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Existing Surveillance Technologies for Upper Class E Traffic Management (ETM)

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1 Abstract

Expected activity at and above Flight Level (FL) 600 includes expanded use of Uncrewed Free Balloons (UFBs), High Altitude Long Endurance (HALE) operations, and the reintroduction of supersonic passenger flights. Upper Class E Traffic Management (ETM) is the system envisioned to support these operations [1]. Potential 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, and current level of support for ETM.

2 Introduction

Operations above 60,000 feet (ft) are expected to increase in the near future. Multiple vehicle types are anticipated to be active in this volume. UFBs with minimal flight path control and short mission durations may operate up to altitudes of 160,000 ft. HALE balloons, potentially operating up to 100,000 ft, will extend mission durations and employ some degree of altitude control allowing changes on the order of 10,000 ft. HALE telecommunication balloons have been flown in various locations around the world up to altitudes of 70,000 ft. Solar-powered, HALE fixed-wing aircraft are expected to loiter between FL600 and FL900 for several months with daily climbs during daylight and minimally powered descents at night to maintain 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), including both larger airliner models and smaller business jets. These passenger aircraft are expected to initially cruise at speeds between Mach 1.0 and Mach 2.5 at altitudes between FL500 and FL600. Subsequently developed SSTs may be capable of even greater speeds at greater cruise altitudes. Hypersonic aircraft, while still mostly in the concept phase, are also vehicles that will potentially operate in this airspace (e.g., possibly up to FL900). Figure 1 depicts (clockwise from left) renderings of a HALE telecommunications balloon, a HALE fixed-wing aircraft, and an SST.

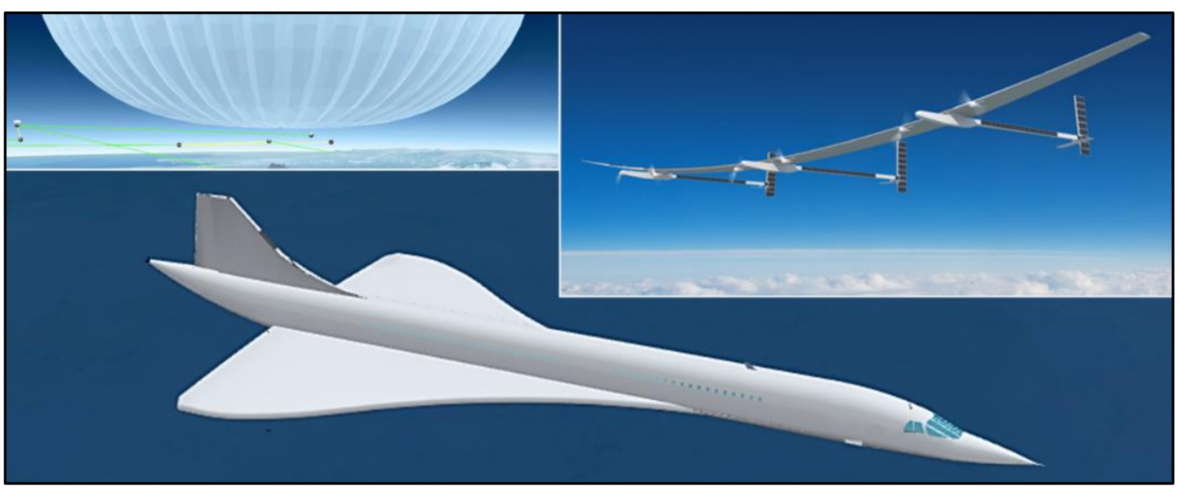

Figure 1: High-Altitude Vehicles

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

Figure 2: Notional Depiction of the ETM Environment

This document focuses on the surveillance component of the ETM concept. Four technologies were considered in this assessment. Two of these alternatives, radar and 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, ADS-B and 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 Surveillance Technologies

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 up to altitudes of 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 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 ATC-managed separation of civilian and military aircraft. Excluding several relatively small volumes of airspace over mountainous terrain, most of the Contiguous United States (U.S.) (CONUS) is covered by radar surveillance at an altitude of 18,000 ft. This is illustrated by Figure 3, adapted from [2].

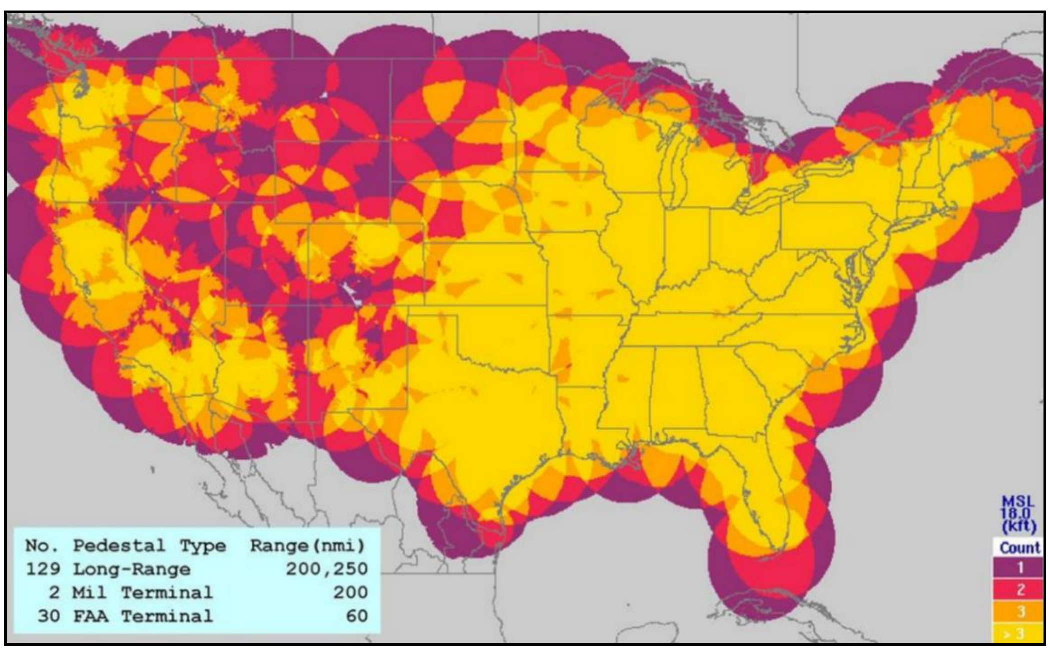

Figure 3: CONUS Radar Coverage at 18,000 ft

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 traditional 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) surveillance inputs. 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 (TFM) and Collaborative Decision Making (CDM), e.g., the Traffic Flow Management System (TFMS). Radar (and multilateration-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 only 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 traffic 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 (ADCs) that calculate pressure altitude based on static port inputs are not required to be tested for operation 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 many commercial barometric altimeters are 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].

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. However, it should be noted that one manufacturer/operator developed, gained approval for, and operated pressure altimeters that functioned up to 70,000 ft based on extrapolated test criteria from [7]. It may be possible to develop similar systems that function at slightly greater altitudes, however, above 80,000 ft, atmospheric density may be too low to support pressure altimetry.

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 due to overlapping radar coverage.

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 above FL600. However, there are several 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 Title 14 of the Code of Federal Regulations (CFR), Section 101.35. Some operators voluntarily equip with SSR transponders; however, these are typically operated intermittently at cruise altitude to conserve power [10]. While SSR transponder pressure altitude transmission codes are currently defined to 126,750 ft [11], the accuracy of inputs to these devices is often degraded 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 upper Class E 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 HALE aircraft. This includes fixed-wing, balloon, and airship vehicles. 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 70,000 ft may be adequately surveilled by long range radars. 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 at high altitudes are visible to some radar systems. However, limitations 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 expected ETM airspace. Concorde achieved speeds of Mach 2.0 in oceanic airspace inside of long range radar coverage. Figure 4 depicts the North Atlantic Track SM used by Concorde flights into New York and the descent/deceleration region near Nantucket, Massachusetts. ATC typically provided Concorde flights with altitude blocks (e.g., FL500 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 above FL600 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.

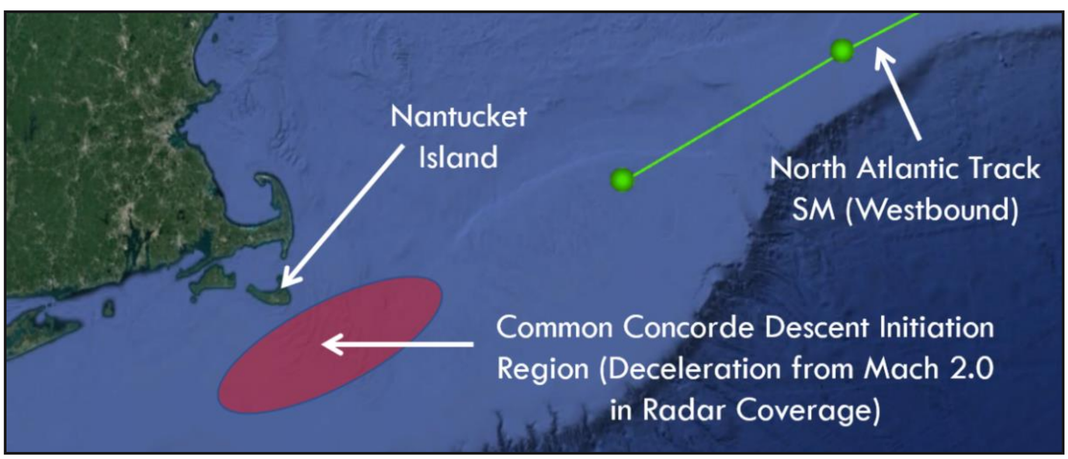

Figure 4: Concorde Supersonic Flight Segment

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. However, it could be noted that, at least anecdotally, there is concern around maneuverable hypersonic weapons due to potential difficulty in tracking these vehicles.

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 5 depicts a generic architecture for multilateration systems adapted from [3].

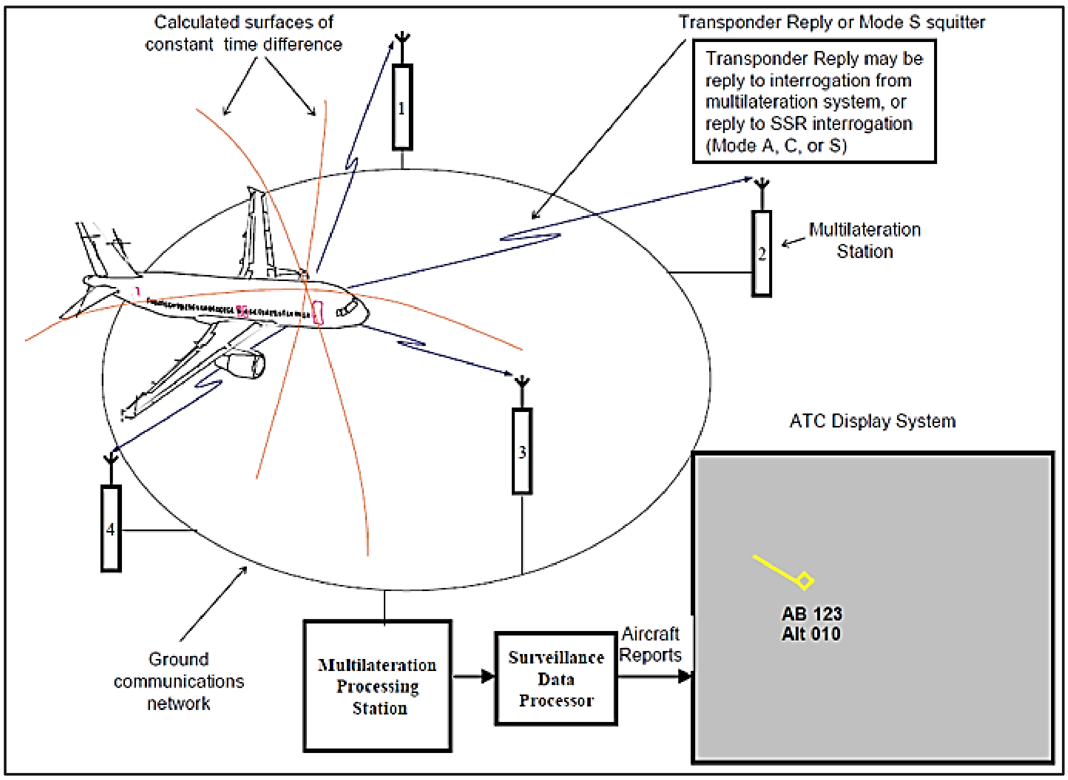

Figure 5: Generic Multilateration System Architecture

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 ETM operations and are considered to be out of scope. WAM, however, may be capable of surveilling traffic transiting to/from upper Class E airspace or within flexible floor volumes in upper Class A airspace. WAM is operational at multiple locations in the U.S., including several airports in the Colorado mountains; Juneau, Alaska; Charlotte, North Carolina; and Los Angeles, California. 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 L3Harris Technologies, Inc. Phase 2 systems employ SBS system radios also used for ADS-B services. Another key difference in operation between Phase 1 and Phase 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 being converted Phase 2 sites hosted within SBS.

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 traditional ATM environment [4].

WAM provides an update interval of 3.0 seconds (95%) for the terminal domain. Phase 2 installations typically provide observed 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 may 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 above FL600 may be characterized as extremely limited due to system configurations and pressure altimeter accuracy issues. System filters prevent appropriate acquisition of targets above 60,000 ft. If position can be determined, potential pressure altitude errors may negatively impact calculations. However, aircraft in upper

Class A airspace transiting to or from CAs, or within a flexible floor below FL600, would be surveilled by WAM in an appropriate coverage region if equipped with pressure altimeters that provide accurate measurements.

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).

3.2.1 Automatic Dependent Surveillance – Broadcast (ADS-B)

ADS-B, as initially designed and implemented in the U.S., consists of airborne equipment and SBS system ground infrastructure. ADS-B transceivers 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 Megahertz (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 International Civil Aviation Organization (ICAO) global 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 were 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 coverage in the Gulf of Mexico. Figure 6 depicts ADS-B coverage provided by the SBS system.

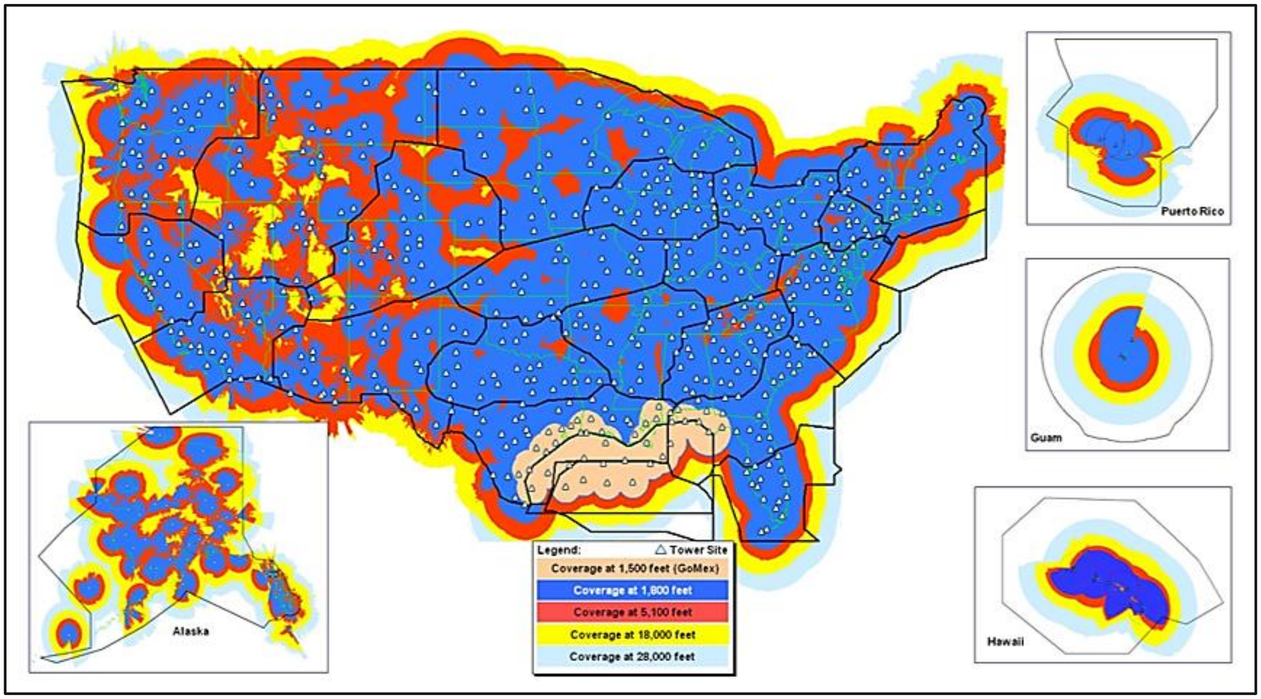

Figure 6: ADS-B Coverage Provided by the SBS System

Space-Based ADS-B (SBA), provided as a commercial service, 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. SBA is available as a paid service from Aireon.

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 ATAS – ADS-B, ADS-R, and TIS-B based conflict detection with 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. 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%), independent of proximity to ground-based radios. 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 traditional 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. Additionally, ADS-B supports enhanced situational awareness for flight crews. ADS-B, ADS-R, and TIS-B provide flight crews with a nearly complete picture of surrounding traffic. This is in contrast to the limited information traditionally conveyed by TCAS and ATC advisories.

The most recent Version 3 1090ES ADS-B standards were developed by the RTCA Combined Surveillance Committee (CSC) to accommodate support for supersonic, hypersonic, and commercial space vehicles. Horizontal and vertical velocities consistent with a space shuttle launch profile can be supported, as well as altitudes up to roughly 1,000,000 ft Above Ground Level (AGL). New/alternate airborne position and velocity message formats and transmission mechanisms were developed for vehicles in high-altitude airspace and/or traveling at high velocities.

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 Los Angeles basin, even with short range transmissions (e.g., less than 40 NM) [13]. UAT equipment does not 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, International Traffic in Arms (ITAR) regulations published in 2016 specify that GNSS receivers should be disabled at speeds in excess of 600 m/s or Mach 2.03 (at FL600), assuming the Standard International Atmosphere (ISA) and no wind. These limitations would, in theory, impact both 1090ES and UAT ADS-B installations by disabling population of horizontal state fields. Unrestricted GPS receivers do exist and have been used to test prototype ADS-B installations for ETM operations [16].

Many commercial pressure altimeters may not provide useful barometric altitude information above 60,000 ft. This limitation could impact pressure altitude reported in 1090ES and UAT messages (e.g., via invalid data input). Additionally, this impacts geometric altitude information provided by widespread Version 2 1090ES systems. In 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 the more recent, but less common Version 3 1090ES ADS-B is availability of absolute geometric altitude.

Version 2 ADS-B requirements also 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 World Geodetic System 1984 (WGS-84) latitude and longitude data. Consistent decoding of CPR position messages is algorithmically dependent on aircraft traveling 1000 knots (kts) or less. The Version 2 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 could occur as interference to GPS signals. Spoofing is possible through the 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 mechanisms provide validation of ADS-B messages in the SBS system to mitigate such a vulnerability. Additionally, ADS-B is susceptible to GPS disruptions from solar storms or human action (e.g., Anti-Satellite (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.

Another significant disadvantage of ADS-B is that UAT technology is not consistently deployed internationally. Oceanic airspace coverage is available through the SBA service, however, at a cost to users.

3.2.1.3 Current ADS-B Support for ETM

ADS-B surveillance of HALE telecommunication balloons has been provided up to altitudes of 70,000 ft. The integrated Communication, Navigation, and Surveillance (CNS) system employed by the manufacturer/operator relied on ADS-B to provide vehicle positions such that navigation commands could be sent to them via the communications mechanism. However, it should be noted that the manufacturer developed, and received approval to use, a high-altitude barometric altimeter that provided accurate pressure altitude measurements. Optional messages provided by Version 3 ADS-B would be capable of reporting geometric altitude up to roughly 1,000,000 ft AGL.

Additionally, multiple experiments indicate that ADS-B is a viable surveillance source for expected 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. More recently, the National Aeronautics and Space Administration (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 power climb and a supersonic dive at Mach 1.4. 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) also found that a 1090ES receiver on a vehicle at an altitude of 92,850 ft [18] successfully detected ADS-B messages emanating from lower (e.g., Class A) airspace. These observations indicate that vehicle-to-vehicle transmissions and receptions are also feasible in the ETM environment.

Additionally, 1090ES and UAT signal characteristics do not preclude support for initial high-speed operations. 1090ES equipment employs pulse modulation and is reasonably immune to doppler shift issues associated with high velocity transmissions. Potential 1090ES installations in SSTs, initially expected to operate up to speeds of Mach 1.7, should not encounter doppler shift issues, as evidenced by the flight tests described in [16]. However, it should be noted that later generations of SSTs (e.g., those capable of speeds up to Mach 3.0) or hypersonic aircraft could potentially experience doppler shift with 1090ES transmissions. UAT signals are phase modulated and should not encounter issues at high speeds. Additionally, GNSS receivers operating at speeds greater than Mach 2.03 at FL600 are required to disable output, which would cease inputs to ADS-B position and velocity fields.

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) [19]. ADS-C and CPDLC support lateral separation of 30 NM and longitudinal separation of 30 NM in oceanic airspace [20].

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) [20], forwarded to Ground Earth Stations (GES), and relayed to the Aircraft Communications Addressing and Reporting System (ACARS) network. This architecture is depicted by Figure 7. ADS-C also supports traditional Very High Frequency (VHF) transmissions, however, with reduced performance.

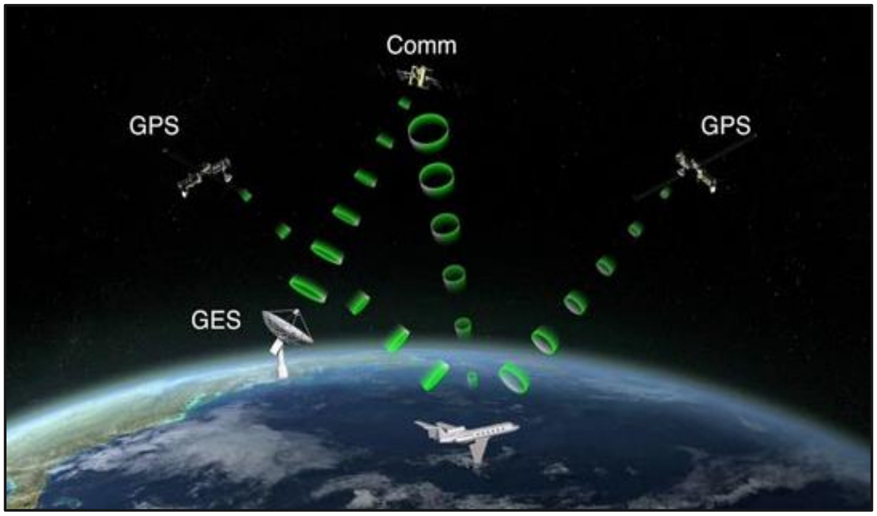

Figure 7: ADS-C Architecture

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 reports barometric altitude with an accuracy of 200 ft (99.7%) for commercial aircraft currently operating in the vertical band of traditional ATM airspace [4]. ADS-C is also an established input to the Advanced Technologies and 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, depending on the satellite service employed, ADS-C may not provide coverage over the poles.

Existing standards set the lowest achievable ADS-C update interval to 64 seconds [21]. The lowest update interval required for minimum separation in oceanic airspace is currently 10 minutes; however, it should be noted that the ICAO Separation and Airspace Safety Panel (SASP) is investigating further reduced oceanic separation minima supported by ADS-C surveillance. Potential changes to international standards may include required update rates between 64 seconds and 5 minutes, aircraft route conformance monitoring revisions, and alert modifications. The FAA is researching “enhanced ADS-C” with a lower update interval (3.2 minutes) to support reduced separation minima. Figure 8, excerpted from [22], contains enhanced ADS-C characteristics.

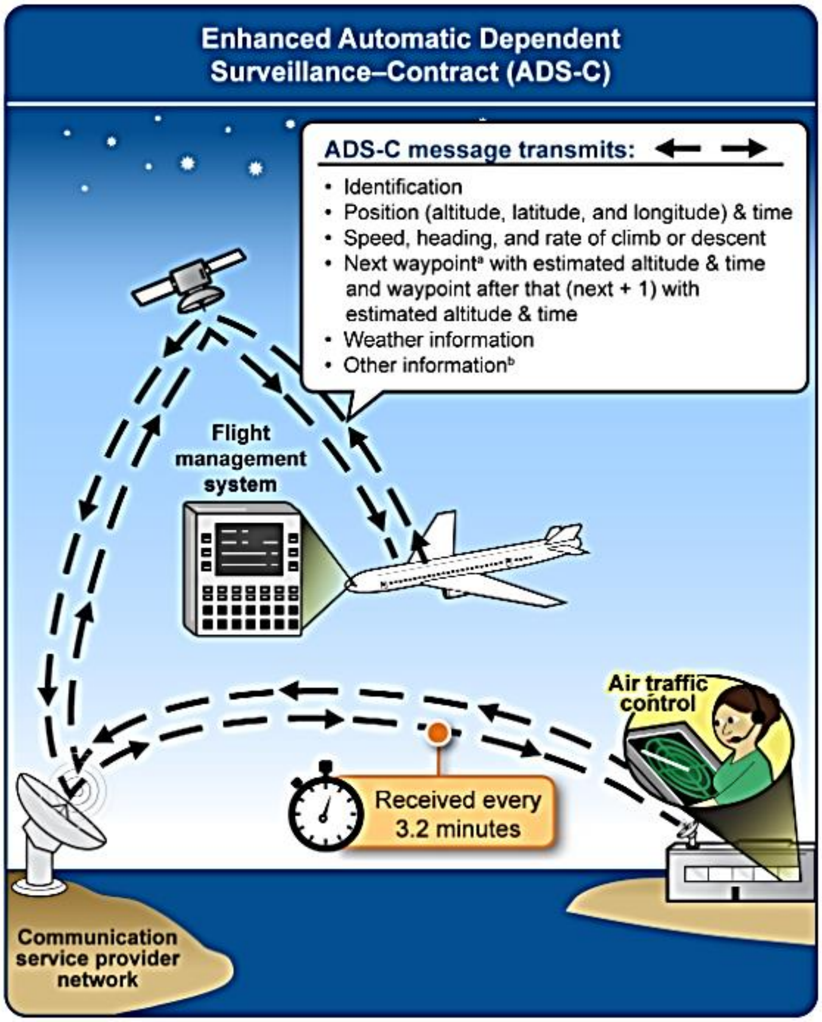

Figure 8: Enhanced ADS-C

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 with many existing systems.

ADS-C end-to-end latency averages 4.5 seconds with the newer Inmarsat SB-S broadband constellation [20]. However, it should be noted that standards allow for up to 180 seconds of latency for surveillance data. This is significantly greater than observed 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.

Similar to other surveillance systems analyzed in this assessment, ADS-C relies on pressure altitude reporting. Many barometric altimeters may not be capable of populating the ADS-C pressure altitude field with accurate or useful information above FL600. Additionally, fees are typically charged for the transmission of each ADS-C message, with costs typically incurred by airlines. ADS-C does not provide enhanced situational awareness to flight crews. It is primarily used by ANSPs for monitoring procedural separation.

3.2.2.3 Current ADS-C Support for ETM

ADS-C surveillance of commercial vehicles above FL600 is likely extremely limited as most current operations that employ the technology are typically air transport flights operating below 60,000 ft. ETM SST stakeholders have indicated a preference for ADS-C as the surveillance source for oceanic supersonic flights.

Commercial SATCOM services supporting ADS-C are subject to doppler shift issues, which could pose challenges for some farther term high-speed operations. The maximum speed for an aircraft using Iridium SATCOM is 800 kts [23], which equates to roughly Mach 1.4 at FL600. With Inmarsat SATCOM, the maximum speed is one that would create a +2.5 kilohertz (kHz) doppler shift or a + 30 Hertz per second (Hz/s) rate of change in the doppler shift [23]. A 2.5 kHz doppler shift corresponds to a speed of roughly 950 kts (or Mach 1.66), in a direction towards a satellite, and depends on the exact L-band frequency. The maximum speed for Inmarsat SATCOM would likely be greater than Mach 1.66 due to typical angles between the direction of flight and satellites. With these characteristics, it is expected that ADS-C enabled by at least one SATCOM service would likely be capable of supporting initial SST deployments, with cruise speeds up to Mach 1.7. Appropriate pressure altimetry systems (e.g., similar to those employed in Concorde or HALE balloons) may be necessary to support accurate state reporting via ADS-C. ITAR restrictions on GNSS receivers would not apply below Mach 2.03 at FL600.

3.3 Additional Considerations

While still mostly in the concept phase (e.g., engine design and testing), hypersonic commercial vehicles may ultimately operate in the ETM environment (e.g., cruising at FL900). At speeds above Mach 5, it is possible for electrically charged gas (plasma) to develop around vehicles. Plasma is capable of blocking Radio Frequency (RF) signals and is responsible for communication blackouts that have historically occurred in most space operations (e.g., during re-entry). Potential disruptions to many existing CNS capabilities should be a key consideration in development of commercial hypersonic vehicles. There is anecdotal evidence that international programs are focusing on specialized antennas with wire patterns capable of reliably transmitting and receiving data in the 5.2 to 5.8 gigahertz (GHz) frequency range at hypersonic speeds.

4 Conclusions

Operations above 60,000 ft are expected to increase in the future. Multiple vehicles are anticipated to be active in this airspace, including but not limited to UFBs, HALE vehicles (fixed-wing, balloons, and airships), reintroduced SSTs, 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 examined: radar, WAM, ADS-B, and ADS-C. Each technology was characterized in terms of general advantages, disadvantages, and current level of support for ETM. Limitations of peripheral systems (e.g., pressure altimeters and GNSS receivers) that impact some of these surveillance sources were also discussed.

Some radar installations are capable of surveilling multiple vehicles expected in upper Class E airspace, including UFBs, HALE balloons, and supersonic aircraft. However, SSR is dependent on accurate measurements from pressure altimeters, many of which may not be useful above 60,000 ft. Industry development of high-altitude barometric altimeters could potentially support SSR surveillance of traffic above FL600 (e.g., to FL700). However, many automation systems with inputs from SSRs have software settings that limit coverage ceilings.

Vehicles participating in ETM could potentially be surveilled by WAM in appropriate coverage regions. However, this would only be available for Phase 2 systems and would likely be limited to operations in transit to or from upper Class E airspace, or those within flexible floor volumes extending in upper Class A airspace. Software settings limit the Phase 2 WAM coverage ceiling to FL600.

Version 2 1090ES ADS-B may be an adequate surveillance source for many ETM participants, both in continental and oceanic airspace, via the SBS system and SBA, respectively. However, as with radar, more accurate pressure altimeters may be necessary to support this. Additionally, Version 2 ADS-B would likely be limited to vehicles traveling below Mach 2.03 due to both encoding limitations and ITAR restrictions on GNSS receivers that populate position and velocity data. Version 3 ADS-B messages could potentially support operations up to a geometric altitude of roughly 1,000,000 ft AGL, however ITAR speed restrictions would still apply.

Lastly, ADS-C could also be used for surveillance of ETM participants. Similarly, accurate pressure altitude reporting would be needed and ITAR speed restrictions for GNSS receivers would apply. Initial SST deployments, operating up to Mach 1.7, are expected to be able to use at least one SATCOM service supporting ADS-C. However, some SATCOM services and faster aircraft could experience issues with doppler shift.

Appendix A References

[1] Federal Aviation Administration, 2020, Upper Class E Traffic Management (ETM) Concept of Operations, Version 1.0, Washington, D.C., U.S. Department of Transportation.

[2] Crane, L., 2005, The Right Radar Backup for ADS-B, Proceedings of the 2005 Integrated Communications Navigation and Surveillance (ICNS) Conference, Fairfax, VA, IEEE/AIAA.

[3] International Civil Aviation Organization, 2007, Guidance Material on Comparison of Surveillance Technologies (GMST), Bangkok, Thailand, ICAO Asia and Pacific Office.

[4] Federal Aviation Administration, 2016, Advisory Circular 90-101A: Approval Guidance for Required Navigation Performance (RNP) Procedures with Authorization Required (AR), Washington, D.C., U.S. Department of Transportation.

[5] Federal Aviation Administration, 2019, Advisory Circular 91-85B: Authorization of Aircraft and Operators for Flight in Reduced Vertical Separation Minimum (RVSM) Airspace, Washington, D.C., U.S. Department of Transportation.

[6] Federal Aviation Administration, 2010, Automatic Dependent Surveillance-Broadcast (ADS-B) Out Performance Requirements To Support Air Traffic Control (ATC) Service; Final Rule, Federal Register, Volume 75, Number 103, Washington, D.C., pp. 30160 – 30195.

[7] SAE Committee A-4, 1981, Air Data Computer Minimum Performance Standards, AS 8002, Warrendale, PA, Society of Automotive Engineers.

[8] Hunter, S., 2015, Safe Operations Above FL600, Space Traffic Management Conference, Daytona Beach, FL, Embry-Riddle Aeronautical University.

[9] RTCA Special Committee 186, 2014, Minimum Operational Performance Standards (MOPS) for Aircraft Surveillance Applications (ASA) System, DO-317B, Washington, D.C., RTCA Inc.

[10] Federal Aviation Administration, 2017, Order 7110.65X: Air Traffic Control, Washington, D.C., U.S. Department of Transportation.

[11] International Civil Aviation Organization, 2007, Annex 10: Standards and Recommended Practices for Aeronautical Telecommunications; Volume 4, Surveillance and Collision Avoidance Systems, Fourth Edition, Montreal, Canada, ICAO.

[12] Federal Aviation Administration, 2016, Surveillance and Broadcast Services Program Wide Area Multilateration (WAM) Critical Service Specification, FAA-E-3024, Revision A, Washington, D.C., U.S. Department of Transportation.

[13] RTCA Special Committee 186, 2009, Minimum Operational Performance Standards for 1090 MHz Extended Squitter Automatic Dependent Surveillance-Broadcast (ADS-B) and Traffic Information Service-Broadcast (TIS-B), DO-260B, Washington, D.C., RTCA Inc.

[14] RTCA Special Committee 186, 2009, Minimum Operational Performance Standards for Universal Access Transceiver (UAT) Automatic Dependent Surveillance-Broadcast (ADS-B), DO-282B, Washington, D.C., RTCA Inc.

[15] Bauer, F., 2015, GNSS Space Service Volume and Space User Data Update, 15th Meeting of the GNSS Provider's Forum, Boulder, CO, NASA.

[16] Arteaga, R. et al., 2019, Enhanced ADS-B Flight Tests on F-18 Supersonic Aircraft, Proceedings of the 2019 Science and Technology Forum and Exposition (SciTech), San Diego, CA, AIAA.

[17] Stansbury, R. et al., 2013, Initial Flight Tests of UAT ADS-B Unit for Suborbital Reusable Launch Vehicles, Proceedings of the 2013 Integrated Communications Navigation and Surveillance (ICNS) Conference, Herndon, VA, IEEE/AIAA.

[18] Francis, R. et al., 2011, The Flying Laboratory for the Observation of ADS-B Signals, International Journal of Navigation and Observation, Volume 2011, Article 973656, London, U.K., Hindawi Limited.

[19] Federal Aviation Administration, 2016, Advisory Circular 91-70B: Oceanic and Remote Continental Airspace Operations, Washington, D.C., U.S. Department of Transportation.

[20] Lane, T., 2018, An Analysis of ADS-C Surveillance Services and Implications for Separation Standards and Other Efficiency Improvements, Alexandria, VA, Air Traffic Control Association.

[21] RTCA Special Committee 170, 1992, Minimum Operational Performance Standards for Airborne Automatic Dependent Surveillance (ADS) Equipment, DO-212, Washington, D.C., RTCA Inc.

[22] Government Accountability Office, 2019, Air Traffic Control: FAA's Analysis of Costs and Benefits Drove Its Plans to Improve Surveillance in U.S. Oceanic Airspace, GAO-19-53, Washington, D.C., U.S. GAO.

[23] RTCA Special Committee 222, 2017, Minimum Operational Performance Standards for Avionics Supporting Next Generation Satellite Systems (NGSS), DO-262C, Washington, D.C., RTCA Inc.

Appendix B Acronyms

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

Table 1: Acronyms

Acronym	Definition
1090ES	1090 MHz Extended Squitter
2D	Two-Dimensional
3D	Three-Dimensional
ACARS	Aircraft Communications Addressing and Reporting System
ADC	Air Data Computer
ADS-B	Automatic Dependent Surveillance – Broadcast
ADS-C	Automatic Dependent Surveillance – Contract
ADS-R	Automatic Dependent Surveillance – Rebroadcast
AGL	Above Ground Level
AIRB	Basic Airborne Situation Awareness
ANSP	Air Navigation Service Provider
ARSR	Air Route Surveillance Radar
ARTCC	Air Route Traffic Control Center
ASA	Aircraft Surveillance Application
ASAT	Anti-Satellite
ASDE-X	Airport Surface Detection Equipment Model X
ASE	Altimetry System Error
ASSAP	Airborne Surveillance and Separation Assurance Processor
ASSC	Airport Surface Surveillance Capability
ATAS	ADS-B Traffic Advisory System
ATC	Air Traffic Control
ATM	Air Traffic Management
ATOP	Advanced Technologies and Operating Procedures
CA	Cooperative Area
CDM	Collaborative Decision Making
CDTI	Cockpit Display of Traffic Information
CFR	Code of Federal Regulations
CNS	Communication, Navigation, and Surveillance
CONUS	Contiguous United States

Acronym	Definition
CPDLC	Controller Pilot Data Link Communications
CPR	Compact Position Reporting
CSC	Combined Surveillance Committee
deg	Degree
ERAM	En Route Automation Modernization
ETM	Upper Class E Traffic Management
FAA	Federal Aviation Administration
FL	Flight Level
FOM	Figure of Merit
fpm	Feet Per Minute
ft	Feet
GA	General Aviation
GBAS	Ground Based Augmentation System
GDOP	Geometric Dilution of Precision
GES	Ground Earth Stations
GHz	Gigahertz
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HALE	High Altitude Long Endurance
Hz/s	Hertz per Second
ICAO	International Civil Aviation Organization
IRU	Inertial Reference Unit
ISA	Standard International Atmosphere
ITAR	International Traffic in Arms
ITP	In-Trail Procedure
kHz	Kilohertz
kt	Knots
MHz	Megahertz
MSSR	Monopulse Secondary Surveillance Radar
MST	Multi-Sensor Tracker
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NAT-OTS	North Atlantic Organized Track System

Acronym	Definition
NM	Nautical Mile
PSR	Primary Surveillance Radar
RF	Radio Frequency
RMCC	Royal Military College of Canada
RMS	Root-Mean-Square
RVSM	Reduced Vertical Separation Minimum
SASP	Separation and Airspace Safety Panel
SATCOM	Satellite Communication
SBA	Space-Based ADS-B
SBS	Surveillance and Broadcast Services
SSR	Secondary Surveillance Radar
SST	Supersonic Transport
STARS	Standard Terminal Automation Replacement System
TCAS	Traffic Alert and Collision Avoidance System
TDOA	Time Difference of Arrival
TFM	Traffic Flow Management
TFMS	Traffic Flow Management System
TIS-B	Traffic Information Service – Broadcast
TRACON	Terminal Radar Approach Control
TSAA	Traffic Situation Awareness with Alerts
TSV	Terrestrial Service Volume
UAS	Uncrewed Aircraft Systems
UAT	Universal Access Transceiver
UFB	Uncrewed Free Balloon
UTM	UAS Traffic Management
U.S.	United States
VHF	Very High Frequency
WAAS	Wide Area Augmentation System
WAM	Wide Area Multilateration
WGS-84	World Geodetic System 1984