be responsible for implementing cooperative separation principles.

A high resiliency construct, built upon the low resiliency option, adds surveillance sources including radar and a modified version of Phase 2 WAM. Lastly, space-based ADS-B would provide additional GPS dependent coverage of supersonic and space operations in oceanic airspace.

Additional work is needed to fully characterize the concepts presented in this paper. This should be performed collaboratively with government and industry stakeholders. Considerations for ETM navigation and communication systems are also critical and may influence additional surveillance work. For example, multilateration technology may provide both surveillance and navigation functions.

6. Acknowledgements

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