



Space-Based ADS-B: Performance, Architecture and Market Options

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1.0 Executive Summary

In the last several years, Automatic Dependent Surveillance – Broadcast (ADS-B), has achieved significant traction with Air Navigation Service Providers (ANSPs) and the worldwide aviation community. Compared to ground-based radar, ADS-B offers greater accuracy and consistency, lower costs, and shared situational awareness. Implementation of the FAA’s rule requiring aircraft to have operational ADS-B Out transmitter equipment by January 1, 2020 is now in the rearview mirror. Many other ANSP’s have or are implementing a similar requirement.

However, “traditional” ADS-B lacked coverage over oceans and remote areas. The satellite industry responded to this capability gap and market need with a range of services that augment or replace ground-based ADS-B. This paper provides a market assessment of space-based Air Traffic Service (ATS) surveillance and aircraft tracking systems.

1.1 Paper Framework

This paper: provides a review of current, emerging, and potential space-based ADS-B systems; discusses how satellite-based service offerings provide ATS; and provides a guide to assist ANSPs in assessing competing systems across a range of performance parameters.

There are three ATS application areas:

1. **Tracking and Surveillance** - ADS-B – Focus of this paper.
2. **Communications** - CPDLC and ADS-C for communications between air traffic controllers and the aircraft. This paper touches on communications as it relates to ADS-B systems.

Several new entrants seek to offer Airband VHF and UHF communications from satellites to augment ground-based networks along with space-based ADS-B. These potential offerings are briefly discussed.

3. **Navigation** - Equipage within the aircraft such as Global Navigation Satellite System (GNSS), Satellite-based Augmentation System (SBAS) and inertial systems. This application is not discussed in this paper.

In many cases, market options are not mutually exclusive. Rather, a range of complementary solution sets exist. Most importantly, integrating a range of solutions into the overall systems architecture can enhance performance and resilience.

Figure 1-1 illustrates space-based ADS-B system elements and **Figure 1-1** also illustrates this paper’s content per section.

- Ultimately, various **Actors and Stakeholders** must be satisfied and cooperative to ensure operation of the system.
- To perform an ADS-B tracking and or ADS-B surveillance function, various key **Service Objectives** must be met.
- Comprehensive, internationally accepted, **Performance Requirements** must be established.
- The **Infrastructure Equipment** must meet ANSP performance requirements.

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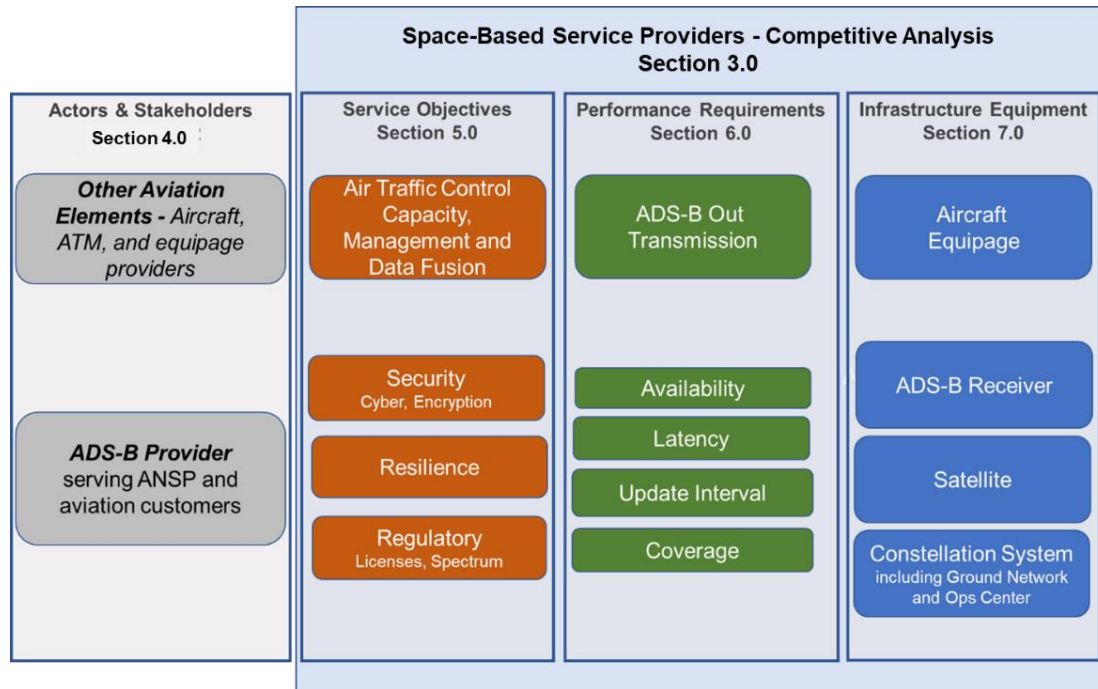


Figure 1-1 Space-based ADS-B system elements and corresponding sections in this paper.

1.2 Space-Based Surveillance Performance Requirements Same as Ground-Based Heritage Systems

These requirements set a high bar for space systems. Four key requirements are:

- **Availability** – 99.9% - Meeting the overall 99.9% Availability requirement translates into having approximately 99.95% Availability for data transport from space to ground and 99.95% receiver/satellite bus Availability. Meeting these two targets requires a substantial, robust space network with redundant elements.
- **Latency** – Less than 1.5 seconds - Providing latency of less than 2 seconds over remote regions rules out the potential of “storing forward” data and downloading when over a ground station.
- **Probability of Update (PoU)** – Less than 8 seconds at 96% confidence - Meeting this requirement is difficult over high-traffic regions, not only because of increased numbers of aircraft but also because of ground-based 1090 MHz interference (coming primarily from ground-based radars). Multiple overlapping signals must be processed simultaneously to meet this requirement. This requires overlapping satellite coverage, multiple beams on each receiver, on-orbit processing, large bandwidth and significant receiver power and thermal control.
- **Regulatory** – ATS surveillance requires that ALL spectrum used in a system be protected for “safety of life” by the International Telecommunications Union (ITU). Getting ITU approval is challenging and can literally take a decade or more. This is a significant barrier to entry for surveillance systems. Approval is not required for tracking.

These requirements drive the space-based surveillance solution to be a Low Earth Orbit (LEO) constellation with Inter Satellite Linked (ISL) satellites. LEO constellations with “bent-pipe” communication to ground stations cannot provide surveillance performance over remote areas where it is impractical to place ground stations. Geostationary (GEO)/Medium Earth Orbit (MEO) with bent-pipe communication to gateways are possible but ADS-B receiver design

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becomes complicated at high altitude requiring an expensive dedicated mission with multiple satellites.

A key conclusion is that “CubeSat” satellite constellations cannot meet ADS-B surveillance requirements. Specifically, Availability and PoU surveillance requirements cannot be met with a CubeSat system. Also, latency of less than 1.5 seconds over remote regions is not possible. CubeSat systems can provide aircraft tracking data where the target update rate is every 15 minutes.

Another key conclusion, is that satellite constellations, using small satellites, cannot provide dual ADS-B surveillance and VHF-UHF two-way communications. It is possible to have a satellite constellation that performs these two functions but it requires satellites with significant mass and power. The currently proposed dual-mission concepts, discussed in this paper, are simply not credible.

1.3 Space-Based ADS-B Market Entrants

In moving towards interoperability, a global, space-based ATS has an advantage over traditional ground-based systems because it avoids much of the ground-based infrastructure. This is especially important in remote regions.

In oceanic areas, beyond the reach of ground-based ATS Surveillance, space-based systems are enhancing safety, improving efficiency, and allowing for greater flight predictability and air traffic flow management. In locations where ground-based ATS surveillance is currently available, space-based ATS fills in the gaps, provides a contingency layer and enables a rationalization of ground ATS surveillance.

Space-based ATS surveillance systems must demonstrate the same high performance as ground-based systems. Space-based ATS surveillance systems require regulatory safety-of-life spectrum protection. Space-based ATS surveillance systems must also pass the same regulatory safety audits as ground-based systems.

Space-based aircraft tracking systems must meet a lower performance requirement bar than ATS Surveillance systems as discussed in Section 2.0. The aircraft tracking market will continue to evolve. Innovative companies such as Spire continue to produce valuable products combining ADS-B tracking data with other data sets. Aircraft tracking stakeholders should watch the market closely as existing Aircraft tracking providers, Inmarsat and Iridium will likely enhance their current service offerings. Also, Aireon is now focused on offering Aircraft tracking data in addition to their current higher-grade ATS surveillance data.

This paper compares the strengths and weaknesses of potential space-based ATS systems and provides a realistic assessment of existing players and market options based upon compatibility with existing aircraft equipment, coverage, ground station networks, performance, and costs. The technical differences between these offerings are discussed in Section 3.0 and summarized here.

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Company	Status	Service Level	Coverage	Equipage	Position Validation	EASA Certification	Safety-of-life Protected Spectrum
Automatic Dependent Surveillance – Broadcast (ADS-B) Systems							
Aireon (McLean, VA)	Operational	ATS Surveillance or Tracking	Global	Uses Existing	Validation Independent of GPS	ADS-B Surveillance Certified	All system frequencies approved for safety-of-life
Globalstar (Covington, LA)	Delayed, No progress	Tracking	Regional - No polar coverage	Need ALAS transceiver	None	None	None
Spire (California)	Operational ADSB MLAT Early Development	Limited Tracking and Weather Data Fusion	Regional focus equator +/- 15°	Uses Existing	None	None	None
GOMspace and Aerial & Maritime (Denmark)	Defunct, Assets Liquidated	Tracking	Demo in arctic region	Uncertain	None	None	None
Dual-Mission Automatic Dependent Surveillance – Broadcast (ADS-B) and VHF-UHF Two-Way Radio Communications							
Skykraft (Australia)	Prototype-Concept satellites on-orbit	Goal - Tracking and ATS Communications	Regional	Uses Existing	None	None	None, ADS-B, UHF and VHF must be approved for space-based “safety of life”
Starticle (Madrid, Spain)	Concept Phase	Goal - Surveillance and ATS Communications	Global	Uses Existing	None	None	None, ADS-B and VHF must be established for use in space. ISL frequencies must be approved.
HEAD Aerospace (China)	Concept Phase	Goal - Surveillance and Data Communications	Regional	Uses Existing	None	None	None
Communication Systems Adapted for Aircraft Tracking							
Inmarsat (London, UK)	Operational	Tracking and ATS Communications	Global except poles. Planned polar augmentation	Installed on many commercial aircraft	None	None	All system frequencies approved for safety-of-life
Iridium (McLean, VA)	Operational	Tracking and ATS Communications	Global		None	None	All system frequencies approved for safety-of-life

Table 1-1 Space-based Aircraft tracking and ATS surveillance market entrant comparison.

Space-based ADS-B Surveillance – Surveillance level performance is 48 times more difficult than tracking, see Section 2.0. Currently there is only one company that can meet the ground-based derived surveillance requirements with a space system.

- **Aireon** – Aireon leverages the Iridium NEXT constellation capabilities by operating as a hosted payload. Iridium NEXT is the only constellation that has Inter Satellite Link (ISL) capability. Iridium provides Aireon with multiple space routing path options coupled with multiple terrestrial paths. This provides highly redundant, resilient data transport paths that meets ATS surveillance requirements.

Aireon currently maintains “first mover” advantage for space-based ATS surveillance using ADS-B. There are no equivalent service offerings with protected “safety of life” spectrum, global coverage, operational satellites, and ground systems. There are no other ATS surveillance entrants. Aireon enjoys barriers to entry:

- A comparable system will take several years to build and deploy.
- Regulatory approval must be obtained.
- A space-based ADS-B system capable of surveillance will require substantial investment.
- As of October 2023, Aireon has over 60% of the World’s oceanic traffic market. After several more years Aireon will likely gain even greater market share. There will be little opportunity left for new entrants to justify a large investment.

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Recently, Aireon has focused on leveraging their ADS-B data set. Because Aireon is the only company that can provide space-based ADS-B surveillance, they have the best ADS-B data set. Aireon's comprehensive ADS-B data set literally holds second-by-second ADS-B data for every ADS-B equipped aircraft in the world. This provides an advantage over ADS-B tracking-only competitors.

Dual VHF-UHF and ADS-B Surveillance – Skykraft, Starticle and HEAD are proposing systems that provide both space-based ADS-B as well as VHF-UHF aircraft communications. These entrants are not credible for several reasons:

- ADS-B systems can leverage overlapping coverage to receive the same ADS-B transmission on several satellites as discussed in Section 3.1. Having the chance to receive the same signal over several redundant paths provides high availability and confidence levels. However, this multiple signal architecture scheme cannot be used on VHF-UHF systems for communications. A single transmission must be carried on a single satellite. The transmission can be “handed-off” to other satellites but care must be taken not to drop the connection. This would operate similarly to the multi-billion-dollar Iridium L-band communications system as described in Section 6.
- Interference between an ADS-B receiver and the UHF and VHF transceivers is a major issue. The smaller the satellite, the more difficult it will be to circumvent this issue. Transmitting and receiving at the same time may not be possible limiting performance. Operational workarounds may be required.
- Providing VHF-UHF communications, especially voice, in remote regions may require a constellation with Inter Satellite Links (ISLs). Iridium is the only company to have implemented ISLs although several other companies are planning to do so. An ISL capable satellite constellation is expensive and difficult to implement.
- Regulatory requirements are strict with respect to ATS services. ALL spectrum must be primary or protected allocation for safety services. This includes satellite links to ground and it also includes ISLs. The regulatory environment is competitive and the process is difficult and timely to navigate.
- CubeSat / small satellite constellations are not capable of providing ADS-B surveillance as their singular primary mission, see Section 2.1. Obviously, there is no way these systems could support a dual mission.

A dual mission with both VHF-UHF communications as well as ADS-B surveillance is possible but would require per satellite power levels of around 2000 Watts, an ISL constellation and multiple regulatory approvals. A system with these capabilities would cost billions and take several years to deploy. This dual-mission cannot be achieved using “CubeSats” or small satellites.

Space-Based Aircraft Tracking - Space-based aircraft tracking systems must meet a lower performance requirement bar than ATS Surveillance systems as discussed in Section 2.0. The aircraft tracking market will continue to evolve. Innovative companies such as Spire continue to produce products combining ADS-B tracking data with other data sets. Aircraft tracking stakeholders should watch the market closely as existing Aircraft tracking providers, Inmarsat and Iridium will likely enhance their current service offerings. Also, Aireon offers Aircraft tracking data that leverages their current higher-grade ATS surveillance data set.

- **Globalstar** – Operates a constellation of bent-pipe LEO satellites. Globalstar can only provide service to regions where a given satellite can be simultaneously connected to

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both a user and a ground station. This has prevented Globalstar from serving some remote regions and oceans. For communications services, a system built with this type of architecture may be advantageous. However, where key air traffic routes cross remote regions and oceans, the Globalstar's bent-pipe LEO constellation architecture presents a significant disadvantage.

Globalstar's ADS-B offering has not yet been fully deployed. The Globalstar ADS-B system also requires additional aircraft equipage. This is a disadvantage relative to competitors that can operate without additional equipage. No progress has been made over several years based on limited publicly available information.

- **Spire** - Spire creates product offerings by fusing unique data sources. The company has demonstrated the value and capability of CubeSats. Spire designs, builds, tests, and operates all its satellites. As of mid-2023, Spire has over 110 active satellites in LEO orbit. About half, of these satellites have ADS-B payloads. Around 30 ground stations are active.

July 2023, the European Space Agency (ESA) awarded Spire a €16 million phased contract for the EURIALO project. ESA's focus is to develop an additional air traffic surveillance system that is complimentary and independent of GPS-based systems. Note, the ADS-B signal contains aircraft position data derived from the GPS system. Spire will lead a team to develop the preliminary design and demonstrator for a global space-based independent aircraft surveillance system.

Spire's current focus is to provide a global ADS-B tracking service with 15-minute update capability. The Spire system will not be capable of providing ADS-B surveillance due to:

- Spire's bent-pipe architecture makes coverage in remote areas difficult and requires a significant ground segment infrastructure.
 - The Spire satellite ADS-B receiver lacks capability such as dynamic multi-beams and on-board processing. Also, bandwidth, getting data to the ground, is limited. This limits performance in higher traffic Flight Information Regions (FIRs).
 - Formation flying is not possible because CubeSats lack or have limited propulsion system capability. This further increases the number of satellites required.
- **GOMspace and subsidiary Aerial and Maritime (AM)** – AM had plans for a CubeSat ADS-B LEO constellation similar to Spire. GomSpace said June 16, 2020 that AM will be liquidated, and that GomSpace will retain ownership of eight satellites.¹ GomSpace will attempt to sell the eight CubeSats, or find another purpose for them.

Space-based Communications Systems Adapted for Aircraft Tracking - Inmarsat and Iridium are satellite telecommunications companies that have adapted communications technologies to support ATS communications as well as aircraft tracking. These systems cannot provide ATS surveillance. The offerings are complimentary to Aireon. Now that Aireon global aircraft ADS-B surveillance is available, the need for ATM communications in remote regions is more important and will increase.

Conclusion – Aireon enjoys first mover advantage.

- Aireon will continue to gain surveillance market share with ANSPs that cover remote regions as they have no competition.

¹ GomSpace shuts down constellation spinoff, SpaceNews, Caleb Henry, June 19, 2020.

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- Aireon will also gain ANSP customers where interoperability with neighboring ANSPs is important.
- Also, the space-based service is less expensive than building ground-based traditional infrastructure for some ANSPs.
- Aireon has the best quality ADS-B data set that covers all the world's ADS-B equipped aircraft. Aireon is focused on leveraging this data set for various commercial purposes.
- As of early 2020 Aireon has over 60% of the World's oceanic traffic market. After several more years Aireon will likely gain even greater market share. There will be little opportunity left for new entrants to justify a large investment.

Aireon enjoys barriers to entry as discussed in Section 1.3.

While new entrants might introduce competition, it is equally plausible that market participants find an appropriate level of cooperation. The right balance could increase overall market size and allow each participant to thrive. Cooperation could be further encouraged by interoperability and a “systems of systems” approach – leveraging multi-source and multi-path systems. The goal is a system of systems seamless global air traffic service, which includes several space-based sources and paths. This will increase safety, efficiency and predictability over both congested areas and provide a global ATS capable of serving remote regions and a larger number of stakeholders.

1.4 Current Value Proposition – Remote Areas

The space-based ADS-B value proposition is well acknowledged as a primary means to cover remote areas beyond the reach of traditional ADS-B which relies on ground stations. Space-based solutions offer an opportunity to overcome existing ground-based impediments with seamless, harmonized, and interoperable ATS surveillance and Aircraft tracking.

Space-based ADS-B is quickly becoming the primary means for monitoring aircraft over remote regions. The International Civil Aviation Organization, or ICAO laid out a comprehensive plan to implement the Aireon service over the North Atlantic Track (NAT).² The plan's implementation is complete and aircraft traversing across the NAT are now doing so using Aireon's service.

In high-traffic density areas, such as JFK or Frankfurt, receiving and processing ADS-B signals becomes much more challenging.

- The ADS-B 1090 MHz frequency is shared with existing ground-based air traffic radars. Also, the airborne Traffic Collision Avoidance System (TCAS) uses 1090 MHz as well.
- Ground radar interrogations create interference. This further complicates space-based system operations within the crowded 1090 MHz frequency.
- For space-based systems to operate in high-traffic areas, ground-based radar systems must adhere to regulations that limit their use.
- Space-based receiver tuning and error correction processing have been proven to be valuable.
- Overlapping receiver beams have been shown to improve performance. This allows for multiple opportunities to receive the same data.

Space-based ADS-B services over high-traffic regions are possible but requires a coordinated effort between ground and space-based service operators.

² Implementation Plan and Task List for an Operational Trial of Advanced Surveillance-Enhanced Procedural Separation (ASEPS) using ADS-B, International Civil Aviation Organization, As approved by NAT SPG/55, June 2019.

2.0 ADS-B Surveillance versus Aircraft Tracking

There is a significant difference between aircraft “tracking” level of service and ATS “surveillance” level of service.³ ATS surveillance systems must perform an order of magnitude better than aircraft tracking systems.

- The primary purpose of an air traffic control system is to prevent collisions between aircraft and to provide a safe, orderly, and expeditious flow of traffic.
- Closing speeds between opposite direction jet aircraft often exceed 1,000 mph.
- ATS surveillance technologies, as defined by Procedures for Navigation Services – Air Traffic Management (PANS ATM) Doc 4444,⁴ must provide near-instantaneous position information to ensure the safe separation of aircraft.
- The performance of ATS surveillance systems is strictly defined and regulated through organizations such as the European Organization for Civil Aviation Equipment (EUROCAE). Also, ATS surveillance system requirements have recently been updated to the Eurocontrol Generic Surveillance (GEN-SUR) Safety Performance Requirements.

Latency and PoU requirements for non-air traffic control Aircraft tracking systems are much less stringent. There is a Global Aeronautical Distress and Safety System (GADSS) requirement for airlines to track assets once every 15 minutes.⁵ Other upcoming requirements call for airlines to track assets once every 1 minute.

This paper compares the relative significance of requirements between Aircraft tracking versus ATS surveillance systems. The Probability of Detection (P_d) is defined as the percentage ratio between the actual number of position messages received over the expected number of position messages transmitted.⁶ The theoretical minimum aggregate average P_d can be computed as follows:

$$(1 - P_{UI}) = (1 - P_d)^{(T_{UI} * f_{position_tx})}$$

Where:

P_d = Probability of Detection is found

P_{UI} = Required P_d of the position message within the UI timeframe

T_{UI} = UI timeframe

$f_{position_tx}$ = Rate of ADS-B position information transmitted from the aircraft = 2 pulses per second or 2Hz

ADS-B aircraft transmitters produce two ADS-B position messages in each second. There will be 1,800 ADS-B position messages produced per aircraft in 15 minutes. Only one of those messages must be received by a satellite and then successfully relayed to an ANSP to meet the aircraft-tracking requirement. However, for ATS surveillance, 16 aircraft signals will be produced per aircraft over 8 seconds making the detection problem much harder.

Table 2-1 contrasts Probability of Update (PoU) requirements for aircraft tracking against ATS surveillance systems. Aircraft ATS surveillance systems must perform 48 times better than a 15-minute Aircraft tracking system.

³ Craig Foster et al; “Aircraft Surveillance Versus Tracking: A Comprehensive Analysis of the Differences Between Surveillance and Tracking Aircraft;” Valour Consultancy; March 2016.

⁴ Procedures for Air Navigation Services Air Traffic Management, Doc 4444, International Civil Aviation Organization, November 3, 2022.

⁵ Manual on Location of Aircraft in Distress and Flight Recorder Data Recovery, Doc 10054, First Edition, International Civil Aviation Organization, 2018.

⁶ SALSA project ADS-B User Requirements Deliverable D1.2 v 01.01.00 28 November 2016.

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ADS-B Type	Probability of Update Requirement Period	Confidence Requirement	ADS-B Messages per Aircraft over UI	Required Probability of Detection	Times 15-min ADS-B Tracking System Required Performance Increase
Tracking 15	15 minutes	100 %	1,800	0.383%	1
Tracking 5	5 minutes	100 %	600	1.15%	3 X
Tracking 1	1 minute	100 %	120	5.59%	15 X
Surveillance	<8 seconds	96 %	16	18.2%	48 X

Table 2-1 ADS-B tracking versus ATS surveillance system performance requirement comparison.

2.1 CubeSats Cannot Support ATS Surveillance

Companies such as Spire have demonstrated that CubeSats can punch above their weight. Spire uses CubeSats to provide weather and maritime services. Spire also has fused ADS-B data with weather and maritime data to provide valuable products. However, aviation ATS safety-of-life services such as ADS-B surveillance require performance at levels far above what CubeSats can provide.

We have no doubt that uses for CubeSats will continue to expand and that CubeSat technology will continue to advance. Also, innovative ways to use CubeSat data will continue to be developed. But these advances are not fundamental to aviation ATS safety-of-life services.

- RF signals still require power and antennas to be transmitted and received at high Availability.
- Ground station sites can be practically placed in some regions. Surveillance quality service is possible in these regions where traffic and terrestrial ground radars are limited. However, space-based reception of convoluted ADS-B signals from high-traffic airspace requires dynamic antenna beams and powerful processing to meet surveillance requirements. These factors limit the usefulness of bent-pipe CubeSat systems.
- Transporting the data from the satellite to the air traffic controller at high Availability requires a substantial system.

Larger, more capable satellites are required for safety-of-life ATS. CubeSat entrants will be constrained. The CubeSat bus and payload will limit capabilities to aircraft tracking services.

2.1.1 CubeSats Fall Short on Availability

Four elements comprise the ATS surveillance system Availability calculation, Figure 2-1. The calculation assumes all four elements are in series. ICAO requires ATS surveillance systems maintain an Availability greater than 99.9 % (or 0.999).

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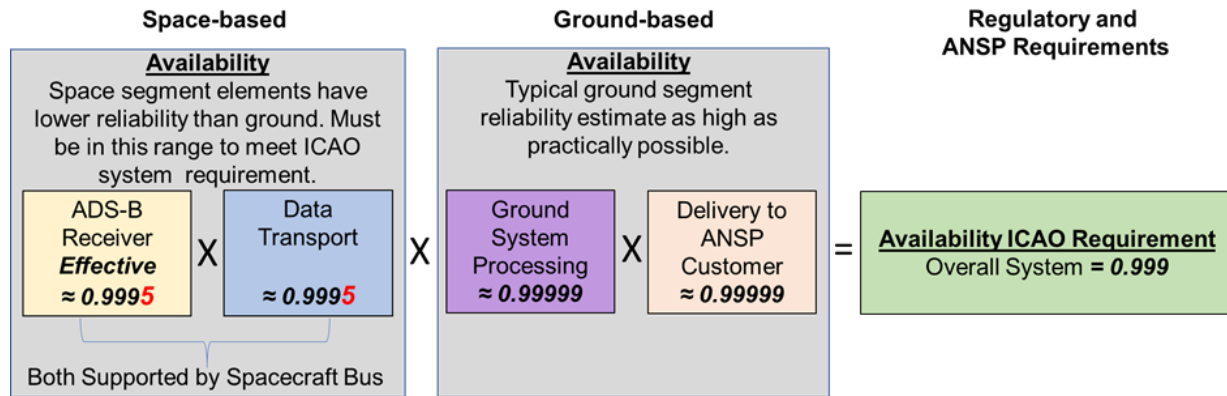


Figure 2-1 ATS surveillance space-based ADS-B system Availability requirements.

When we assume typical Availability values for the ground segment, it allows us to bound the space segment Availability:

- The ADS-B Receiver must effectively be ≈ 99.95 Availability.
- The Data Transport element must also be ≈ 99.95 Availability.

If one of the space segment elements is slightly lower than 99.95 then the other must be higher to meet the target threshold value of 99.9%. If the Availability is significantly lower for either of the space segment elements, the system will not meet the ICAO 99.9% system Availability requirement.

2.1.2 Ground-based Availability

It is less costly and easier to build high-reliability ground systems versus space systems. Therefore, for the entire system to meet 99.9%, the ground-based elements must have a significantly high Availability. The above example assumes 0.99999 for the two ground-based elements shown in Figure 2-1. This value is reasonable for well-built space system ground segments that are fully redundant.

Bent-pipe CubeSats will require many expensive ground stations to have global coverage. To meet ATS surveillance requirements, ground station Availability must be around 0.99999. Meeting this high Availability requirement essentially requires that all ground segment elements be redundant. Also, security, disaster recovery, cyber security, data processing capacity, redundancy, operations and 24/7 control will be required. High-Availability stations may not be practical to build in remote areas.

CubeSat satellites with simple bent-pipe payloads must have a line-of-site view to a ground station to transfer data. Without a connection, data could be stored onboard the satellite until a later time when a ground site is in view. “Storing and forward” can reduce the number of ground stations needed and extend coverage, however, surveillance application requirements cannot be met with this approach.

2.1.3 Data Transport Availability

99.95% data transport Availability is a high bar for any space system. Data transport for a space-based system is the most difficult aspect for meeting Availability requirements. Data transport Availability is the Availability of the data delivery path from the space receiver to the ANSP customer. This includes:

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- The data transport Availability of the satellite constellation including Inter Satellite Links (ISLs) if used.
- The Availability of the satellite platform that supports the ADS-B receiver operations. This includes: power, local data connectivity, thermal control, etc.
- The transmission of data from space to ground must be performed with the highest reliability possible. Weather related outages can be prevented by employing diverse downlink paths.

CubeSat class satellites, Table 7-1, may be capable of receiving ADS-B signals in remote regions at ATS surveillance performance levels. However, transporting this data, ultimately to the ANSP customer, is problematic.

Some CubeSat constellation concepts seek to employ satellite ISLs. ISLs allow for signals to be routed between satellites in space. ISL constellations somewhat decouple ground segment requirements from coverage. This allows for remote region coverage without the need for remotely located ground stations. However, implementing space-based ISLs is difficult and expensive. To date, Iridium is the only operational ISL LEO constellation ever deployed.

For ATS surveillance ISLs must achieve a space-to-ground data transport Availability of about 0.9995, see Figure 2-1. This level of performance is a tall order and barely achieved by satellites hundreds of times larger and more capable than CubeSats. Achieving 0.9995 space-to-ground data transport Availability will require larger, more expensive satellites also.

2.1.4 Spacecraft Bus and ADS-B Receiver Availability

The satellite bus and receiver must support an effective Availability around 0.9995 as well. This is a high bar and leaves little room for challenges such as radiation induced electronics Single Event Upsets (SEUs). CubeSats with little radiation shielding and single string systems are vulnerable to SEUs.

2.1.5 CubeSats cannot achieve high-traffic airspace surveillance Probability of Update (PoU) requirements.

ADS-B space-based receiver beams can become saturated over high-traffic airspace as discussed in Section 1.4. Space-based ADS-B over high-traffic airspace is challenging due to:

- the limited number of on-orbit receiver beams and coverage overlap,
- data bandwidth throughput limitations and
- ground radar sites, operating at 1090 MHz, are concentrated in high-traffic regions creating significant ADS-B interference.

Specifically, for ADS-B, CubeSat receivers have at most a few receiving beams. While this may be adequate for ADS-B tracking level performance, it is not adequate for ATS surveillance. A single beam can easily become saturated under high-traffic situations, making it impossible to meet PoU surveillance requirements. For example, Aireon has found the need to employ 80 ADS-B listening beams per payload of which 20 are active at any time to meet PoU surveillance requirements. With 66 operational payloads, that is 1320 active receiver beams constellation wide. Hundreds to thousands of CubeSats would be required for equivalent coverage. While deploying a satellite mega-constellation is possible, it is impractical from a cost, complexity and ultimately competitiveness perspective. Also, sustaining such a system will be difficult and costly.

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CubeSats cannot adequately meet high-traffic airspace PoU surveillance requirements because they have a limited number of receiver beams, limited on-orbit processing capabilities and bandwidth data transport restrictions.

2.1.6 CubeSats lack power.

This is especially important for ATS aircraft-to-controller communications. This requires significant power to close a Radio Frequency (RF) link with high Availability.

Also, significant power, 10s of Watts, is required simply to receive ADS-B signals over high-traffic airspace. Power must be produced on the satellite. Also, with power comes the requirement to dump waste heat in space; with radiated heat transfer being the only means.

2.2 Resilience

Resilience is not specifically called out as a requirement for space-based ADS-B, yet it remains necessary. Space-based ATS surveillance systems will often be relied upon when ADS-B information is needed most – particularly during heavy air traffic periods when there is an increased chance of Radio Frequency (RF) interference. In addition to ensuring robust communication signals, space hardware presents unique challenges because it is not possible to fix once assets are in orbit. Parallel signal processing architecture, overlapping coverage, large on-orbit bandwidth and redundant ground elements ensure the system will be available during critical situations.

2.3 Regulatory

A key aspect for ATS surveillance service is that **ALL** spectrum used by the system must be protected from harmful interference. The International Telecommunications Union (ITU) Radio Regulations identify certain bands for the Aeronautical Mobile (Route) Service (AM(R)S) or Aeronautical Mobile-Satellite (Route) Service (AMS(R)S).

- These exclusive ATS bands are reserved for communications relating to safety and regularity of flight.
- The Radio Regulations define protection. Administrations widely enforced these protections to ensure safety of flight.
- To date, only Inmarsat and Iridium currently have ITU safety-of-life frequency protection. Aireon's hosted payload rides on the Iridium NEXT satellites and uses the same Iridium protected frequencies for data transport. Therefore, these are the only companies that are currently qualified to provide safety-of-life ATS services from an international regulatory perspective.
- In 2015 the ITU adopted a primary allocation allowing ADS-B 1090 MHz frequency band signals to be received by satellite from aircraft. The decision was made during the World Radiocommunication Conference (WRC-15) in Geneva, Switzerland. This opened the door, from a regulatory perspective, for ATS space-based ADS-B surveillance.
- Others may apply to use such frequencies, but the process is involved and takes time.

Regulators, such as EASA, audit all aspects of ATS surveillance including software. Also, each ANSP must also present the safety case to their respective country's Civil Aviation Authority. These audits are extensive. The audit must be successfully completed before an ATS surveillance system is authorized for use. Also, the ANSP must work with the ATS surveillance system provider to close the safety case to the regulator's satisfaction.

3.0 Space-based ATS Providers - Competitive Analysis

The satellite services industry is highly competitive despite significant barriers to entry. Obtaining regulatory spectrum licenses can take years. Successfully building and launching a satellite network with associated ground systems is costly and time consuming. Recently, many non-traditional companies have entered the space industry. These new players have proposed “mega-constellations” of hundreds and sometimes thousands of CubeSat Low Earth Orbit (LEO) satellites. These mega-constellations have shorter life expectancies and thus will require high sustainment costs. However, frequent technology insertion can accelerate technological advances which may yield additional capabilities – including ADS-B related services and perhaps a surprising future competitive advantage.

Space-based ATS providers compete primarily on service level, coverage, quality, compatibility with aircraft equipage and pricing. The key factors are summarized in Table 1-1 for service selection, including: operational status; service level; geographic coverage; equipage (e.g., whether additional aircraft equipage is required to obtain service), and regulatory spectrum access.

A market overview of space-based ADS-B market entrants is provided. In addition, this paper discusses aviation communications/data service offerings from Iridium and Inmarsat which use communications technology adapted for Aircraft tracking.

This paper also discusses Skykraft, Starticle and HEAD’s space-based dual-mission system that provides ADS-B surveillance as well as VHF-UHF communications. These entrants are not credible for several reasons, see Section 1.3. A dual mission with both VHF-UHF communications as well as ADS-B surveillance is possible but would require per satellite power levels of around 2000 Watts, an ISL constellation and multiple regulatory approvals. A system with these capabilities would cost billions and take several years to deploy. This dual-mission cannot be achieved using “CubeSats” or small satellites.

3.1 Aireon LLC (McLean, VA) – ADS-B Surveillance

Aireon began providing ATS surveillance ADS-B data in April 2019. Aireon enjoys “first mover” advantage. Aireon offers service to ANSPs and other commercial customers worldwide. Aireon data is being used by a significant amount of Air Traffic Controllers today to enhance situational awareness and provide improved real-time control of aircraft in flight. A summary of Aireon status:

Service Level: ADS-B ATS surveillance also tracking

Status/Expected Time to Market: Operational

Safety-of-life Spectrum License: Yes

Architecture: ISL LEO - Hosted Payload

Coverage: Global

Equipage: No new aircraft equipage is required

Independent Validation: Operational, independent of GPS

EASA Certified – Yes, for ADS-B surveillance

First Mover - As of 2023 Aireon has over 60% of the World’s oceanic traffic market. Aireon enjoys the barriers to entry discussed in Section 1.3. There is currently a total of 63 ANSPs. Aireon has ATS surveillance-as-a-service contracts in place with the following 18 ANSPs:

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- **Africa and Madagascar** - Agency for Aerial Navigation Safety in Africa and Madagascar - (ASECNA)
- **Azerbaijan** - Azeraeronavigation (AZANS)
- **Canada** – NAV Canada
- **Central America** - Corporación Centro americana de Servicios de Navegación Aérea (COCESNA)
- **Curaçao** - Dutch Caribbean Air Navigation Service Provider (DC-ANSP)
- **Denmark** – NAVIAIR
- **Iceland** - Icelandic Civil Aviation Administration (ISAVIA)
- **India** – Airports Authority of India (AAI)
- **Ireland** – AirNav Ireland (ANI)
- **Italy** - Ente Nazionale Assistenza al Volo (ENAV)
- **Kazakhstan** - Kazaeronavigatsia (KAN)
- **Papua New Guinea** – NUSKY Pacific
- **Portugal** - NAV Portugal
- **Norway** - Avinor
- **Seychelles** - Seychelles Civil Aviation Authority (SCAA)
- **Singapore** - Civil Aviation Authority of Singapore (CAAS)
- **South Africa** - Air Traffic and Navigation Service Company (ATNS)
- **United Kingdom** - National Air Traffic Services (NATS)
- **Hong Kong** - CAD (Tracking Data Only)

Iridium formed Aireon in 2011 and maintains an equity stake. Aireon received subsequent investments from five ANSPs: NAV CANADA, ENAV, NATS, NAVIAIR and IAA.

Leveraging Iridium - Aireon leverages the Iridium NEXT constellation capabilities and economies of scale by operating as a hosted payload. There are 80 on-orbit Iridium NEXT satellites with 66 in mission orbit and fourteen on-orbit spare satellites. Aireon's hosted payload is on all 80 Iridium NEXT satellites. The hosted payload concept significantly reduced Aireon's capital expenditures. Aireon pays Iridium a host fee. Aireon also pays Iridium data service fees for the delivery of the ATS surveillance data over the Iridium NEXT network.

Iridium's system includes both satellites and a ground network. Aireon benefits from Iridium's proven experience running a constellation. For the past 20 years, Iridium has demonstrated high Availability and global coverage, meeting commercial as well as government defense requirements. Iridium provides Aireon with a high Availability, secure, low-latency data network.

Iridium NEXT is the only constellation that has Inter Satellite Link (ISL) capability. ISLs route signals through space. However, Iridium also has a somewhat parallel capability to route signals through a globally distributed ground-based network. Multiple routing path options in space (with four ISLs per satellite) coupled with multiple terrestrial paths (through several globally distributed ground stations) provides for a highly redundant, resilient data transport path that meets ATS surveillance requirements.

Each Iridium NEXT satellite has the capability to ensure adequate power and stability for its Aireon hosted payload. The Iridium NEXT satellite platform Availability is adequate to support ATS surveillance services.

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Space Segment - Iridium's satellites fly in a near polar Low Earth Orbit (LEO) at around 780 km. 66 satellites are in active mission orbit. There are six orbital planes with 11 mission operational satellites per plane. The Iridium satellite platform provides Aireon with a uniform grid covering the entire earth, see Figure 3-1. The most significant advantage of the Iridium NEXT constellation is the ISL capability. Each satellite is connected by an ISL to its four neighbors. Iridium is the only operational constellation with an ISL architecture. Aireon data is transferred/routed in space, sometimes through several satellite hops. The data is downlinked at an optimal location in Iridium's terrestrial ground station network. This provides Aireon with an avenue to get "real-time" ADS-B data from anywhere in the world to a user in less than a second.

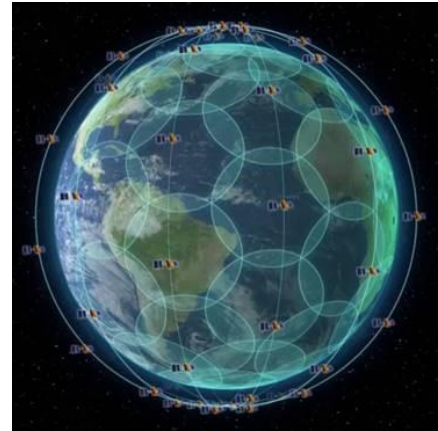


Figure 3-1 Aireon satellite constellation global coverage for an instant in time.

Each Aireon space-based payload rides on an 860 kg, 1400-Watt Iridium NEXT satellite, see Figure 3-2. The Aireon payload itself has a mass of 52.5 kg and requires about 80 Watts of power.

The Iridium NEXT satellites are medium class, see Table 7-1. The Iridium NEXT satellites were designed to meet stringent telecom standards and thus can provide adequate power and data transport which allow Aireon to meet ADS-B surveillance requirements.

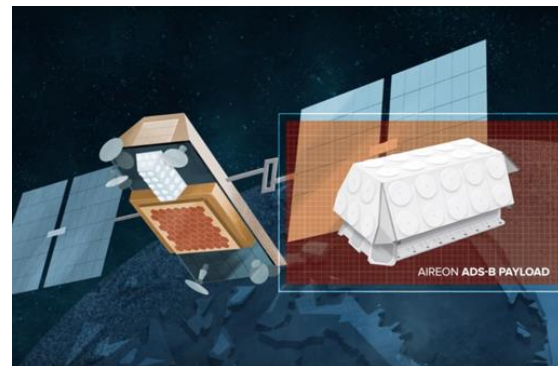


Figure 3-2 Iridium NEXT satellite showing Aireon hosted payload.

Hosted payload missions have unique challenges. The Aireon payload must operate within Iridium's constraints such as power, thermal and bandwidth limitations. Also, the Aireon payload must operate within the local satellite environment. Operating a sensitive receiver inches away from several large antennas was a challenge. Aireon and Iridium have proven that the Iridium satellite antennas do not interfere with the Aireon receiver.

The Aireon payload's software defined receivers that can be changed on-orbit. Initial performance over some high-traffic airspace proved inadequate. This was largely caused by ground-based inference. Aireon improved performance by increasing the number of unique receiver beams to 80 beams.

Ground Segment - Aireon leverages Iridium's ground-based assets. Several of these sites are located at high northern latitudes and one site is located at high southern latitude. Iridium's satellites are in polar orbit. Sites near the Earth's poles are best as they can view the most satellites at any one time. In theory, Iridium can operate their constellation with a single ground station since signals can be routed in space. However, Iridium has multiple ground stations. Several terrestrial routing paths are required to maintain high Availability, minimize latency, and optimize data throughput.

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All Iridium ground stations have fully redundant subsystems. Each ground station has primary and redundant data connections. Backup power systems are incorporated. The Aireon ground segment is a node in the overall Iridium network. Aireon maintains full redundancy on all their ground segment assets.

Regulatory - In early June 2019, Aireon was officially approved by the European Union Aviation Safety Agency (EASA) as an Air Navigation Service Provider (ANSP) Organization to provide Air Traffic Management (ATM)/Air Navigation Service (ANS) surveillance services, to support the separation of aircraft. This authorizes Aireon as the first ever certified provider of aircraft surveillance-as-a-service.

With this certification, Aireon can provide its customers with an EASA accepted Service Definition Document and Safety Case. The EASA certification validates Aireon's processes, procedures, and safety-case. This key regulatory approval is recognized globally and ensures Aireon's systems meet ATS standards. This allows Aireon to be a provider for Pan-European services to multiple ANSPs. EASA certification is also recognized by non-European ANSPs.

Aireon and Iridium have also obtained "safety of life" International Telecommunications Union (ITU) approval for all spectrum used in both systems. ITU safety-of-life approval for ALL system spectrum, this includes ISLs, is required for ATS surveillance service.

Coverage - Aireon payloads constantly move relative to the Earth's surface. Coverage is shown for a random moment in time in Figure 3-3.

The Aireon system achieves significant coverage overlap. Coverage overlap increases the probability of detection at the system level because of a parallel signal architecture.

- Areas denoted by blue have three or more satellites covering them.
- Areas denoted by yellow have at least two satellites covering them.
- The areas denoted by green have single satellite coverage.

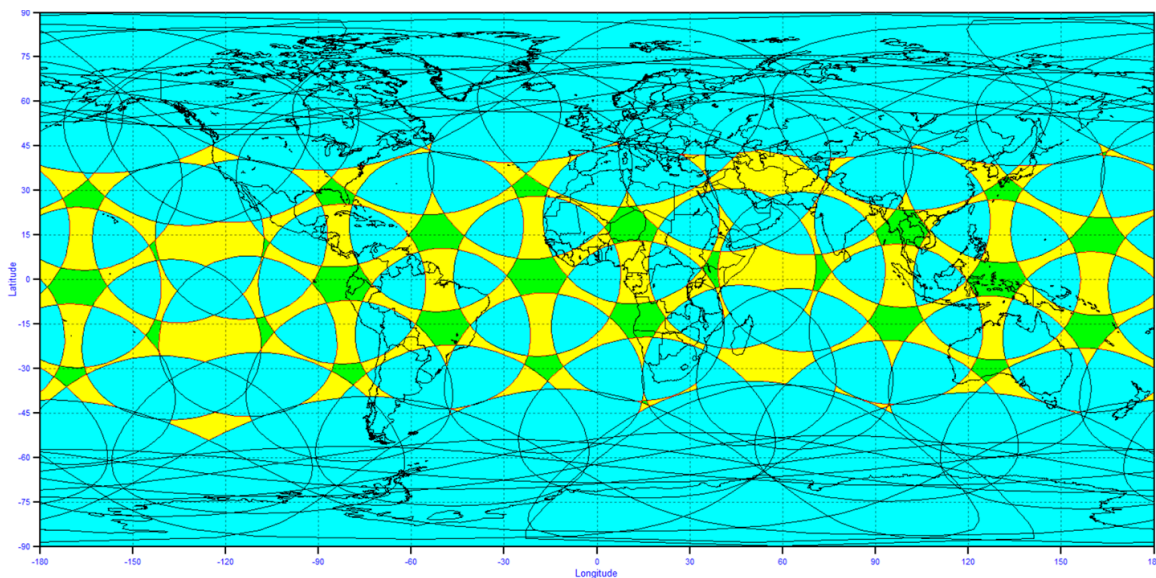


Figure 3-3 Aireon coverage: blue – three or more satellites, yellow – two or more satellites, green – one or more satellites. (Source: Aireon provided coverage analysis).

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Only green areas will be impacted if there is a hole in the constellation because those are covered by only one satellite. Equatorial ANSP service areas will be exposed to approximately 10 minutes of downtime per day due to one satellite hole.

Independent Position Validation – For terrestrial operations scenarios, validation can be done through comparison to radar, WAM, or other ATS surveillance sources. However, for transoceanic scenarios, this is not possible.

Aireon implements position validation to authenticate the state vector integrity of ADS-B data.⁷ In the areas where the payload coverage overlap occurs, the Aireon system picks up two or more measurements of the same information on different satellites. These measurements can be used to perform Time Difference of Arrival (TDOA) calculations. This allows for verification of an aircraft's reported position independent of GPS. This makes the Aireon system resistant to "spoofing," faulty avionics and GPS outages.

Coverage overlap is required for validation. Validation is not possible 100% of the time. Validation is not possible in the green areas, Figure 3-1. Since the coverage pattern constantly changes and the green areas are small, the validation feature would operate most of the time. Coverage overlap increases as aircraft move either North or South of the equator. Also, Aireon has implemented a technique that projects aircraft position to compensate when overlapping coverage validation is not possible.

Aireon's validation layer alleviates concerns about using ADS-B as a single source of ATS surveillance. ANSP's demand for such a validation feature is expected to increase, see Section 5.3. Although, validation is not currently required by most ANSPs, it is desirable. Aireon is unique and is the only player with an operational validation capability.

Going Forward – The multi-billion-dollar Iridium system was built to meet demanding telecom requirements. Using Iridium as a platform yields a combination of high Availability and high data transport confidence. This allows Aireon to meet ATS surveillance performance levels, Section 2.1.

Aireon has been operating payloads on-orbit for several years. Some high-traffic regions have proven to be more challenging than expected. The Aireon receivers are highly reconfigurable and have significant processing power. This has allowed Aireon to tune the receiver operation to optimize performance. The company continues to show progress, extending their ATS surveillance capability across the globe.

The Aireon payload alone has a mass of about 52.5 kg and requires a maximum power of 80 Watts. This can be compared to CubeSat receivers that typically have a mass less than a single kilogram and power at a fraction of a Watt. The larger payload provides Aireon with far greater on-orbit ADS-B capability as well as on-orbit flexibility. The payload design has allowed Aireon to significantly increase the number of receiver beams. Aireon also leverages their payload's on-orbit processing capability to improve performance and make other key modifications to address high-traffic/high-interference airspaces.

Aireon will not see competition with respect to ADS-B surveillance products for the foreseeable future due to barriers to entry discussed in Section 1.3. Radio Frequency (RF) physics are still fundamental to space-based ADS-B. Technology has advanced since the Aireon-Iridium system

⁷ Aireon Independent Validation of Aircraft Position Via Space-Based ADS-B, Version 4, John Dolan and Dr. Michael A. Garcia: Aireon LLC, 1750 Tysons Blvd, Suite 1150, McLean, VA 22102, January 4, 2019.

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was launched. But RF advances have not been significant. Signals must be comprehensively received, quickly processed, and transported with high confidence levels. Systems that do this still require satellites with substantial mass and power. These types of systems require significant investment.

The Aireon system design is highly focused to provide ADS-B surveillance. Aireon's system only receives and processes signals; it cannot transmit. Other systems must be relied on to provide ATS communications. As such, Inmarsat, and Iridium ATS communications are complimentary to Aireon. Aireon now provides controllers with surveillance for remote areas. ATS communications are required to complete the ATM picture. We expect Aireon's service to drive ATS communications growth.

The Aircraft tracking market will continue to evolve. Aircraft tracking stakeholders should watch the market closely. Inmarsat and Iridium, will likely enhance their current service offerings. Also, Aireon is now highly-focused on offering lower-grade aircraft tracking data products. Aireon's data products leverage their comprehensive, global, ADS-B data. The quality of Aireon's data products is superior to other aircraft tracking players.

3.2 Globalstar Inc. (Covington, LA) & ADS-B Technologies – ATS Tracking

Globalstar is a provider of mobile satellite voice and data services. Globalstar offers these services in more than 120 countries around the world. The Company's products include mobile and fixed satellite telephones, simplex and duplex satellite data modems and satellite airtime packages.

Globalstar owns and operates a fleet of LEO satellites. A constellation is composed of first and second-generation satellites. The constellation architecture has 48 mission orbit slots. The Globalstar satellites are medium class, see Table 7-1. These substantial satellites are capable of high Availability performance, see Section 2.1. Globalstar Status:

Service Level: Aircraft tracking

Status/Expected Time to Market: Operational for General Aviation (GA) applications in Alaska.

Safety-of-life Spectrum License: No

Architecture: LEO Bent-pipe

Coverage: Regional

Equipage: ALAS transceiver required

EASA Certification: No

Globalstar's service is available on a regional basis. The constellation features a "bent-pipe" architecture. For bent-pipe constellations, a satellite must have line-of-sight to both a ground station and a subscriber to provide services. The Globalstar ground segment consists of a 24 gateways network, each serving an area of approximately 700,000 to 1,000,000 square miles. Three network operations centers are in France, California, and Louisiana.⁸ Usually at least one satellite is visible from any point on the Earth's surface between the latitudes 70 degrees North and 70 degrees South.

Ground stations are positioned to provide coverage for most of the Earth's land and human population. Globalstar owns 14, while 8 are independently operated. Each ground station has multiple antennas that can pass calls seamlessly between antenna beams and satellites.

⁸ Globalstar 2022 Annual Report, Globalstar Incorporated, December 31, 2022.

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Globalstar partnered with ADS-B Technologies (Anchorage, Alaska) which developed the ADS-B Link Augmentation System (ALAS). ALAS requires modification to the aircraft equipage. A special transceiver must be installed in ADS-B-equipped aircraft. The transceiver sends ADS-B information to Globalstar satellites. The data is then retransmitted to ground stations and then to ANSPs or other users. Modifying aircraft equipage is a key issue that hinders ALAS deployment.

The ALAS signals are encrypted which provides added security. However, from a regulatory perspective, ALAS uplink and downlink frequencies are not protected by the ITU for safety-of-life applications. Therefore, ALAS cannot be relied on for ATS surveillance. The system can be used for Aircraft tracking applications.

Going Forward - The window is closing as Globalstar delays. Other competitors discussed here continue to gain market share with related offerings. As market opportunity closes, it becomes more difficult to justify investment. Globalstar's ALAS offering becomes increasingly unlikely as time passes.

Globalstar can only provide service to regions where a given satellite can be simultaneously connected to both a user and a ground station. This has prevented Globalstar from serving some remote regions and oceans. For communications services, a system built with this type of architecture may be advantageous. However, where key air traffic routes cross remote regions and oceans, the Globalstar's bent-pipe LEO constellation architecture presents a significant disadvantage.

Globalstar's ALAS offering has not yet been fully deployed. ALAS requires additional aircraft equipage, putting ALAS at a disadvantage relative to competitors that can operate without additional equipage. No progress has been made over the past several years based on limited publicly available information.

3.3 Spire Global Inc. (San Francisco, CA) – ATS Tracking and Weather

Spire creates product offerings by fusing unique data sources. The company has demonstrated the value and capability of CubeSats. Spire designs, builds, tests, and operates all its satellites. Commercial-Off-The-Shelf (COTS) components are leveraged. As of late-2023, Spire currently has about 110 satellites in operation. Around half the satellites have ADS-B payloads. About 30 ground stations are active. The company launches about 20 satellites per year.

ESA MLAT Project - July 2023, the European Space Agency (ESA) awarded Spire a €16 million phased contract for the EURIALO project. ESA's focus is to develop an additional air traffic surveillance system that is complimentary and independent of GPS-based systems. Note, the ADS-B signal contains GPS aircraft position data. Spire will lead a team to develop the preliminary design and demonstrator for a global space-based independent aircraft surveillance system. The project is part of ESA's Advanced Research in Telecommunications Systems (ARTES) efforts.

ESA sees the need for an additional complementary solution to ADS-B that will complement the current European infrastructure. Spire's project will focus on independently verifying the location of a plane through geolocation Multilateration (MLAT). MLAT is a form of "triangulation" by which data from multiple receivers is combined to infer an aircraft position. Data, from a single aircraft, must be received by at least four different satellites to perform the MLAT calculations. The more spacecraft receive a signal; the more accurate the calculation becomes.

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Concept of Operation's details around the proposed MLAT system are not available. The project is at the early developmental phase. Many challenges must be overcome to provide surveillance quality data from Spire's CubeSat-based constellation as discussed in Section 2.0.

Summary of Spire's status:

Service Level: Aircraft tracking (ICAO's 15-minute tracking standard)

Status/Expected Time to Market: Over 110 operational satellites on-orbit. About half have ADS-B payloads as of mid-2020. More satellites required for global coverage.

Architecture: Phase 1 – LEO Bent-pipe, Phase 2 – LEO ISL



Figure 3-4 Spire technicians assemble a batch of Lemur satellites.⁹

As of late-2021 Spire does not expect to grow its constellation of Lemur satellites, as the company did not see "any customer demand" that would require a larger constellation of satellites. Despite not growing its constellation, Spire will continue to build and launch satellites as the Lemur satellites are refreshed on a three-year hardware replacement cycle.¹⁰

Coverage: Spire does not currently have full global coverage. Some coverage gaps are regional due to lack of ground stations, some gaps due to lack of satellites.

Equipage: Compatible with existing aircraft equipage.

EASA Certification: No

Spire has diversified its portfolio in three separate data-service businesses:

1. **ADS-B** - Spire's "AirSafe" payload provides tracking service.
2. **Automatic Identification System (AIS)** - Spire satellites also provide data for maritime tracking.
3. **Weather Models** - GPS Radio Occultation (GPS ROO) – This provides atmospheric measurements that feed into weather forecasting models.

Selected Aviation Related Products:

1. **Flight Schedules** – Advanced information flight schedule data is offered. Schedules are also available with positional updates.
2. **Aviation Weather Forecast** – Weather forecasts are available at every 1000 feet of vertical resolution. These contain: clear air turbulence, winds aloft and icing information.
3. **Combining ADS-B and Weather** - This combined data set is leveraged to optimize flight plans. Detailed wind vs. altitude information is provided. The severity of air turbulence versus altitude can be determined.
4. **Combining ADS-B and AIS** – These two data sources can be combined to estimate freight transport on a global scale.

Based on Spire's website, they appear to be firmly focused on the maritime market. Here they leverage fusing weather and shipping AIS data.¹¹

⁹ <https://spire.com/>

¹⁰ Sheetz, Michael (August 17, 2021). "Satellite company Spire begins trading on the NYSE after completing SPAC merger". CNBC.

¹¹ <https://spire.com/>, see Whitepapers

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Satellites - Spire satellite life is between 2 and 5 years. Spire is constantly refining and updating their satellite design. Old satellites are replaced with more capable new satellites.

Spire's offers four different classes of satellites; 3U, 6U, 12U and 16U. Spire's on-orbit fleet is made up of mostly Lemur satellites based on limited information. Lemur's have a 3U form factor (10x10x30 cm). The body is about the size of a wine bottle gift box. The satellites are approximately 4.6 kg. The Spire CubeSats feature a 3-axis attitude control system. Spire claims their Lemur satellites have electric propulsion but this cannot be verified. Radio Frequency communications are provided via UHF-band and S-band. Two high-gain antennas are located at both ends of the spacecraft. Spire satellites carry different payloads. Spire satellites typically carry, not all, but some combination of four payload types:

1. an AIS receiver,
2. an ADS-B receiver and a
3. radio occultation weather receiver.
4. Also, some satellites carry hosted payloads for third party customers.

The satellites fly in 400-650 km orbits. Most satellites are at 51.6 deg inclination. The more recently launched satellites are around 85 degrees inclination. The satellites are not optimally spaced in orbit, probably because the propulsion system capability is limited. Some Spire satellites were launched on ride share missions. For these satellites the orbital location is not optimal. These factors increase the number of satellites required to achieve global coverage.

As of late-2023 around 50 Spire satellites carry an ADS-B payload. The satellite ADS-B payload has a four-segment antenna with a tilted main beam. A software-defined ADS-B receiver is implemented. Signal processing is done with an ARM Cortex-9 / Xilinx Zynq 7000. ADS-B demodulation is done via FPGA. Message decoding/processing is done via the CPU. Peak capacity per satellite is 7500 messages per minute.¹² This capacity will support the reception of 125 aircraft ADS-B messages in the coverage footprint with each aircraft broadcasting 6.2 messages per second.

Ground Segment - Spire satellites have simple bent-pipe payloads. CubeSat bent-pipe LEO constellations require a substantial amount of ground stations to provide global service. Spire operates about 30 ground sites with a total of 70 antennas.

Without a ground station connection, a bent-pipe satellite cannot transfer data. This would be problematic for ATS surveillance applications due to stringent latency requirements. However, for tracking, data can be stored and brought down to a ground station when one becomes visible to the satellite. "Storing forward" capability requires that on-board data storage and downlink capacity be adequate. This technique can be used to extend coverage to some regions where there are no ground stations.

Will Spire provide ATS surveillance? With CubeSats this is not possible per the discussion in Section 2.1. The bent-pipe Spire system can provide regional coverage in "near-real-time." Bent-pipe systems are at a significant disadvantage because coverage of some remote regions will not be possible.

¹² Seizing Opportunity: Spire's CubeSat Constellation of GNSS, AIS, and ADS-B Sensors, Dallas Masters, Spire Global, Inc., Stanford PNT Symposium, November 8, 2018.

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Besides technical issues, Spire will require a path to certification. Spire must achieve and demonstrate ATS surveillance performance and achieve safety certification. Also, ITU spectrum protection as safety-of-life must be achieved for all system frequencies.

Spire's tracking capabilities appear limited. Spire offers a paper that uses their ADS-B data to measure aircraft emissions.¹³ The paper is telling and reveals holes in Spire's ADS-B capability. The author, Dr. Sun, is required to collect flight traffic data from flights between the US and Europe for the month of March over three consecutive years: 2020, 2021, and 2022. Dr. Sun discusses, in detail, how he was required to rely on several data sources to augment Spire's limited data. The paper can be accessed on Spire's website, link in footnote below. Spire can provide aircraft tracking data. However, the data is not comprehensive as shown.

Aviation Services Going Forward - Spire has successfully developed products by leveraging ADS-B tracking data. If the company stays on the path of building and launching CubeSats, we do not expect them to provide ADS-B surveillance service. Surveillance requirements are too stringent for CubeSat class satellites.

Spire's current focus is to provide a global ADS-B tracking service with 15-minute update capability. Also, the primary focus of the company appears to be on maritime applications where their system is much more capable of meeting requirements versus aviation.

Spire is innovative. They have a proven ability to develop new data products, fusing different types of data, such as AIS and weather, that yield valuable new services. We expect Spire to continue to find niches. The profit from these market niches will have to justify an increasing investment.

3.4 GOMspace A/S (Denmark) and subsidiary Aerial and Maritime Ltd. (AM) – ATS Tracking

On June 16, 2020 GOM closed AM and announced they will liquidate AM assets.¹ GOMspace and subsidiary Aerial Maritime Limited (AM) collaborated with the European Space Agency (ESA) to develop a dual-purpose satellite constellation for ADS-B tracking/surveillance as well as Automated Information System (AIS) ship tracking.

- **AM**, founded in 2015, was to operate a system with both space-based and ground-based elements. The system supports ADS-B for Aircraft and AIS for Ships. AM was co-owned by GomSpace group, private equity firms and the Danish Government. GomSpace built CubeSats for AM. Also, the AM ground segment was provided as a service by GomSpace.
- **GomSpace** is a major European CubeSat maker. GOMspace has been at the forefront of CubeSat development. GomSpace has developed and flight-tested compact ADS-B and AIS receivers. GomSpace has demonstrated CubeSat capabilities – including miniaturized technologies, flying in formation, and ISLs. GomSpace has produced thousands of components and many complete satellites for customers world-wide.

AM planned a two-phase satellite constellation roll out. A total of eight satellites were built but not launched.

¹³ Improving carbon emission estimates with space-based ADS-B data and upper wind component integration, Dr. Junzi Sun, Faculty of Aerospace Engineering, June 20, 2023, <https://spire.com/blog/aviation/improving-carbon-emission-estimates-with-space-based-ads-b-data-and-upper-wind-component-integration/>

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June 16, 2020 GomSpace and AM entered a settlement agreement. GomSpace will liquidate AM. GomSpace will retain ownership of the yet to be launched eight satellites. GomSpace will attempt to sell the eight CubeSats, or find another purpose for them.¹

3.5 Skykraft – ATS Tracking and VHF-UHF Communications

Background - The Skykraft satellite hardware currently on-orbit is far from that which will be required to meet their ambitions objectives. This Australian company seeks to provide space-based ATC surveillance services using ADS-B signals while also providing ATC VHF communications for both data and voice. Skykraft's Constellation is planned to grow over the coming years to provide redundant global coverage, with an average of more than seven satellites within range of any aircraft at anytime, anywhere in the world.

- **Service Level:** ADS-B ATS surveillance also tracking also VHF and UHF voice and data communications
- **Status/Expected Time to Market:** Prototypes launched
- **Safety-of-life Spectrum License:** Required to be obtained
- **Architecture:** Bent Pipe LEO – Each satellite must have an established ground site connections to establish user link.
- **Coverage:** Regional, depends on ground station availability
- **Equipage:** No new aircraft equipage is required
- **Independent Validation:** Potential, independent of GPS
- **CASA Certified** – TBD

Skykraft's satellites are designed, manufactured, and operated from the Canberra Center. The company states that the full 210 satellite constellation will be on-orbit and will commence operations in 2025. The constellation will be maintained with a regular five-year satellite replenishment cycle, supporting a sustainable space manufacturing capability in the nation's capital that will produce 40-50 satellites annually.



Figure 3-5 Skykraft constellation conceptual drawing. ¹⁴

¹⁴ Australia's largest satellite stack launched today, to make global air travel smoother and more efficient, AM News, January 4, 2023.

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Based on publicly available information, Skykraft's system is described as:

- A constellation of 210 satellites operates in Low Earth Orbit across seven orbital planes.
- The satellites will have a five-year life cycle.
- Satellite solar arrays generating a total power output of 2.6 kW.
- Along with an ADS-B receiver, each satellite is equipped with an S-Band antenna, UHF antennas and VHF antennas. S-Band is used for command-and-control telemetry. UHF and VHF are used for communications services to aircraft.
- "The satellites will be the size of a small car when all antennas and solar panels are deployed."
- Based on available information, the satellites will be "bent pipe" configuration, no Inter Satellite Links.
- Mass for the Versions II and III satellites is about 60 kg each.
- All regions of interest will have at least seven satellites providing overlapping coverage.

Status:

- January 4, 2023, five Skykraft Block II satellites were launched.
- June 12, 2023, five Skykraft Block III satellites were launched.

Skykraft chief executive Michael Frater said the company developed its satellite plan over 12 months in a project that would cost "something under \$200 million".

Review - The idea of a space-based multipurpose surveillance and communications system has merit. However, Skykraft's proposed ADS-B/UHF-VHF communications satellite constellation is not realistic relative to the Block II and Block III satellites currently on-orbit. Much larger, more complex satellites will be required.

The Skykraft system as proposed will likely only provide regional service. If the service were to be used for ATC applications, the company would have to meet many performance and regulatory requirements as well as establish redundant ground networks for each customer.

Power – Skykraft satellite technical information is limited. Mass and power values are quoted. Skykraft specifies that each satellite has a total power output capability of 2.6 kWe. Based on website pictures of spacecraft during assembly and the drawing shown in **Figure 3-5** each Skykraft satellite has about 1 to 2 square meters of solar array area. Optimally pointed satellite solar arrays generate no more than about 300 Watts/m² of electric power. Also, the Skykraft solar array pointing capability is limited based on the hinged design. Summit expects the maximum solar array output for these Skykraft satellites will be about 10X less than the claim or about 200 Watts. On-orbit, average power is less than maximum as LEO satellites are in the shade for a significant portion of their orbit. A good assumption for Skykraft's on-orbit average power is 150 Watts.

150 Watts of satellite power is not adequate. For comparison, Summit provides typical satellite power loads shown in Table 3-1 for the required Skykraft satellite functions. Summit estimates the Skykraft mission will require about 1015 Watts of orbit average power. This would require a solar array capable of producing about 1500 to 2000 Watts depending on how optimally the array can be pointed throughout orbit.

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Function	Typical Power Watts
Payload	
VHF Communications	250
ADS-B Receiver and Processing	80
Downlink	250
Payload Units (processors, storage, heaters)	200
Platform	
Secondary Link	20
Platform Heaters	40
Avionics	150
Power System Losses	15
Wiring Harness Losses	10
Total	1015

Table 3-1 Summit typical spacecraft power estimates for Skykraft satellite functions.

Mass - Skykraft's current 60 kg per satellite mass will need to be about 10X greater to meet their planned mission objectives. For comparison, the current 60 kg mass is only slightly greater than the Aireon 50 kg receiver (not considering the Iridium NEXT 810 kg satellite bus). The Skykraft satellites receive ADS-B signals and support user communications as well as satellite bus and telemetry communications.

Skykraft's current satellites have limited capabilities. ADS-B performance will be limited without on-board processing and multi-beam receivers and each satellite will be overwhelmed over crowded airspace. VHF-UHF transmission and receiver capabilities will also be limited. Satellite platform downlink, data processing, data storage... will be of low quality and limited capability. These small satellites will never perform surveillance and communications functions that meet ATC standards.

Coverage - Skykraft plans to have seven-satellite-overlapping coverage over regions of interest. This level of coverage overlap will only be possible near the poles with a polar orbiting constellation.

Coverage overlap helps increase ADS-B performance, however, it does not directly increase VHF-UHF performance as only one satellite at a time can support a voice communications link.

The constellation features a bent-pipe architecture. Little information is provided and some graphics imply the system has ISLs. ISLs, with reasonably high availability, require a satellite bus with much more mass and power.

There is no doubt that the satellites will receive signals as they orbit globally, however, a communications link cannot be established unless a given satellite is connected to a ground station. When satellites are not connected to a ground station, they can store data and forward when a connection is established, "store and forward." This increases latency significantly and cannot be done with VHF-UHF voice communications. Establishing a global ground network that covers oceanic and remote regions will be difficult at best and expensive. Skykraft will likely focus on specific regions.

Summary - The company will gain valuable experience with their prototype satellites. This will allow for design modifications. This will reduce risk and demonstrate the need for larger, more capable satellites. Key points:

- Interference between the ADS-B receiver and the UHF and VHF transceivers is a major issue. Early on-orbit testing will help to retire this risk. Although, resulting satellite design modifications will increase satellite production costs.

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- Satellites must be capable of high Availability and data rates needed to meet ATC requirements. Early testing will demonstrate performance shortfalls.
- Skykraft's satellite power level is quoted at 2.6 kWe maximum output power. This is a reasonable per satellite maximum output power for the stated mission. However, the satellites being launched produce about a tenth of this power which is inadequate as discussed above.
- Although the satellites likely have few to no redundant systems, redundancy can be maintained at the constellation level with active spare satellites.
- Skykraft plans to overlap coverage to meet ATC performance goals. This only directly helps the ADS-B service but will require thousands of small satellites which will be prohibitive. Coverage overlap does not directly help VHF-UHF communications quality as links are supported by one satellite at a time. Larger, much more expensive satellites will be required.
- The \$200 million cost, per Mr. Frater, is likely the cost of the initial 210, 60 kg, satellites. This may exclude launch costs and the cost of the ground segment. To achieve Skykraft's vision, a system very similar in mass, size, power, and cost to Iridium NEXT would be required.
- Skykraft's 2025 schedule is ambitious. Added technical and regulatory complexity will push schedule out.
 - All system spectrum must be protected and certified as "safety of life" by the International Telecommunications Union (ITU). The ITU approval must protect the use of these frequencies from space. Coordination of VHF communications from space will require a significant process.
 - For ATC applications, a high-level of documentation and process definition must be developed, maintained, and certified by international organizations such as EASA. This may not be factored into the company's schedule.
 - A redundant ground network must be established for each ANSP customer.

3.6 HEAD Aerospace Skywalker Constellation

The "Skywalker" constellation is a 48 micro-satellite constellation independently developed and planned by Beijing HEAD Aerospace Technology.¹⁵ Nine satellite have been launched to date.¹⁶ The satellites are tens of kilograms in mass. The planned system will provide narrow-band space Internet of Things two-way data communication, ship position monitoring (AIS/VDES), Aircraft (ADS-B) monitoring and other spatial information services.

Conclusion - HEAD Aerospace has high expectations that are not grounded in reality. Information is limited but it is unlikely that Skywalker CubeSats will be capable of providing aircraft surveillance. CubeSats have limited capability and the number of satellites is relatively low. Also, aircraft tracking capabilities will be limited relative to Aireon. CubeSats have limited power for data transmissions. Data capacity will also be very limited.

3.7 Starticle

Starticle is a Public-Private-Partnership (PPP) company formed by Enaire, Indra and the Spanish government.

- Indra Sistemas, S.A. is a Spanish information technology and defense systems company. The company operates in more than 138 countries and has more than 43,000 employees worldwide. Enaire is the fourth-largest national air navigation manager in Europe and a partner with the Spanish Ministry of Transport.

¹⁵ <https://www.head-aerospace.eu/skywalker-iot-solution>

¹⁶ <https://www.linkedin.com/company/head-aerospace>

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- The maximum Spanish government investment is pegged at 29.2 million euros over three years.
- Phase 1, 2021 to 2023, will address technology development. Phase 2, 2024 to 2027, is expected to be the deployment phase.
- Information on the satellite and constellation design is limited. An Inter Satellite Linked (ISL) mesh architecture appears to be baselined.

Late 2019, Indra proposed a similar concept with a mesh architecture 210 LEO satellite constellation. Starticle appears to be a continuation of this concept. The constellation is dedicated to ATS and provide both ADS-B surveillance as well as Very High Frequency (VHF) communications. The constellation would provide global coverage. Starticle seeks to disrupt the market by offering both services on one dedicated system.

Conclusion - There are few details. It is stated that this will be accomplished with “small satellites.”¹⁷ Starticle’s concept is technically possible but not with small satellites. The same points made above for Skykraft apply here. As with Skykraft, an ADS-B-VHF/UHF constellation is possible but a system very similar in mass, size, and power to Iridium NEXT would be required.

Deploying a high-Availability, mesh network, constellation and the associated ground network will take several years. Also, ITU frequency protection approval will be required for ATC applications. Space VHF communications will require regulatory coordination.

Starticle’s early research and design phase is funded. However, a several billion-euro investment will be needed to deploy such a system. Incumbent space-based ADS-B suppliers will continue to gain ANSP and airline customers. The large investment must be justified based on a limited, shrinking market.

3.8 Inmarsat PLC (London, UK) – ATS Tracking and Communications

Inmarsat PLC is a British satellite telecommunications company offering global mobile communication services. It provides telephone and data services to users via mobile terminals which communicate with fourteen Geostationary (GEO) telecommunications satellites. On 8 November 2021, a deal was announced between Inmarsat’s owners and Viasat, in which Viasat was to purchase Inmarsat. The acquisition was completed in May 2023.¹⁸

Inmarsat began offering a service called Classic Aero in 1990, tracking aircraft with Automatic Dependent Surveillance – Contract (ADS-C). This service has been upgraded to what is now called Swift Broadband-Safety (SB-S). The shift to SB-S provides more bandwidth over two channels. One channel is for high-priority ATS information. The other channel for lower priority data. Modern commercial aircraft literally have thousands of sensors and produce hundreds of Gigabytes of data per flight. Inmarsat’s SB-S offering allows this data to be beamed to the ground in real time. Inmarsat enables the various services discussed in Section 5.2.

Iris ATS Digital Communications - Iris is intended to relieve pressure on the existing ATM channels. This could be especially useful in the European high-interference environment. ATS communications will be supplemented with digital text for position reports, clearances, and runway conditions. Iris will require satellite cockpit terminals. High-capacity digital data links via satellite will carrying continental and oceanic ATS communications and data. Although valuable

¹⁷ <https://www.startical.com/en/>

¹⁸ “Viasat Completes Acquisition of Inmarsat”. Viasat. 31 May 2023. Retrieved 26 July 2023.

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for ATM operations, Iris typically runs the CPDLC application. Iris is part of the Single European Sky ATM Research (SESAR) program. Flight trials were successfully concluded in 2022 and the Iris system has been validated by regulators.

easyJet is the first to implement the Iris system. They fitted Iris equipage to several newly delivered Airbus A320neo aircraft. Flying began commercially in November 2022.

Iris provides ATC communications and position tracking data. However, to fully take advantage of better ATC communications, reduced aircraft separation is desired. Reduced separation requires surveillance quality aircraft position data which the Iris system is not capable of providing. Currently surveillance quality position data can be obtained from ground-based systems as well as the Aireon ADS-B system in remote regions.

Aircraft WiFi Communications - Inmarsat brings WiFi to aircraft through an S-band European-based hybrid satellite/terrestrial network. The network is not indented to support ATS applications. A complementary ground network consists of around 300 LTE base stations. The “European Aviation Network” faced legal challenges that delayed implementation.

Now, Inmarsat offers aviation services through the European Aviation Network, developed in partnership with Deutsche Telekom. The European Aviation Network and Inmarsat satellites provides 50Gbit/s capacity to aircraft in European airspace. The service is operational and offered on hundreds of European routes through British Airways, Iberia and Vueling.¹⁹ The Inmarsat satellite communications technology has been adapted for Aircraft communications and tracking and cannot be used for ATS surveillance, see Section 3.8. A summary of Inmarsat’s status:

Service Level: Aircraft tracking and ATS communications

Status/Expected Time to Market: Operational since 1990

Safety-of-life Spectrum License: Yes, for selected frequencies

Architecture: GEO, Bent-pipe

Coverage: Global, except for polar regions.

Equipage: Service integrated into a high percentage of commercial aircraft. Inmarsat claims their equipment is installed on over 90% of transoceanic aircraft traffic.²⁰

EASA Certification: Yes, for communications related items.

Space Segment - The Inmarsat satellite constellation consists of 13 satellites in a geosynchronous (GEO) orbit approximately 22,000 miles above the earth. The satellites are positioned to transmit radio beams in two global configurations covering the oceans and major land masses. Inmarsat coverage extends from latitudes of -82° to 82° regardless of longitude, so higher latitudes like the polar regions are not covered.

This fleet delivers global maritime and aviation safety, L-band broadband, high-speed Ka-band, and European inflight Wi-Fi S-band services. The Inmarsat satellites are large class, Table 7-1, GEO satellites. These satellites are capable of high Availability performance as well as high throughput data rates. The system can provide “real time” data links with typical latency between 1 to 2 seconds.

Ground Segment - Inmarsat’s satellites employ a bent-pipe architecture. An Inmarsat satellite must have a line-of-site to both a user as well as a ground station to establish a connection.

¹⁹ Töre, Özgür (19 January 2021). “Europe’s Fastest Inflight Wi-Fi Service Expands Coverage”. ftnnews.com. Retrieved 15 February 2021.

²⁰ Inmarsat – Powering Aviation Connectivity, Aviation Overview, Inmarsat, March 2017.

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However, only a few ground stations are required since GEO satellites appear to be stationary relative to the earth's surface. The high-altitude GEO orbit is advantageous because it allows a single satellite to view about a third of the entire Earth's surface. Inmarsat can provide coverage in remote regions with only a few ground stations. Also, there is great flexibility in locating ground stations. Convenient ground station locations can be selected where weather is good and data connections and power have high reliability.

Regulatory - Inmarsat benefits from having their operating frequencies protected by the ITU with safety-of-life status.²¹

Going Forward – Inmarsat will not compete with Aireon for ATS surveillance. Inmarsat's services are complimentary. Now that Aireon global aircraft ADS-B surveillance is available, the need for ATM communications in remote regions is more important and will increase.

Inmarsat will compete with Iridium for ATS related communications. As discussed in Section 5.2, the amount of data generated by modern aircraft is substantial and will likely increase. GEOs allow for more focused capacity giving Inmarsat's large GEO satellites an advantage over LEO constellation systems. Inmarsat can provide customers with 5 to 10X more capacity than Iridium for example. When capacity is not the primary issue, Iridium and Inmarsat will compete for ATM communication opportunities based on equipment, coverage, and price.

Inmarsat enjoys ATS regulatory approval. We expect Inmarsat to remain focused on ATS communication opportunities such as Iris and WiFi. Inmarsat will continue to grow their aviation business by finding innovative ways to offer services.

3.9 Iridium Satellite LLC – ATS Tracking and Communications

Iridium operates a constellation with 66 mission satellites plus 9 spare satellites. Iridium satellites were initially launched in the late 1990s. The "Block 1" satellites were replaced with new Iridium NEXT satellites. The NEXT constellation deployment was completed in early 2019. May 20, 2023 Iridium launched an additional 5 spare satellites on a SpaceX rideshare mission, for a total of 80 Iridium NEXT satellite on orbit. The Iridium satellites are medium class, Table 7-1, and operate in near polar LEO orbits of 780 km.

Iridium's principal vertical lines of business include land mobile, maritime, aviation, IoT, hosted payloads and other data services. Iridium also supports the U.S. government with unique secure services.²²

Service Level: ATS aircraft tracking and
ATS communications

Status: Operational

Safety-of-life Spectrum License: Yes

Architecture: ISL LEO

Coverage: Global

Equipment: The number of aircraft using Iridium communication equipment is not publicly available.

EASA Certification: No

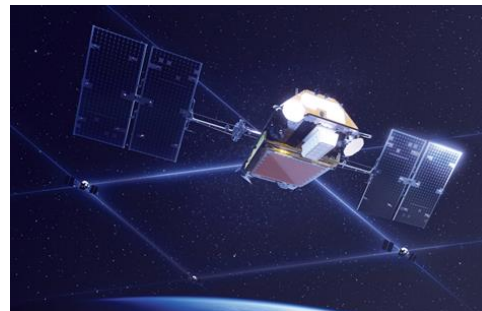


Figure 3-6 Iridium NEXT satellite showing Inter Satellite Links.²³

²¹ Annual Report and Financial Statement for the Year Ending 31 December, 2018, Inmarsat Group Limited.

²² 2022 Annual Report, Iridium Communications Incorporated, December 31, 2022.

²³ Happy Birthday Iridium NEXT, Thales Alenia Space, January 14, 2020.

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Iridium provides the aviation industry with air-to-ground telephony and data communications for position reporting, emergency tracking, weather information, electronic flight bag updates and airline operational communications. A summary of Iridium's status:

Iridium's primary aviation related services follow those listed in Section 5.2. Iridium has teamed with Collins Aerospace (ARINC) and SITA, two leading aviation voice and data link communications providers, that have integrated Iridium services into their offerings.

Iridium also offers the following Aviation services:

- **Aviation Passenger Communications:** Corporate and private fleet aircraft passengers use Iridium services for air-to-ground telephony and data communications.
- **Rotary and General Aviation Applications:** Iridium addresses this sector with small antenna designs that work under rotor blades. Services include: traditional voice communications, fleet tracking and management, and real-time flight diagnostics.
- **Unmanned Aerial Vehicles (UAVs):** The small antenna system enables reliable beyond-line-of-sight communications.

Although Iridium supports various ATM services, each Iridium NEXT satellite hosts an Aireon ADS-B payload, see Section 3.1.

Regulatory - ICAO, has approved standards and recommended practices. ICAO has certified Iridium to provide Aeronautic Mobile Satellite (Route) Services (AMS(R)S) to commercial aircraft on long-haul routes. This allows member states to evaluate and approve Iridium services for ATS communications on flights in oceanic and remote airspace.

All Iridium spectrum links are protected by the ITU as "safety of life." ITU safety-of-life approval is required for frequencies used in the system. This includes ISLs.

Going Forward – Iridium will participate in ADS-B surveillance through their ties to Aireon.

Iridium and Inmarsat enjoy regulatory approval that allow them to offer ATS communications. Now that global aircraft ADS-B surveillance is available through Aireon, the need for ATS communications in remote regions is more important and will increase. Iridium remains focused on ATM communication opportunities.

Iridium will compete with Inmarsat for ATS business. Inmarsat can provide 5 to 10X Iridium's bandwidth. When capacity is not the primary issue, Iridium and Inmarsat will compete for ATS communication opportunities based on equipage, coverage, and price. Iridium will continue to find innovative ways to increase their ATS business.

4.0 Actors and Stakeholders

Public Interest - The travelling public is the ultimate stakeholder. Regulatory bodies are chartered to provide oversight and ensure safe, efficient travel. International and regional aviation safety organizations continually work together to implement safety policies and oversight activities. States implement safety programs and safety management systems.

ANSPs (The Direct Customer) - The key goal of each ANSP is to conduct worldwide traffic flow in a safe and efficient manner. ANSPs control flights within each country's sovereign and delegated airspace. They perform an extensive range of functions, including:

- Air Traffic Management (ATM)
- Communications, Navigation and Surveillance (CNS)
- Meteorological service for air navigation (MET)
- Search And Rescue (SAR)

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- Aeronautical Information Services/Aeronautical Information Management (AIS/AIM)

Many ANSPs, once government owned, are now mostly commercial and they sell their services to generate revenue. Both commercial and government owned ANSPs seek to optimize their airspace from an operational perspective. Space-based systems could address these challenges by providing:

- Aircraft ADS-B tracking coverage over the entire airspace, including remote areas
- Real-time ATS ADS-B surveillance over the entire airspace, including remote areas
- ATS aircraft to controller communications using ADS-C, CPDLC and data links
- Seamless interoperability and observation across neighboring airspaces. This supports ANSP planning and allows for better predictability.
- Flight planning and operations communications
- Real-time aircraft operations data

ANSPs seek space systems with resilience, robustness, and sustained operation. If the space system is to be relied upon, operation for multiple years must be guaranteed. The space-based ADS-B provider must commit to multi-year comprehensive service level agreements. ANSPs may consider using multiple space-based ADS-B providers to reduce risk.

Aircraft Owners/Operators (Key Stakeholder) - Aircraft will need ADS-B Out transmitter equipage. Some countries require its use. The FAA, for instance, has mandated ADS-B Out capability for flights after January 1, 2020, in airspace where a transponder is required today. ADS-B Out is also mandated by EASA after June 7, 2020. Not all aircraft owners are required to equip with ADS-B, although many are choosing to do so for situational awareness reasons.

Data Providers (Opportunistic Stakeholders) - Flight data aggregators, such as FlightAware and Flightradar24, offer global Aircraft tracking of flight data through product offerings which combine ground based and satellite fed data. These systems provide global ADS-B coverage and “gate-to-gate” visibility of flight routes. These data providers may expand their products and features based upon new data feeds from satellite-based ADS-B providers.

5.0 Service Objectives

Traditional ATS objectives continue to drive services. Across the world community there is increasing interest and need to integrate systems and environments. ANSPs seek to extend ATM capability over their entire area of responsibility and have visibility into neighboring airspace.

Most recently the interest in Unmanned Aircraft Systems (UAS) for civil and commercial purposes has gained momentum. UAS uses include: package delivery, inspection, surveillance, and transport. As UAS applications increase, traditional ATS will be stressed. There is a need for solutions that support the co-existence of manned and unmanned aircraft. Space-based solutions will be part of the UAS solution.

5.1 Air Traffic Control Capacity, Management and Data Fusion

Integrating a range of solutions can enhance performance. Discussions are ongoing between the US (NextGen) and Europe (SESAR) regarding the possibility of having a joint strategy that would provide “a holistic view of ATS surveillance infrastructure needs.”^{24, 27} Moving towards a

²⁴ “NextGen – SESAR State of Harmonization;” SESAR Joint Undertaking; 2016.

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shared and common global system will not occur overnight. Over time, ADS-B usage will grow to harmonize and optimize traditional ATS surveillance infrastructure.²⁵

Europe's airspace is nearing a limit. Europe's fragmented airspace will see traffic increase and delays worsen. Space-based ATS enables data-sharing across borders. This can give all ANSPs access to high-performance ATM systems and take the region closer to its Single European Sky goals.

5.2 ATS Satellite Communications

Airlines continue to increase satellite connectivity. New networks bring more avenues to connect. Airlines look to achieve additional revenue and gain efficiencies. ATS certified communications are increasing efficiencies by reducing fuel consumption and the resulting emissions. ATS communications allow for the optimization of: aircraft maintenance, flight operations, fleet utilization and airspace capacity. Also, better communication increases safety.

A global ADS-B surveillance provider, Aireon, has entered the market. With global aircraft ATS surveillance now possible, the need for ATS communication in remote regions has increased. ATS communications cannot take the place of ADS-B surveillance. However, space-based ATS communications provide remote controller-aircraft communications and are complimentary to broadcast only ADS-B. Satellite communication operators that provide remote region service have an opportunity to increase their business.

Inmarsat and Iridium have both achieved regulatory approval to offer ATS data services to the cockpit, Section 2.3.

Inmarsat and Iridium have a variety of product offerings and integrated solutions. Communications occur through three systems/formats:

- ADS-C
- Datalink communications
- Controller-Pilot Data Link Communications (CPDLC)

Inmarsat and Iridium also provide aircraft crew and ground operations with AMSS satellite telecom services for air-to-ground telephony and data communications. This includes:

- Aircraft position
- Aircraft condition data
- CPDLC for clearance
- Other information services

5.3 Security – Independent Validation

Incorrect ATS surveillance information provides hazardous and misleading information to air traffic controllers. An inability to validate ADS-B data reliably and independently that is being used for aircraft separation carries risks.

Validation is currently not a requirement of European Organization for Civil Aviation Equipment's (EUROCAE) standard ED-129B for ADS-B systems.²⁶ Yet it remains a desired feature of most ANSPs and is required by the FAA. Validation may become a de-facto standard once EUROCAE's composite ADS-B/Wide Area Multilateration (WAM) guidance is published.

²⁶ Technical Specification for a 1090 MHz Extended Squitter ADS-B Ground System, EUROCAE ED 129-C, European Organization for Civil Aviation Equipment, December 15, 2022.

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For terrestrial operations scenarios, validation can be done through comparison to radar, WAM, or other ATS surveillance sources. However, for transoceanic scenarios, this is not possible. Aireon is the only player to offer position validation independent of GPS, see Section 3.1.

5.4 ATS Surveillance and Resilience

Resilient space-based ATS surveillance systems can be relied upon when ADS-B information is needed most. ATS surveillance control information is most important when there is heavy air traffic and greater potential for interference. This is when signals become difficult to process.

ATS surveillance systems must be resilient to meet high confidence level requirements. Space systems are composed of many elements. Each element adds a potential for failure. Hardware in space is especially unique in that it cannot be fixed or replaced directly.

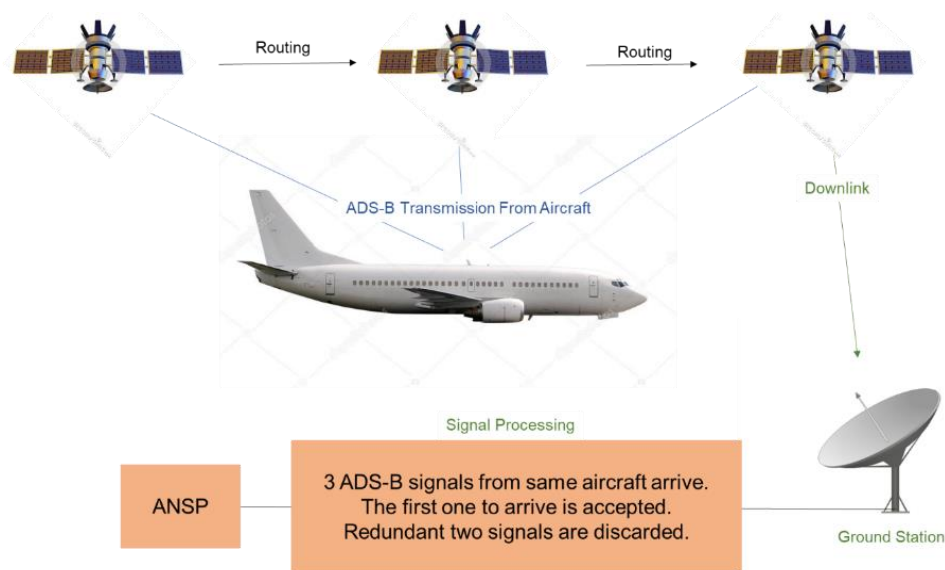


Figure 5-1 Space-based ADS-B parallel signal architecture.

The foundation for resilience of an ATS surveillance space-based ADS-B is based upon three communication system design elements:

- **Parallel Signal Processing Architecture, Figure 5-1** - Processing the same aircraft signal through multiple paths, simultaneously, ensures that if one signal is lost, another one will get through.
- **Overlapping Coverage, Figure 3-3** - Highly overlapping coverage provides the most parallel signals from the same aircraft.
- **On-orbit Bandwidth** – Processing multiple signals from the same aircraft requires significant bandwidth. Resources are most expensive in space and take time to build and replace. A space-based ADS-B system must have adequate bandwidth to process multiple signals from the same aircraft.

Redundancy - All ground elements of the space-based ADS-B surveillance service provider must be redundant. Some space-based ADS-B ground elements may be critical bottlenecks where data is processed. These items must be redundant because a failure could take down the system worldwide.

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Hardware failures in space are always a primary concern, since access to on-orbit assets is extremely challenging. On-orbit spare satellites should be maintained so that satellite failures can be addressed in days rather than years. Satellite single point failures should be minimized. The ability to absorb hardware failures and computer upsets should be designed in each satellite. Also, at a constellation level, there should be capability to absorb failures through multiple data links and coverage overlap. Single string designs should be avoided.

Controllers should know when a system element has failed. Failure of an element may not be visible and/or impact performance because a redundant element may be exercised. When a system element has failed but performance is not compromised, the controller should be notified that the system is “degraded.”

Long Gap – Space-based ATS surveillance systems must meet Long Gap needs to be practical.

ATS surveillance data feeds into a comprehensive air traffic control system. Space-based ADS-B may be one of several systems an air traffic controller may use. Assume a case where space-based ADS-B is the only system that can provide specific ATS surveillance. If the signal is not received within the 8-second requirement, air traffic control software goes into “coast” mode. This is called the “Long Gap.” Coast mode continues for 24 seconds. After 24 seconds, coast mode stops and controller action is required.

Missing the Long Gap time interval adds significant work load to air traffic controllers. If too much action is required, the controller will be overloaded. The space-based system would likely become unusable if an aircraft position did not get reported within 24 seconds on a regular basis.

ATS surveillance space-based systems must be resilient so that the Long Gap can be avoided. Long Gap is not applicable for Aircraft tracking applications.

5.5 Regulatory

Regulatory approvals for ATS surveillance systems are unique and difficult to achieve. Whereas, the regulatory aspects of aircraft tracking systems are more typical of those encountered by communications satellite operators.

Establishing a safety case for a space-based system is challenging because ANSPs will apply the heritage ground-based safety case process to space-based systems. Successfully establishing a safety case for a space-based ATS surveillance system requires all system elements to be sustainable and operate at high Availability, Section 6.2. The safety case must validate that the system can meet demanding performance objectives such as:

- capacity,
- safety,
- environment,
- cost-effectiveness,
- efficiency,
- flexibility,
- predictability,
- security,
- access,
- equity,
- participation, and
- interoperability.

5.5.1 Congested and Protected Spectrum

The general trend towards “anytime, anywhere” connectivity through 5G, mobile communications, the Internet of Things (IoT), smart cities, connected cars, is driving the need for more spectrum, which has finite capacity limits. The aviation spectrum is attractive to telecommunication service providers and it is reasonable to expect that competition will intensify in the future.

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SESAR²⁷ notes that it is not surprising that the exclusive aeronautical and navigation band 960-1215 MHz is under increasing pressure to allow channel sharing with non-aviation services. Potential new entrants may not be compatible with incumbent aeronautical applications. Under these circumstances, there is always risk of “uncontrollable service degradations or outright denial of service to the aviation application, including Mode S radar, multilateration and ADS-B.”²⁸ Aviation advocates must focus on maintaining spectrum protection. This situation makes getting new approvals for safety-of-life spectrum protection that much more difficult.

5.5.2 Timely Spectrum Coordination

The International Telecommunication Union (ITU), a specialized agency of the United Nations, is responsible for maintaining international regulation of telecommunications and spectrum matters. Spectrum regulation is defined in the Radio Regulations, a multi-lateral treaty updated about every four years by a World Radiocommunication Conference (WRC). Separately, aviation focused ICAO meetings are traditionally held in preparation, to develop positions on the various WRC agenda items. Aviation representatives attend the WRC as observers, and their influence is limited where they do not participate on the delegations of the Member States. Even here, the influence of the aviation community might be limited if Member States have other competing priorities, such as International Mobile Telecommunications (IMT).

The ITU recognizes ADS-B surveillance systems provide a safety-of-life service, and consequently spectrum is granted protection from other radio systems interfering with their frequency band.³ Despite the increasing competition for spectrum and a crowded agenda at previous WRCs, aeronautical spectrum has enjoyed, for many years, “safety-of-life” spectrum protection. Regional ICAO offices oversee frequency aviation assignments.

As a space-based ADS-B surveillance provider, Aireon has obtained international spectrum assignments in the aeronautical safety-of-flight bands^{29, 30}. This protection also covers all Aireon intersatellite link frequencies as well as all uplink and downlink frequencies to ground-based gateways. This includes command and control.

Inmarsat and Iridium are the only other operators that have obtained similar protections. An important distinction is made by regulators between ATS surveillance and Aircraft tracking; Aircraft tracking systems do not require the same precision as ATS surveillance and thus may not be granted the same level of protection of spectrum. Existing spectrum protection ensures Inmarsat’s and Iridium’s networks will benefit from a degree of interference protection not offered to other Aircraft tracking provider entrants.

Aireon, Inmarsat, and Iridium are in better position than those service providers who are seeking to obtain safety-of-flight spectrum assignments, and must either demonstrate protection of the existing networks or seek new allocations and wait to get on the crowded WRC agenda. The WRC meets only about once every four years, and typically, the meeting agenda has been set at the previous WRC. In practice, it can take up to ten years to get safety-of-life allocation, except in rare circumstances.

²⁷ SESAR 3, Joint Undertaking, Multi-Annual Work Program, 2022 to 2031, published 2022.

²⁸ SESAR Deployment Manager; “ADS-B and Other Means of Surveillance Implementation Status;” May 15, 2018.

²⁹ Mobile Satellite Communications Markets: Dynamics and Trends, Ramesh Gupta, Dan Swearingen, pp 171 – 196, Springer International Publishing Switzerland 2017.

³⁰ International Telecommunications Union Protects Spectrum to Operate Space-Based ADS-B, Aireon LLC, Press Release, November 12, 2015.

6.0 Performance Requirements

ADS-B was originally introduced during the mid-90's and relies upon GPS for aircraft positions and velocity and ground-based stations for relaying information to ANSPs. ADS-B represents a major change in ATS surveillance philosophy:

- instead of using ground-based radar to interrogate aircraft and determine their positions,
- each aircraft will use GPS to determine with high accuracy its own position and
- then automatically report it in real time.

ADS-B space-based ATS performance requirements are generally derived from ground-based system requirements. This approach sets a high bar.

6.1 Aircraft ADS-B Transmission Out

There are multiple ADS-B aircraft equipage types. We focus on the lowest power transmitters as they are the most challenging to receive in space. The 125-Watt ADS-B signals drive the overall design of the space-based ADS-B receiver. Modification to aircraft equipage is undesirable. Space-based ADS-B systems should attempt to be compatible with aircraft equipage.

6.2 ATS Surveillance Availability

The overall ATS surveillance system Availability calculation considers four elements as discussed in Section 2.1, Figure 2-1. The calculation assumes all four elements are in series. The ICAO requires ATS surveillance systems maintain an Availability greater than 99.9 % (or 0.999).

When we assume typical Availability values for the ground segment, it allows us to bound the space segment Availability:

- The ADS-B Receiver must effectively be ≈ 99.95 Availability.
- The Data Transport element must also be ≈ 99.95 Availability.

If one of the space segment elements is slightly lower than 99.95 then the other must be higher to meet the target threshold value of 99.9%. If the Availability is significantly lower for either of the space segment elements, the system will not meet the ICAO 99.9% system Availability requirement.

99.95% data transport Availability is a high bar for any space system to meet. Data transport for a space-based system is the most difficult aspect for meeting Availability requirements. Data transport Availability is the Availability of the data delivery path from the space receiver to the ANSP customer, Section 2.1.

The transmission of data from space to ground must be performed with the highest reliability possible. Due to weather concerns for some sites, parallel sites can provide additional coverage to prevent outages.

Data transport Availability is best calculated using Monte Carlo numerical methods.

6.3 Latency

The flow of ADS-B data through the various system elements is shown in Figure 6-1.

- ADS-B signals are time stamped at the aircraft.
- The signals will be received at the satellite and processed as discussed in Section 7.2.
- The data is then transmitted to a ground station.
- The ground station receives the signals and processes them.
- After processing, the data is driven through a terrestrial network to a data center.

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- The data center subsequently processes the data and distributes ADS-B data through a terrestrial network to the final ANSP customer. Signals will be time stamped prior to delivery. The time stamps can be compared to calculate latency.

The space-based ADS-B Latency metric from aircraft to ANSP is expected to be less than 1.5 seconds at 99% confidence³¹.

- The Latency calculation will not be impacted due to bad or blocked aircraft transmitters. If the signal is not received at the satellite, it cannot be stamped or counted.
- High interference and or high traffic do not impact Latency. The signal is stamped when it is received. If it is not received, it cannot be stamped or counted.

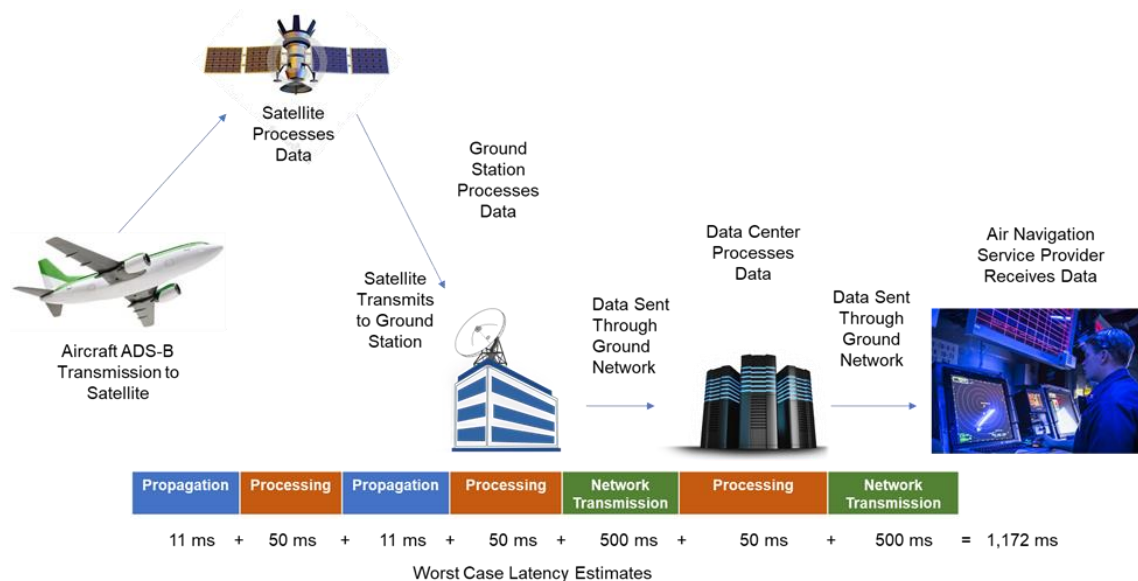


Figure 6-1 Space-based ADS-B system tasks that create latency.

ADS-B signals are transmitted once every half second. If one satellite is blocked, an overlapping coverage satellite may have an opportunity to pick up that signal. If there is no overlapping coverage, another transmission from the aircraft will occur one half second later. If the median confidence level Latency is a fraction of a second, there is still an opportunity for the following signal to be received in the 2-second window.

Signal propagation latency from the aircraft to the LEO satellite and from the LEO satellite to the ground station is very small, approximately 11 ms for each, or 22 ms total, Figure 6-1.

Signal processing causes latency. Each time a signal is processed one can expect about 50 ms of delay. Processing on the satellite and twice on the ground, see orange steps in Figure 6-1, can add about 150 ms delay.

Signal routing on an intersatellite linked LEO system adds a step not shown in Figure 6-1. Depending on the number of “hops,” intersatellite transfers can be as much as 250 ms.

³¹ Latency ≤ 2.0 s (99th percentile) in accordance with the EUROCONTROL Safety & Performance Requirements Document for a Generic Surveillance System Support Air Traffic Control Services (GEN-SUR SPR VOLUME 1) as set forth in Section 3.7.3.1.5 (ATC SUR Processing + SUR Distribute) – See SPR 9 and Table 33.

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Transferring data between ground sites will cause delay – adding approximately a 0.5 second latency for one transfer in the worst case.

Worst case values for all latency elements cannot simply be added since it is unlikely that all elements will be worst case at the same moment in time. However, these values do sum to less than 2 seconds even when including an additional 250 ms for constellation intersatellite links, if applicable.

Although LEO ADS-B systems can meet the 2 second Latency requirement at a stringent 99% confidence level, Latency must be carefully considered for the overall space system design as there are many elements and each one can erode latency margin.

6.4 Coverage

ANSPs have unique service volumes. Each unique ANSP service volume is specified by a unique ANSP document, the “Service Volume Description Document.” Each service volume is defined by a set of map tiles contained in a polygon and an altitude floor and ceiling. A tile area is defined as one-degree longitude by one-degree latitude, Figure 6-2. This description is derived from legacy ground-based radar systems. It provides tolerance so that a limited number of ground radar sites can fail and the system still be considered operational.

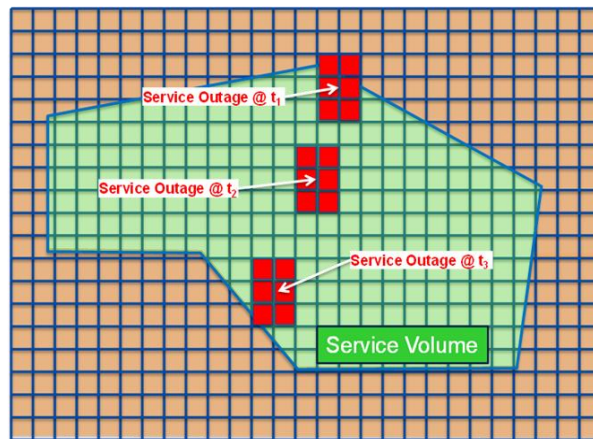


Figure 6-2 Example ANSP airspace Service Volume segmented in tiles with service outage zones.

Coverage outages, due to holes in the satellite constellation, are highly deterministic. The satellite operator can calculate exactly where and when ANSP coverage outages occur. The specific ANSP tiles that are not covered along with the exact corresponding time step can be provided. The calculation process can be specified in ADS-B Provider/ANSP agreements.

The overall ANSP Service Volume is a summation of all tiles for each time step. Coverage will be classified based on the corresponding number of covered tiles divided by the total number of tiles in an ANSP’s Service Volume.

$$\text{Coverage Availability \%} = \frac{\text{Tiles Covered per Time Step}}{\text{Total ANSP Tiles}} \times 100$$

Service level requirements may vary between ANSPs. Expected Availability requirements are:

- $100\% \leq \text{Tile Coverage} > 90\%$ = Running
- $90\% \leq \text{Tile Coverage} > 80\%$ = Degraded
- $80\% \leq \text{Tile Coverage}$ = Failed

6.5 Probability of Update (PoU)

PoU is the time between aircraft position updates. ADS-B messages must be logged to measure PoU. The EUROCAE technical specification for ADS-B surveillance is a UI of less than

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or equal to 8 seconds at over 96% confidence.³² Achieving this is the most challenging aspect of space-based ADS-B as discussed in Section 2.1.5.

The system must be capable of receiving signals from small planes with 125-Watt transmitters, flying in crowded airspace. It is these challenging environments where the most difficult 4% (100% - 96%) of the data determines compliance or noncompliance. ADS-B tracking systems have much less stringent requirements.

7.0 Infrastructure Equipment

Figure 7-1 illustrates the high-level architecture of an ADS-B LEO intersatellite link constellation. Space-based ADS-B systems require space and ground segments, including a Data Operations Center where signals are processed prior to customer delivery. Signal processing can occur at several locations or at a single point in the system.

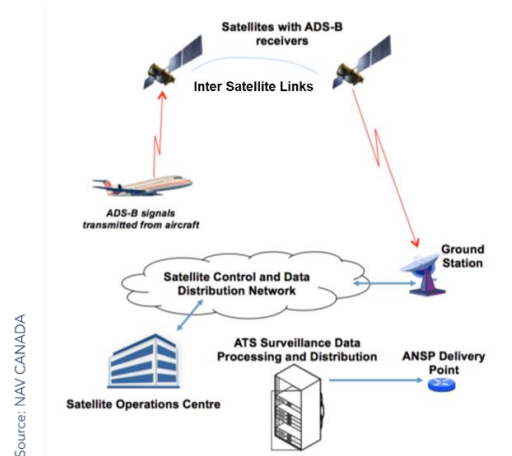


Figure 7-1 Space-based ADS-B system elements.

7.1 Aircraft Equipage

Modern aircraft have several antennas for navigation, radar, and communications purposes. The antenna location on the aircraft is important. The free space antenna pattern can be degraded due to aircraft mounting location. Aircraft fuselage mounted antennas can be adversely impacted by back radiation lobes. Masking effects from the plane's wings and the tail can degrade performance. It would be advantageous to develop a single low-profile antenna shared by various ATM communications as well as systems such as GNSS, VHF, other SatComs (Inmarsat and Iridium), Distance Measuring Equipment (DME), TCAS and ADS-B. However, blending different systems together does present integration challenges.

ADS-B has been implemented around the world. ADS-B is the air traffic management backbone. Aircraft equipage requirements have been levied and operators have incurred sunk costs.

It is unlikely that ADS-B equipage requirements will be modified in the near term. Any practical space-based ADS-B system should be compatible with current types of aircraft ADS-B equipage.

An ADS-B surveillance system must have the ability to receive signals using the lowest allowed aircraft transmitter power, which is 125-Watt. This is challenging for ADS-B space-based surveillance providers.

Compatibility with existing aircraft equipage is a drawback for Inmarsat and Iridium communications and tracking systems, see Section 3.8 and 3.9. Both companies actively pursue efforts to integrate their equipment into higher-level aircraft equipage offerings. For example, the Future Air Navigation System (FANS) aircraft avionics system allows a direct data

³² EUROCAE Technical Specification for a 1090 MHz Extended Squitter ADS-B Ground System, ED-129B; Revision B, as set forth in Section 3.3.1.1 [Probability of Update (PU) Requirement – See REQ 17 and Table 3, Row #1, March 1, 2016.

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communication link between the pilot and the Air Traffic Controller leveraging Inmarsat and Iridium.³³

7.2 ADS-B Satellite Receiver

The heart of a space-based ADS-B system is the receiver in space. An antenna receiver must be mounted on a satellite platform. The receiver must be powered and data from the antenna must be transmitted back to earth in a reliable manner.

ADS-B receivers are comprised of elements – each involving some type of antenna, i.e., patch antenna or helix. Each antenna element has a specific field of view, or beam. ADS-B receiver element beams become saturated with aircraft ADS-B signals as traffic increases.³⁴

For ATS surveillance applications, the ADS-B satellite receiver antenna design objective is to maximize the probability of ADS-B signal detection over the largest possible airspace. The challenge for an ADS-B service provider is to accomplish this with the lowest equipment mass and lowest power usage.

Dynamic Beam Forming - ATS surveillance receivers must use multiple antenna elements. Multi-element antennas produce receiving beams that can be manipulated throughout the orbit. The chance of meeting PoU performance requirements increases with the number of aircraft signals received. The number of aircraft signals received is often proportional to the amount of airspace a given beam covers.

For example, if a single beam were to center on JFK airport at a peak traffic time, the beam would become saturated. Little to no ADS-B data would be obtained. However, if several overlapping beams were to each cover part of the airspace around JFK, a high percentage of data could be successfully obtained. Coordinated operation of multiple beams allows for successful crowded airspace ATS surveillance.

Advanced ADS-B receivers have dynamic beam forming that adapts beam patterns to achieve the highest PoU possible. This requires sophisticated hardware and software to coordinate operation of multiple beams.

Signal Processing – The 1090 MHz frequency is crowded. Several applications share this frequency including heritage Mode S radar and the aircraft collision avoidance TCAS system. Incomplete or garbled ADS-B signals are often received in space. These signals cannot be thrown out when working to high ATS surveillance confidence requirements. Signals can be quickly reconstructed using standard error correction techniques. It is advantageous to perform error correction on-orbit. This requires on-orbit data processing capability.

Large Field of View – Multiple elements with dynamic beam forming and on-board signal processing enable a large field of view. This minimizes the number of satellites required. The best case would be for a satellite ADS-B antenna to be capable of receiving aircraft signals from the earth's horizon to horizon (from the receiver's point of view in space). A large field of view allows for greater satellite to satellite coverage overlap. Coverage overlap provides an additional opportunity to capture the same ADS-B signal. This increases data confidence and enhances system resilience.

³³ ICAO initiated the Special Committee on Future Air Navigation Systems in 1983.

³⁴ Recommendations for Limiting Mode S Replies, R1, Michael Garcia, Andy Hoag and John Dolan, Aireon, RTCA Combined Surveillance Committee Meeting #08, WP08-29_C-R1, Miami, FL, January 22 – 26, 2018.

7.2.1 Aircraft tracking ADS-B Receivers

Meeting ADS-B tracking requirements is much less difficult than ADS-B surveillance, see Table 2-1. Some CubeSat aircraft tracking concepts use a single ADS-B receiver antenna element. Simple helix antennas and patch antenna elements have been used³⁵. Single elements have a small field of view compared to an ADS surveillance antenna such as Aireon with 80 beams. Single beam antennas can easily be saturated in and around high-traffic airspace. The operator has little control to resolve saturation and interference issues. These simple, low cost, antennas may support an ADS-B tracking mission where limited numbers aircraft position updates are required every several minutes. However, they cannot reliably be used for ADS surveillance applications.

7.3 Satellite Platform

The satellite bus must provide power to operate the ADS-B receiver, process the data (in some systems) and either transmit the data to the ground or route the data to another satellite. Satellite platform requirements for ADS-B surveillance versus ADS-B tracking are different. A first order satellite platform discussion is provided below.

Data Connectivity – Data from the ADS-B payload must be delivered reliably to the ground. ADS-B surveillance receivers will deliver between about 100 kbps to 1000 kbps depending on air traffic density. Whereas ADS-B tracking payloads deliver about 50 kbps to 100 kbps of data. ADS surveillance requirements demand that the ADS-B payload be connected essentially all the time with high reliability data links. Data connectivity requirements for Aircraft tracking are much less stringent than ADS surveillance. Gaps in data connectivity can be tolerated for Aircraft tracking applications.

Data transport for ADS surveillance applications is about 10X that of Aircraft tracking. Connectivity for ADS surveillance applications must be on 100% of the time, whereas Aircraft tracking connectivity can be sporadic. Data transport hardware requires power. The per satellite power requirements for the data transport hardware are in the hundreds of Watts for surveillance applications. Whereas the satellite power for data transport Aircraft tracking missions is much smaller, around 50 Watts or less.

Packet Loss – Stringent performance requirements make packet loss a concern for ADS surveillance. Packet loss occurs when data packets transmitted over a network fail to reach their intended destination. This can occur in ground-based networks or space-based networks because of: network congestion, system element performance bottle necks, software issues and faulty hardware.

Packet loss can be significant for LEO intersatellite link systems because the link hardware must operate within tight tolerances and in unison with complex software.

While satellite packet loss will be localized, packet loss due to the ground segment elements can impact the entire system, quickly degrading system performance. To avoid packet loss, high quality space components should be used along with rigorous software validation.

Radiation Induced Single Event Upsets (SEUs) – Satellites fly without the protection of the earth's atmosphere. Consequently, they are not shielded from harmful radiation which impacts and degrades the performance of electronic components among other things. Prolonged exposure to radiation can cause semiconductor electronics to fail.

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Radiation exposure throughout a satellite's life will upset computers. Single Event Upsets (SEUs) typically require a computer reboot. The shut down and reboot time intervals can impact Availability.

Satellites smaller in size are more vulnerable to radiation because they have less shielding mass. The orbit altitude also strongly influences radiation exposure levels. Commercial-Off-The-Shelf (COTS) electronics may be more vulnerable than military grade electronics. COTS electronics performance and life should be known before these devices are used for spaceflight.

Satellite designers understand SEUs and have specifications for SEU downtime. The impact of SEUs on system Availability can be calculated based on the satellite design Mean Time between Failure and Mean Time to Recovery estimates from the satellite bus manufacturer. Downtime must be considered for a given ANSP service volume. Multiple satellites could provide overlapping coverage. In this case, a given ANSP service volume may not be impacted if one satellite goes down. The space system in total must be considered to fully assess SEU impact.

Power - ADS-B surveillance receivers, as discussed in Section 7.2, use a significant amount of electrical power. ADS-B surveillance receivers must be powered on nearly 100% of the time. A satellite power lapse can result in a double impact to both the ADS-B Receiver and Data Transport Availability. This will quickly degrade Availability performance.

A space-based ADS-B receiver, capable of supporting ATS surveillance, can be expected to use between 50 to 100 Watts of orbit average electrical power. The power is used for beam forming, signal amplification, processing, error correction and more. This can be compared to simple Aircraft tracking helix and single patch antenna receivers used on various CubeSats that require around 2 Watts of continuous orbit average power.

ADS-B receiver power needs vary with time. Power consumption is driven by the number of ADS-B signals received or air-traffic density. Peak power levels are expected to be about double orbit average levels. Also, the earth blocks the sun for a significant fraction of a LEO satellite orbit, requiring that LEO satellites produce extra power during the in-sun portion of the orbit to allow for operation in the night portion of the orbit. Batteries are required to store energy. Also, additional emergency reserve power must be maintained. If a satellite has no power, it could be lost.

Mass and Size – ATS surveillance multi-beam payloads are around 50 cm by 50 cm and about 30 cm in height. Mass of an ADS-B surveillance payload is expected to be around 50 to 75 kgs. This can be contrasted with CubeSat ADS-B tracking payloads of about 10 cm by 10 cm and only a few cm in height, approximately 2 kgs in mass.

A comparison of satellite size and mass, relative to key ADS-B, is provided in Table 7-1. Large and Medium size satellites are currently the only platforms capable of supporting ADS-B surveillance. CubeSats are limited to Aircraft tracking. Smallsats currently cannot provide ATS surveillance level performance.

Pointing – Pointing requirements for ADS-B missions, either Aircraft tracking or ATS surveillance, are on the same order of a typical telecom mission. SmallSat and CubeSat buses may have difficulty meeting ADS-B mission pointing requirements. If a receiver beam cannot be steered electronically, the attitude of the satellite may need constant adjustment. Beam pointing is required to avoid saturation over and around high aircraft traffic regions.

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SmallSat technology is developing. SmallSats may be capable of supporting ADS-B surveillance missions in the future. Currently, SmallSats are limited to Aircraft tracking performance using state-of-the-art technology.

Satellite Size	Mass (kg)	Satellite Mission Architecture	Relative ADS-B Points
Large	>1000	Can support high-performance communications, high power for multi-purpose missions. GEO stand alone, MEO and LEO constellations with intersatellite links or bent-pipe. High fidelity attitude control. Long satellite life.	ATS Surveillance Performance -Multi-beam ADS-B receiver, large airspace coverage per satellite, on-orbit processing, continuous data transport, high Availability satellite bus, high pointing accuracy.
Medium	100 to 1000	MEO and LEO high performance communications, high power for multi-purpose missions, constellations either bent-pipe or intersatellite link. High fidelity attitude control. Long satellite life.	
SmallSat	20 to 100	Limited power to support focused missions. Limited high-data rate capability via LEO bent-pipe or LEO intersatellite link constellations. High fidelity attitude control. Long to medium satellite life.	Aircraft tracking Performance – Multi-beam ADS-B receiver, limited airspace coverage per satellite, limited on-orbit processing, non-continuous data transport, medium Availability satellite bus, high pointing accuracy possible.
CubeSat	1 to 20	Limited resources for payload mass, power, and communications. Low data rate capability via either LEO bent-pipe or LEO intersatellite links. Limited attitude control performance. Medium to short satellite life. No propulsion systems. Cannot maintain formation for ISL. Cannot maintain optimal spacing requiring more satellites.	Aircraft tracking Performance - Single beam ADS-B receiver, small airspace coverage per satellite, no on-orbit processing, non-continuous data transport, low Availability satellite bus, pointing accuracy could be marginal based on satellite equipment and requirements.

Table 7-1 High-level satellite comparison description based on size and mass.

7.4 Constellation Systems including Ground Network

Aircraft equipage drives the satellite design link budget and defines on-orbit antenna receiver requirements.

LEO Constellation with Intersatellite Links – LEO satellite constellations with intersatellite links provide the optimal space-based ADS-B system architecture. However, these systems are costly and require substantial satellites. We estimate the standalone mass of a dedicated ADS-B surveillance satellite with intersatellite links to be around 150 kgs. Intersatellite links eliminate the need for direct downlinks from each satellite to ground-based infrastructure. This allows for global operation and coverage of remote areas, including oceans.

For Aircraft tracking applications, low Availability and CubeSat type, intersatellite links may work. If this architecture can be successfully implemented, it could allow for a small satellite constellation to provide ADS-B tracking quality global coverage. Low Availability intersatellite links would not meet ATS surveillance systems requirements, see Section 2.1.

LEO Constellation Bent-pipe - LEO bent-pipe concepts require remote ground stations near where service is provided. This makes providing service over remote areas difficult, expensive, and sometimes impractical. Ground station connectivity, power, and regulatory hurdles can be problematic.

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A bent-pipe LEO system with powerful steerable downlink antennas could yield a feasible ATS surveillance quality system and reduce the number of ground stations needed. A Globalstar or OneWeb type of system for example would require between 40 to 50 ground stations for total global coverage. However, for a standalone ADS-B constellation, such a concept would require a satellite mass of approximately 150 kgs. While a functional LEO bent-pipe ADS-B system is possible, the cost of the satellites, as well as the ground network, will be significant.

CubeSats cannot support powerful and steerable downlink antennas. As a result, CubeSat bent-pipe constellation architecture is impractical because many ground station sites would be required for global ADS-B surveillance. The increased ground segment expense may outweigh the CubeSat satellite and launch cost savings.

Also, these systems could not operate over remote areas unless data were stored on-orbit until a downlink was available. “Storing forward” and then downloading significantly reduces performance.

GEO and MEO Constellations - Higher orbiting satellites, such as GEO or Medium Earth Orbit (MEO), could provide space-based ADS-B with fewer satellites than a LEO constellation. Higher altitude satellites can connect with ground stations in convenient locations while still being capable of provide coverage over remote regions.

However, signal strength drops by two or three orders of magnitude at MEO and GEO. These systems would require multiple, complex, and expensive satellites. The ADS-B antenna size at GEO would be over 30 meters in diameter. Substantial signal processing and sophisticated beam forming would also need to be developed to sort and process the many overlapping aircraft signals. GEO and MEO space-based systems that receive ADS-B aircraft transmitted signals are technically possible but not practical.

8.0 Future Market Evolution and Summary

The global air traffic management system will continue to expand to serve this growing demand. ANSP's should closely monitor and assess space-based ATS offerings and evolving spaced-based air traffic services. It is plausible that market participants find an appropriate level of cooperation or competition. The right balance could increase overall market size and allow each participant to thrive.

8.1 Alternate Communication Paths

Could various market and technology trends “disrupt” the space-based ADS-B status quo, including:

- Alternate communication paths,
- New broadband and avionics equipment,
- Crowd sourced global flight data providers, or
- Spire's MLAT research, see Section 3.3?

However, disruptive ATSS would require a long-term vision, implementation time (i.e., a decade) and significant investment. High barriers to entry include:

- Deploying and operating a satellite constellation of SmallSat to Medium class satellites, Table 7-1,
- Obtaining safety-of-life regulatory approval and
- Integrating services into aircraft avionics, if not compatible with ADS-B Out equipage.

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Aircraft ATS communications and tracking services could complement current ADS-B service offering. Future market outcomes will depend upon how providers integrate communication paths to provide a larger ATM service offering. Providers can cooperate or compete. Players providing the same service can erode each other's market share.

New communication paths could involve a variety of scenarios – including combinations of:

- ADS-B aircraft signal to satellite
- VHF-UHF communications to satellite
- Ku-band, Ka-band or L-band aircraft signal to satellite communications
- Aircraft to aircraft and eventually down to a ground station.

Several new entrants seek to offer both VHF-UHF cockpit communications as well as ADS-B surveillance ATS services from a single satellite constellation, such as Skykraft, Starticle and Head, see Section 3.0. The dual-mission concept has merit but requires a constellation composed of Medium to Large class satellites as shown in Table 7-1. Claims that this dual-mission can be achieved with Small or CubeSats are not credible.

8.2 Broadband in Cockpit and Cabin through New Avionics Equipment

In the future, new avionics systems could be introduced into the addressable aviation market which could disrupt the current incumbents. Mandates to modify aircraft equipage have significant impact on operators. However, with a long-term vision, satellite enabled ATM could be gradually introduced into the aircraft market as avionics upgrades are implemented.

LEO satellite broadband networks promise to deliver low latency, global coverage, and gigabit speeds to users across the globe. Over 20,000 new satellites have been proposed to enter service in the next five years. The majority of these are designed for low earth orbit. Not all proposed LEO constellation satellites will make it to orbit. Instead, a much smaller group now enjoys first mover advantage that allow them to capture market share. This will discourage other potential market entrants.

8.3 Crowd Sourced Flight Situational Awareness

FlightAware and Flightradar24 offer global Aircraft tracking of flight data through product offerings which combine ground based and satellite fed data to provide global ADS-B coverage and “gate-to-gate” visibility of flight routes. This crowd sourced data currently does not offer ATS surveillance level performance. Flight data integrator companies aggregate terabytes of flight data from a variety of sources including crowdsourced and licensed data. Both FlightAware and Flightradar24 offer transponder kits to “AvGeeks” and hobbyists who work to expand global coverage. Collaborations have emerged between various players in the ADS-B value chain. Market providers of crowd sourced flight data typically target a different customer base than ATS providers. These product offerings are more likely to be synergistic rather than competitive.

Flight data providers continue to expand the addressable market, rather than reduce it. Their participation is invoking “Metcalfe’s Law” which posits that in social networks, the greater number of users of a service, the more valuable the service becomes to the community.

8.4 Competition and Cooperation Summary

Only Aireon offers ATS surveillance performance to meet PoU, Latency, and safety-of-life protection requirements.³⁶ Aireon enjoys “first mover” advantage with global coverage. Aireon

³⁶ “Satellite-Based ADS-B for Lower Separation Minima Application;” Multi-Source Report funded by SALSA (Satellite Based ADS-B for Lower Separation- Minima Application); Ref. Ares 2017 – 5713855, November 22, 2017.

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has over 60% of the World's oceanic traffic market. Aireon enjoys the barriers to entry discussed in Section 1.3. Aireon has ATS surveillance-as-a-service contracts in place with many ANSPs.

Aireon will continue to gain surveillance market share with ANSPs that cover remote regions as they have no competition. Aireon will also gain ANSP customers where interoperability with neighboring ANSPs is important. Also, the space-based service is less expensive than building ground-based traditional infrastructure for some ANSPs.

As Aireon moves forward providing global ATS surveillance there will be an increasing need for remote-region communications between the aircraft and controllers. Aireon is narrowly focused on receiving ADS-B signals and providing ATS surveillance. Only Inmarsat and Iridium currently have the regulatory approval to provide ATS communications that complete the remote region ATM picture.

Iridium and Inmarsat will continue to compete. The two companies will continue to find innovative ways to integrate their communications equipment on various aircraft. Inmarsat can bring more focused and higher data capacity than Iridium. Iridium has advantages with respect to smaller antennas and lower latency. Both will likely compete based on coverage and price.

Skykraft (Section 3.5) Starticle (Section 3.7) and HEAD (Section 3.6) are proposing CubeSat/Small satellite constellations for a dual ADS-B surveillance and ATS VHF-UHF communications network. These systems as proposed would disrupt the space-based aviation market. However, these systems as proposed will not work, Section 2.0 and Section 3.0. CubeSats and Small satellites are not capable of providing one of the functions as discussed; they cannot support a dual-mission. The concepts are not credible.

The dual-mission concept is feasible with Medium or Large class satellites, Table 7-1. Designing, building, and deploying this system will take at least several years and will cost billions of dollars. Existing players become more established with time. By the time this system could be deployed, current players will be firmly entrenched.

Spire has stalled. They are not expanding their constellation above 110 active satellites. Spire will never offer ADS-B surveillance or ATS communications with CubeSats. However, the company has done remarkably well. Spire's focus on data fusion has yielded valuable, non ATS, products that provide benefits to aircraft operators and others. Spire will continue to bring new data fusion products to aircraft operators. As of 2023 Spire appears to be focused on the maritime market. The maritime market is a better application of the CubeSat constellation's capabilities versus aviation.

CubeSat entrants will always be constrained. The CubeSat bus and payload will limit capabilities to Aircraft tracking. CubeSat systems will never provide real-time ATS surveillance quality data. CubeSat system Availability, Latency and Probability of Update (PoU) performance cannot meet ATS surveillance requirement levels. These new market entrants will likely erode market share of existing flight Aircraft tracking solutions and cannot compete in the ATS surveillance market.

While new entrants might introduce competition, it is equally plausible that market participants find an appropriate level of cooperation. The right balance could increase overall market size and allow each participant to thrive. Cooperation could be further encouraged by interoperability and a "systems of systems" approach – leveraging multi-source and multi-path systems. The goal is a system of systems seamless global air traffic service, which includes several space-

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based sources and paths. This will increase safety, efficiency and predictability over both congested areas and provide a global ATS capable of serving remote regions and a larger number of stakeholders.

9.0 Acronyms

Acronym	Expanded
AAI	Airports Authority of India
ADS-B	Automatic Dependent Surveillance—Broadcast
ADS-C	Automatic Dependent Surveillance-Contract
AIS	Aeronautical Information Services
AIM	Aeronautical Information Management
AM	Aerial Maritime Limited
AMS(R)S	Aeronautical Mobile-Satellite (Route) Service
AM(R)S	Aeronautical Mobile (Route) Service
ANSP	Air Navigation Service Provider
APD	Aireon Processing and Distribution hub
ASECNA	Agency for Aerial Navigation Safety in Africa and Madagascar
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATNS	Air Traffic and Navigation Service Company
ATS	Air Traffic Service
CAAS	Civil Aviation Authority of Singapore
CANSO	Civil Air Navigation Services Organization
CNS	Communications, Navigation and Surveillance
COCESNA	Corporación Centroamericana de Servicios de Navegación Aérea
CPDLC	Controller–Pilot Data Link Communications
DC-ANSP	Dutch Caribbean Air Navigation Service Provider
DME	Distance Measuring Equipment
EASA	European Union Aviation Safety Agency
ENAV	Ente Nazionale Assistenza al Volo
EUROCAE	European Organization for Civil Aviation Equipment
FAA	United States Federal Aviation Administration
FIR	Flight Information Region
GADSS	Global Aeronautical Distress and Safety System
GEN-SUR	Eurocontrol Generic Surveillance
GEO	Geosynchronous Orbit
GN	Ground Network
GNSS	Global Navigation Satellite System
GPS	Global Positioning System

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Acronym	Expanded
GS	Ground Segment
HA	High Availability
HPOC	Hosted Payload Operations Center
I&E	Infrastructure and Equipment
I&T	Integration and Test
IA	Information Assurance
IAA	Irish Aviation Authority
ICAO	International Civil Aviation Organization
ISAVIA	Icelandic Civil Aviation Administration
ITU	International Telecommunications Union
Ka	Ka-band frequency
Kbps	kilobits per second
Ku	Ku-band frequency
LEO	Low Earth Orbit
MEO	Mid Earth Orbit
MET	Meteorological service for air navigation
MLAT	Multilateration
MTTF	Mean Time to Failure
MTTR	Mean Time To Repair
NATS	United Kingdom National Air Traffic Services
PANS ATM	Procedures for Navigation Services – Air Traffic Management
PNGASL	Papua New Guinea Air Services Limited
PoU	Probability of Detection
RF	Radio Frequency
SAR	Search And Rescue
SBASS	Satellite-based Augmentation System
SCAA	Seychelles Civil Aviation Authority
TCAS	Traffic Collision Avoidance System
VHF	Very High Frequency
WAM	Wide Area Multilateration