ICAO

Study on the convenience and feasibility of space-based ADS-B for regional implementation

2018

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Prologue

According to Project RLA 06/901 - Assistance for the implementation of a regional ATM system based on the ATM operational concept and the corresponding technological support for communications, navigation, and surveillance (CNS)- and in accordance with the framework of its activities approved during the Eleventh Meeting of the Coordination Committee (RCC/11) held in Lima, Peru on October 5, 2017, it was considered necessary to prepare a study to analyze the convenience and feasibility of adopting spaced-based ADS-B services at a regional level within the framework of the action plan for the implementation of surveillance, multilateration and ADS systems in the Region.

For this purpose, the General Directorate of Civil Aviation of Ecuador was asked to support the efforts of CNS Specialist, Mr. Ivan Salas Garzón, for the preparation of this study during a mission held in Lima, Peru from April 23 to 27 of this year, after a preliminary study was prepared and presented at the SAM/IG/21 Meeting, held in Lima from May 21 to 25, 2018. The Implementation Group approved the preliminary study and requested that the States provide more information for the conclusion of the same. In this sense, the CNS Specialist was entrusted with the completion of the study during the week of September 24 to 28, 2018, which was effectively fulfilled and the product is this document.

Executive summary

Purpose of the study

The purpose of this study is to determine the effectiveness of space-based ADS-B services, to fulfill the requirements of air traffic control operations in upper and lower routes, in the South American Region (SAM), and its potential implementation and use at the regional level.

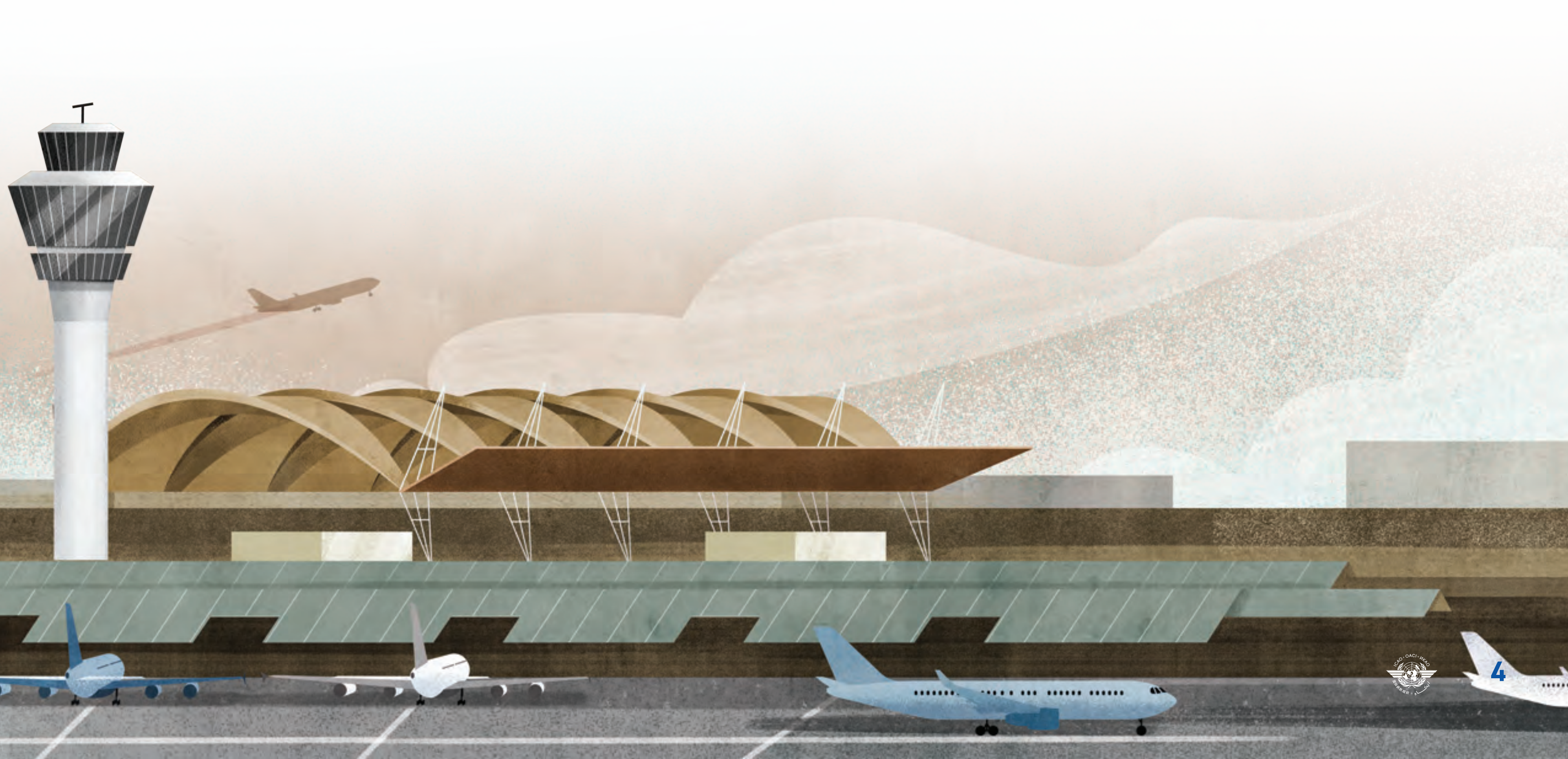
The characteristics of the region, with practically all States having remote or inaccessible areas, whether oceanic, with extensive forests or mountains, point towards the potential use of this technology for aeronautical surveillance, which will be operating as of 2019.

This study supplements a series of documents prepared for the region on ADS-B implementation in accordance to the Global Air Navigation Plan (GANP) and the ASBU methodology such as the Surveillance Strategy for CAR/SAM Regions and the Guide on technical and operational considerations for the implementation of ADS-B in the SAM Region.

About the study

This study begins with an introduction to the essential aspects of aerial surveillance, to then continue with the following topics:

- A review of basic ADS-B and space-based ADS-B concepts, indicating the fundamental differences between both.
- An overview of surveillance technologies present in the ICAO Global Air Navigation Plan (GANP) and current capabilities of surveillance sensors in the SAM Region.
- Analysis of the technical and economic aspects of space-based ADS-B service, compared with the capacities in the region, for its potential use.
- Surveillance coverage in the SAM region to meet operational requirements for air traffic control in upper and lower routes.
- An analysis of potential implementation at the regional level of the space-based ADS-B for the use of the SAM-states.
- Conclusions and recommendations



What is ADS-B?

ADS-B (Automatic Dependent Surveillance-Broadcast), is a surveillance technology that provides the Air Traffic Control (ATC) with a more accurate and precise image of the three-dimensional position of the aircraft during its en-route operation, approach, terminal or surface.

For this purpose, the aircraft transmits its identification, position, altitude, speed, and other information, and this transmission is received by ADS-B ground stations and routed to the control center, to be later visualized on the controller's screen, similar to the trace that is obtained from secondary radar.

ADS-B system delivers the information it receives from the aircraft, through communication circuits, to the air traffic control center (ATC), so that it observes, separates and directs the aircraft more accurately and more efficiently, in the coverage area of the facility used. On the other hand, it should be noted that these surveillance services are now being used in areas where currently there isn't or there is very little radar coverage, backup of radar surveillance systems. It is even known that some Air Navigation Service Providers wish to deactivate radar sites in some areas, to save costs associated with maintaining those systems and reduce dependence on the conventional radar.

This technology also has the potential to provide situational awareness to pilots through ADS-B and other future applications, improving current and future support conditions for these users.

Use of ADS-B for air control surveillance activities

All Aeronautical Administrations of the SAM Region have an Air Navigation Service Provider (ANSP) in the flight information regions (FIR), under their responsibility. These contain many areas with road services and many more areas of approach; therefore, they always require an essential process of surveillance management as part of a strategy based on the effectiveness of the systems that support this management.

The scope of the surveillance service is defined in a general way in the following diagram presented in Figure 1.

In the diagram presented, note that the ADS-B sensor installed on the ground (ground-based) appears and it's related to surveillance activities, in addition to its contribution to the control of air traffic.

Figure 1: Types of surveillance sensors

Introduction

Currently, solutions for aeronautical surveillance have significantly evolved as there are tools that allow air traffic controllers to visualize the space assigned to their responsibility and occupation. Some technologies make surveillance possible in challenging environments, and there are solutions in place that make air traffic control: more accurate, safe and efficient.

Consequently, on land, air traffic controllers ensure that those hundred aircrafts fly safely and achieve certain efficiency, with the fundamental support of modern technologies for air traffic management.

Regarding surveillance, the Global Air Navigation Plan (GANP) reflects on a set of technologies that are/will be available for use in air traffic control. The objective is the standardized implementation of solutions, respecting regional characteristics and priorities to achieve high levels of efficiency and operational safety.

It is always possible to read or hear that some solutions are better than others; the truth is that there is not necessarily a single solution for everyone. One of them could provide exceptional results in a multiplex approach area, but it could become less effective in a mountainous area. It may even be discovered that the only way to achieve optimal results, is through a combination of technologies for surveillance.

Thus, it may be assumed that it is better to study a surveillance solution that adapts to every environment, and to current and projected traffic as well as financial budget. A solution that can satisfy the traffic flows of the future, while fulfilling at the same time its requirements for greater safety, efficiency and lower costs.

For the above purpose and reviewing the global surveillance landscape, there are the collaborative systems, including independent ones, and several ways to combine them, but, considering the nature of this study, we will focus on ADS-B and its alternative reception of ADS messages through a satellite, as will be explained below.

First of all, the concepts of the ADS-B are briefly reviewed, since there is the Guide on technical and operational considerations for the implementation of ADS-B in the SAM Region, to then complement it with the concept of the space-based ADS-B technology, as a basis for the study of feasibility and convenience in its application in the SAM Region.

The following table describes the details of the most significant ADS-B advantages over sensors such as secondary radar.

ADS-B most significant advantages

- Acquisition, installation and operation costs of an ADS-B station are the lowest compared to other surveillance systems.
- There are minimum infrastructure requirements, because the equipment can be installed in a very simple infrastructure. However, the installation of ADS-B sensors in existing infrastructures does not give the necessary redundancy in case of problems of electrical power supply and / or security that compromises the aforementioned site.
- High position accuracy (accuracy given by the Global Positioning System - GPS or similar).
- High update rate (1 second).
- The report of each position is transmitted with an indication of the integrity associated with the data: users can determine with which applications the data can be compatible.
- Immune to multi-path.
- Low latency
- In general, very low cost in its life cycle.
- It is feasible to use it for surveillance of aircraft and land vehicles.
- It is possible to have a data link, air to ground.
- Intent available (level altitude, next waypoint, etc.).
- If the advantages mention more precision and more precise traffic control, the advantages of operational safety and efficiency in the operation increase and generate greater fuel savings and less environmental impact.

The following table shows some more visible disadvantages of ADS-B.

ADS-B most visible disadvantages

- Within the airspace defined by the Air Navigation Service Provider, it requires that the aircraft be equipped with a transponder that has the ability to broadcast an extended squitter in S mode.
- To determine the position and speed of the aircraft, it is based exclusively on the GNSS (global navigation satellite system). The position of the aircraft is determined on board and does not have a validation with ground-based systems.
- The ionospheric effects around the line of ground-based equator that could affect the GNSS.
- The fleet of aircraft operating in the SAM Region does not have a homogeneous avionics, so some flights with ES capacity (extended squitter) transmit messages in version 0 and others in 1 or 2.

Also, for the implementation of ADS-B, some challenges can be considered, such as:

- There is a cost associated with acquiring the transponders needed to power the ADS-B on land, in particular, for general aviation if it uses airspace where the use of the ADS-B transponder is mandatory. General aviation, in many cases, does not yet have FMC / FMS equipment necessary for data processing.
- Many centers where air traffic can be visualized, do not have ASTERIX data processing capacity in its different versions, or with processing and data fusion by the technical recommendations for the SAM Region.

Introduction to the services known as space-based ADS-B (ADS-B Sat)

The general diagram of operation under two modalities is reflected in Figures 2 and 3.

According to Figure 2, note that the ADS-B receiver is located somewhere on the ground and the message from the aircraft requires a line of sight to reach that receiver. This means that there is a significant dependence on the orography and altitude of the aircraft to achieve full coverage within the range of the equipment.

In Figure 3, the ADS-B signal will always be a line of sight towards the low-orbit satellite; therefore, it does not have a dependence on the orography and altitude of the aircraft to receive the message. The fundamental difference between the ground-based ADS-B and the space-based ADS-B is the way in which the data, disseminated by the avionics of the aircraft, is then transmitted to the air traffic control centers.

Figure 2: Conventional ADS-B

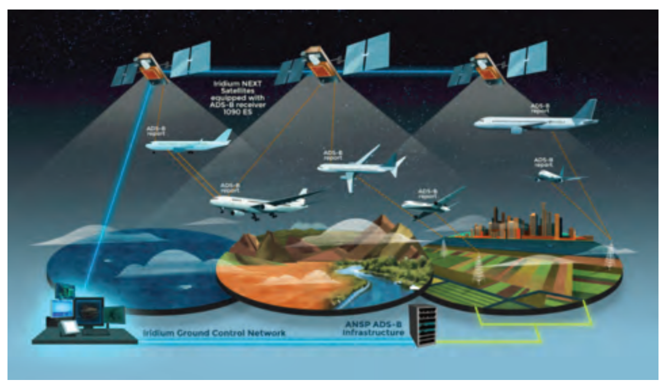


Figure 3: Space-Based ADS-B

Under the traditional system, the ADS-B message broadcast by the aircraft can be received directly by the receiving equipment on the ground, within the previously established technical scope. This equipment is located in a strategic site, to obtain the maximum possible coverage by a line of sight, and then the ADS-B message will be channeled through telecommunications networks and delivered to the end user.	Through the satellite system, ADS-B messages are broadcast by the aircraft can be received directly by a constellation of satellites at low altitude, processed in a data center and then be channeled through telecommunications networks and delivered to the end user.

The difference is significant regarding coverage because while a ground-based receiver has natural or artificial obstacles in its environment, which usually limits its coverage, particularly at low altitudes, a satellite does not have that limitation and could reach 100% coverage even at low altitudes. This is a significant advantage for locating an aircraft at any time and place.

We note the above expressed, especially in large tracts of land and mountain areas, by the range in distance of the equipment and the obstacles by a line of sight, respectively.

It is then confirmed that space-based ADS-B, has no coverage problems in any case, either by reach or orography, as stated. This is the main advantage over one or more ground-based ADS-B receivers.

The data received by the ground-based ADS-B receiver is the same as that collected by the space-based ADS-B system. In general terms, it means that we will have the same information by any means utilized. There's no difference.

Space-based ADS-B data would reach the end users by an external telecommunications provider, which is not part of the ANSP, so the latency time may increase, which must be observed permanently.

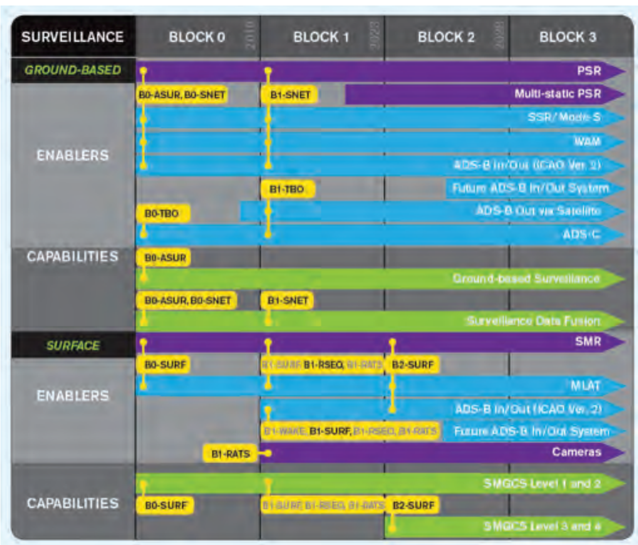
The space-based ADS-B system can receive and process ADS-B signals received in three standards: RTCA/DO-260; RTCA/DO-260A; and RTCA/DO-260B. These standards correspond, respectively, to Version 0, 1 and 2, constants of ICAO Document 9871, which represents another advantage over ground-based ADS-B sensors.

References

GANP and PBIP

The Global Air Navigation Plan (GANP) contemplates some concepts and times, in the subject of surveillance, which are summarized in the following chart:

Figure 4: Surveillance in the ASBU



In the GANP diagram, note that ADS-B systems are envisaged as support (enablers) in two modalities, ground-based ADS-B and space-based ADS-B. The first one is already in Block 0 and the second one is considered from 2018 onwards in the same Block. It is then concluded that both types of service modalities are already part of the GANP.

In the SAM Region, the planning of the surveillance systems is found in the SAM Regional Performance-Based Air Navigation Implementation Plan (PBIP Version 1.5 of November 2017). This document considers the regional planning of air navigation systems for the period 2017 to 2023.

By focusing solely on the space-based ADS-B service, it is also possible to observe what is expected to be achieved in general terms: “Better air traffic synchronization and the initial phase of the trajectory-based operation – TBO.”

B1 – TBO Better traffic synchronization and initial phase of the trajectory-based operation	
Improvements in traffic flow synchronization at *en-route* integration points and optimization of the approach sequence through the use of 4DTRAD and airport applications. For example, D-TAXI.	
Applicability	
Effective synchronization of the facilities on board and on the ground is necessary to derive appreciable benefits, in particular for those who are equipped. The benefits increase with the number of aircraft equipped in the area where the services are provided.	
Benefits	
Effective synchronization of the facilities on board and on the ground is necessary to derive appreciable benefits, in particular for those who are equipped. The benefits increase with the number of aircraft equipped in the area where the services are provided.	
Capacity	Positive effect due to the reduction in workload related to the establishment of the sequence near the convergence point and other tactical interventions. Positive effect due to the reduction of the workload related to the authorizations of exit and taxiing on the runway.
Efficiency	It increases when using the required arrival time capacity (RTA) of the aircraft, to plan the synchronization of traffic through the airspace en route and towards the terminal airspace. The "closed loop" operations in RNAV procedures ensure that the systems on board and on land have a common vision of the evolution of traffic and facilitate its optimization. The efficiency of the flights increases by means of the previous planning of the beginning of the descent, the profile of descent and the measures of delay in route, as well as a greater efficiency of the routes in the terminal airspace.
Environment	More economic and ecological routes, in particular, absorption of some delays.
Operational safety	Increased operational safety at airports and their surroundings by reducing misunderstandings and misinterpretation of complex exit authorizations and on the taxiway.
Predictability	Greater predictability of the ATM system for all stakeholders through a more strategic management of the flow of traffic within the *en route* and terminal airspace of the FIRs, applying the RTA capacity or the control of the speed of the aircraft to achieve a CTA on the ground. Predictable and reproducible sequencing and measurement. "Closed loop" operations in RNAV procedures, ensuring that on-board and on-shore systems have a common vision of the evolution of traffic.
Cost	The establishment of the profitability analysis is in progress. The benefits of the airport services proposed have already been demonstrated in the CASCADE program of EUROCONTROL.

The GANP also indicates what the trends are in what applies to surveillance, as presented in the following table.

Surveillance

The important trends of the next 20 years will be the following:

a) Different techniques will be combined to obtain the best cost-benefit ratio according to local limitations;

b) Cooperative surveillance will be based on existing technologies using 1030/1090 MHz RF bands (SSR, Mode S, WAM and ADS-B =

c) While capacity improvements can be determined, it is anticipated that the planned surveillance infrastructure will be able to satisfy all the demands imposed on them;

d) The on-board part of the surveillance system will become more important and should serve the future with global interoperability for the various surveillance techniques that will be used;

e) Increase the use of downlink aircraft parameters with the following advantages:

f) The functionality will pass from ground to air.

1) Clear presentation of the call sign and the level;

2) Better awareness of the situation;

3) Use of some aircraft parameters by downlink (DAP) and altitude reporting with 25-foot intervals to improve radar tracking algorithms;

4) Presentation of lists of vertical piles;

5) Reduction of radio transmission (controller and pilot);

6) Better management of aircraft in stacks; Y

7) Reductions in the level outputs.

As it may be observed, ICAO, in general, takes into account the service of ADS-B sensors with ground equipment and also the variable for the acquisition of data through low-orbit satellites. Also, it provides several recommendations in this regard evidenced clearly in the GANP and, at the regional level, in the PBIP.

Recommendations of the Industry

Last, as part of the analysis premises, some recommendations indicated by the industry are taken as a reference, as shown in the tables below:

Whatever the geographical difficulties or level of traffic, ANSPs should have the most adequate surveillance capacity	The global surveillance solutions provider has to assist clients to define the best solution to meet their needs
• First, they should focus on the needs and not the products. • A complete vision of safety and protection of air space, from land to en route, should be considered. • Los efectos ionosféricos alrededor de la línea del ecuador terrestre que podrían afectar al GNSS. • The ionospheric effects around the equator line that could affect the GNSS. • Excellence in performance and cost efficiency is mandatory through an optimized solution • Validation tools and a proven simulation of multiple sensors, specially designed, help to optimize the design of the system	• Definition of the desired surveillance coverage. • Identification of limitations related to the site: Complicated coverage and ground restrictions/ Space filling. • Identification of operational restrictions: accessibility of sites, existing systems, limited communications.
Modeling the surveillance infrastructure to cover new routes	**The optimization of the global surveillance system is based on several evaluations**
• Several criteria must be taken into account in order to provide the optimal solution, such as operational requirements, average and maximum traffic density, budget (current and future), environment (land, propagation ...), as well as security and protection objectives.	• Performance indicators (probability of detection / correct identification, location accuracy). • Costs (acquisition of equipment, operations, maintenance). • External footprint (spectral occupation, environmental impact).

Global surveillance systems are an efficient way to combine several technologies, and to distribute among the surveillance layers a part of the load of the "auxiliaries" such as	Frequently PSR and SSR are installed in a joint installation. Also alternative technologies could be implemented in an integrated infrastructure
• Infrastructure (Tower, antenna, etc.). • Energy sources (feeding sources, etc.). • Communication links	• The integration of an ADS-B receiver in an SSR. • The integration of an ADS-B capacity in a WAM station. • The integration of a PSR station and an ADS-B + WAM in a common system.

As the "coverage" parameter is the most significant difference in the two ways of recovering the ADS-B signal emitted by a transponder with this capacity, this document will analyze the coverage in conventional and satellite modalities, since the final product must be transparent for air traffic control. For this reason, coverage graphs will be prepared by a line of sight with data available at the date of preparation of this document and which will be used as a baseline. However, other important parameters such as service availability and latency will also be analyzed.

Analysis of the surveillance capacity in the SAM region

Based on the information contained in the CAR/SAM Regional Plan - Volume II, 2015, an analysis of the surveillance capacity in the region will be based on a total of installed systems that add up to 190 surveillance sensors.

The coverage capacity of the systems is plotted by the software called "radio-mobile" that draws the scope by a line of sight. However, not all systems of the Region are available because of their location coordinates.

Parameters to define the performance of sensors for surveillance

Performance Modeling. In the context of the performance-based approach, the objective of modeling is not to explain how the air navigation system works in terms of data streams, messages, etc., but to build models of ATM performance that help understand, quantitatively or qualitatively, cause-effect relationships between performance variables, showing how individual performance objectives can be achieved and how they interact (improve or interfere) with each other. (Doc. 9883 of ICAO).

From the above, and according to ISO 13236, the four elements considered for quality systems and related to surveillance systems are capacity, integrity, time and continuity of service.

I. Detection of all air operations in the airspace considered;

II. The integrity of surveillance information;

III. Opportunity for surveillance information in control centers; Y

IV. Continuity in time of detection of aircraft.

Support Metrics. They are used to determine the performance indicators. These values will be measured within each airspace and for each surveillance sensor, to then establish the statistics in the spaces that are covered by two or more sensors.

I. Coverage rate expressed in percentage of surveillance sensors in the airspace;

II. Percentage of valid responses of the avionics of the aircraft, with a verified position on the aircraft;

III. Time in seconds between the issuance of the surveillance response by the avionics and its reception in a surveillance center; Y

IV. Percentage of troubleshooting time that affects continuity.

Performance goals. Represent the values of performance indicators that must be met or exceeded to consider that a performance objective has been fully achieved.

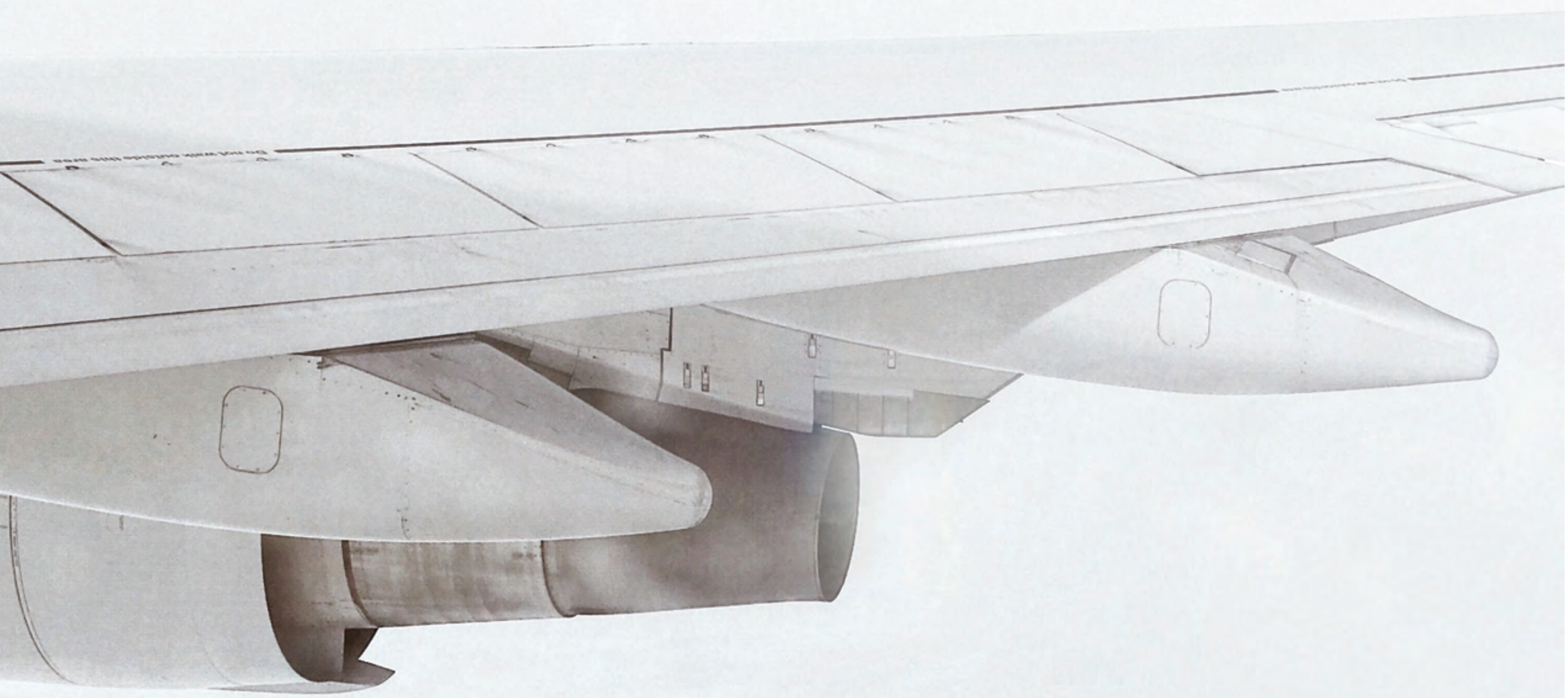
I. The coverage must be sufficient and adequate to detect an aircraft at all times in the operational airspace;

II. The valid emissions/receptions of ADS-B messages by avionics must be higher than 99% of the total number of aircraft emissions, with their position verified;

III. The latency will be 2 seconds of time or less, between the issuance of the surveillance response by the avionics and its reception in a surveillance center; and

IV. The average time to repair faults should not be more than 1 hour on the site if they occur. This last condition added to the fact that the service is supported by systems that do not fail before the 25,000 hours of service.

Then, the concepts described to this point are developed, which, together with the goals to be achieved, will contribute to determine the feasibility and convenience of using the service called Space-based ADS-B, object of this study.



Development of surveillance action parameters

Airspace coverage

With data taken from the CAR / SAM Air Navigation Plan, VOLUME II, 2015, on the capacity of the surveillance sensors (SSR's and ADS's) of the SAM countries and information provided by the States on ADS-B (April 2018), and geographic data of each State, a table with the number of ground-based SSR/ADS-B sensors, extension of the FIR and continental extension in each case is presented.

Based on the provided data, a ratio of how many km2 per SSR or ADS-B sensors is available in each State was calculated (the smaller the number of km2 the more there is coverage).

This division is necessary because naturally in the ocean area it is not feasible to place stations with radar sensors.

Based on the above, it is also essential to have data of the relationship between the extension of the FIR and the continental extension of each country.

No.	Country	SSR	Área(s) FIR (km²)	Area Continent (km²)	Relation FIR/Cont.	Coverage 10.000 feet	Coverage 15.000 feet	Coverage 25.000 feet
1	Argentina	25	17.908.074,62	2.792.573,00	6,41	12,37%	15,27%	18,58%
2	Bolivia	7	1.085.891,42	1.098.581,00	1	26,10%	40,85%	70,35%
3	Brazil	84	22.110.440,00	8.514.877,00	2,6	27,86%	35,01%	46,26%
4	Chile	11	10.038.771,54	756.102,00	13,28	8,96%	11,66%	17,55%
5	Colombia	15	1.648.431,14	1.141.748,00	1,44	37,37%	49,33%	77,73%
6	Ecuador	7	942.758,82	283.561,00	3,32	27,45%	45,74%	74,49%
7	French Gui.	-	1.383.199,17	83.534,00	16,56	n/a	n/a	n/a
8	Guyana	-	270.916,57	214.970,00	1,26	n/a	n/a	n/a
9	Panamá	3	621.464,86	74.177,00	8,38	33,70%	41,63%	59,48%
10	Paraguay	2	399.136,50	406.752,00	1	30,87%	40,39%	69,21%
11	Perú	8	3.564.434,95	1.285.216,00	2,77	13,14%	19,70%	43,21%
12	Suriname	-	262.126,10	163.820,00	1,6	n/a	n/a	n/a
13	Uruguay	2	2.326.000,97	176.215,00	13,2	3,18%	5,30%	7,43%
14	Venezuela	10	1.204.815,45	916.445,00	1,31	48,87%	65,23%	83,64%

No.	Country	ADS-B	Área(s) FIR (km^2)	Area Continent (km^2)	Relation FIR/Cont.	Coverage 10.000 feet	Coverage 15.000 feet	Coverage 25.000 feet
1	French Gui.	5	1.383.199,17	83.534,00	16,56	11,67%	15,34%	16,56%
2	Guyana	5	270.916,57	214.970,00	1,26	91,86%	96,90%	100,00%
3	Paraguay	6	399.136,50	406.752,00	1	92,61%	99,50%	100,00%

From the data obtained, for example Chile and Uruguay have a lot of ocean space in their FIRs in relation to their continental extension. This means that flight routes include large distances. However, Paraguay has only continental routes, and no long-distance routes. The table above describes the general geographical situation of the Region.

Referential measurement of surface

Unidad 1° x 1° = 12.321,00	12.321,00 km^2

Country	FIR Extension	Units
Argentina	17.908.074,62	1.453,46
Colombia	1.648.431,14	133,79
Ecuador	942.758,82	76,52
French Gui.	1.383.199,17	112,26

For this purpose, graphs have been taken that contain the limits of the FIRs and the routes present in them, to observe the coverage of the radar sensors. Ground-based ADS-B sensors are not taken into account in this activity.

For ease of presentation, the FIRs of Colombia-Panama, Ecuador-Peru, and Argentina-Chile are placed. With this, the oceanic part of the Pacific is also reviewed.

Colombia. Concerning the geographical extension of the FIR, it has 1 radar for every 110,000 km2 and 1 radar for every 76,000 km2 in its continental area, approximately. Also, note that it has an ocean area of 506,683 Km2 (FIR extension minus Continent extension) where it is not feasible to install surveillance sensors on its surface.

Panama. Concerning the geographical extension of the FIR, it has 1 radar for every 207,000 km2 and 1 radar for every 25,000 km2 in its continental area. Also, note that it has an ocean area of 547,287 km2 where it is not feasible to install surveillance sensors on its surface

For countries that have position data of surveillance sensors, the coverage areas are calculated, based on units of 1° x 1°. As examples, the units of square areas for Argentina, Colombia, Ecuador, and French Guiana are computed in the table below.

10.000 feet.
Colombia: 37,37% coverage;
Panamá: 33,70% coverage

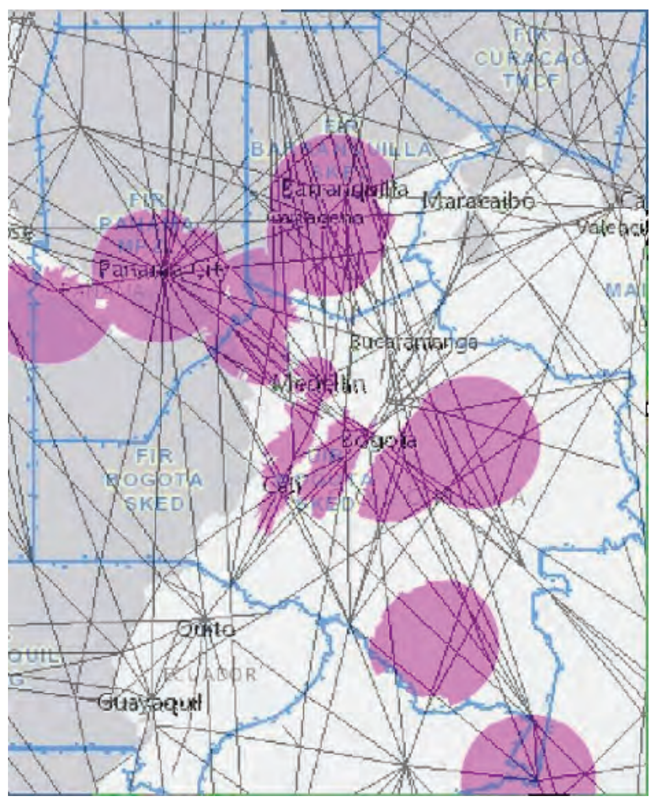


Gráfico 1: Colombia - Panamá 10.000 pies

15.000 feet
Colombia: 49,33% coverage;
Panamá: 41,63% coverage

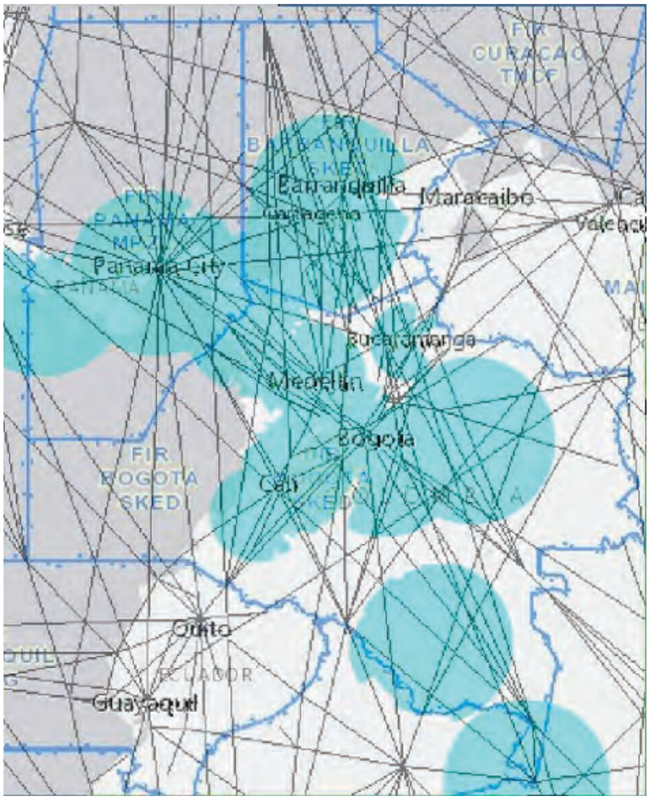


Gráfico 2: Colombia - Panamá 15.000 pies

25.000 feet.
Colombia: 77,73% coverage;
Panamá: 59,48% coverage

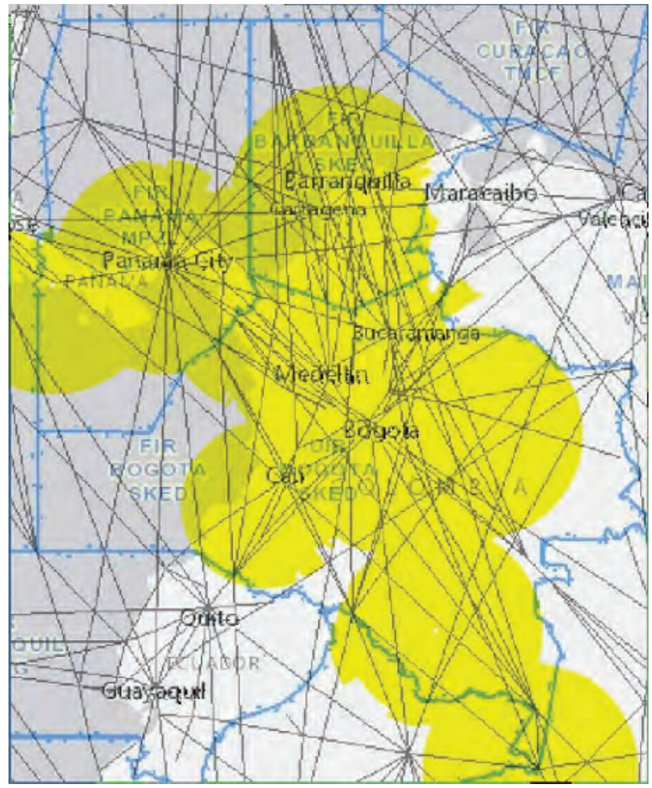


Gráfico 3: Colombia - Panamá 25.000 pies

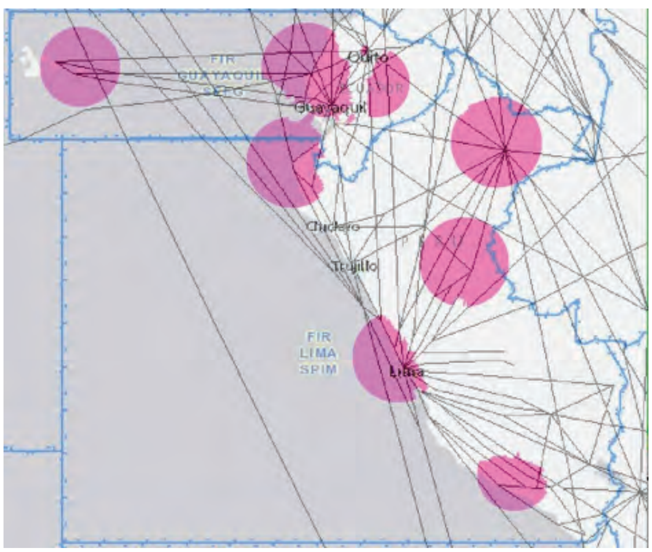
Remarks for Colombia	Remarks for Panama
• Low-altitude coverage (10,000 feet) is a little over one third of the FIR and continues to increase above the initial level, reaching up to approximately 80% at 25,000 feet. • As explained in the previous item, full coverage in the FIR cannot be achieved due to the irregular orography of the land and the existing oceanic space, in which no surveillance systems can be installed on its surface. • The country is located at the interface of the CAR / SAM Regions with great operational responsibility for the two regions. • There are important ocean operational areas that cannot be covered with ground-based sensors.	• Low-altitude coverage (10,000 feet) is the third part of the FIR and continues to increase above the initial level, reaching up to approximately 60% at 25,000 feet. • As explained in the previous paragraph, full coverage in the FIR cannot be achieved, mainly due to the existing oceanic space, in which sensors cannot be installed on its surface.

Then, we have the information from Ecuador with 7 SSR sensors and from Peru with 8 SSR sensors.

Ecuador. With reference to the geographical extension of the FIR, it has 1 radar for every 134,679 km2 and 1 radar for every 40,508 km2 in its continental area. Also, note that there is an ocean area of 659,197 km2 where it is not feasible to install surveillance sensors on its surface.

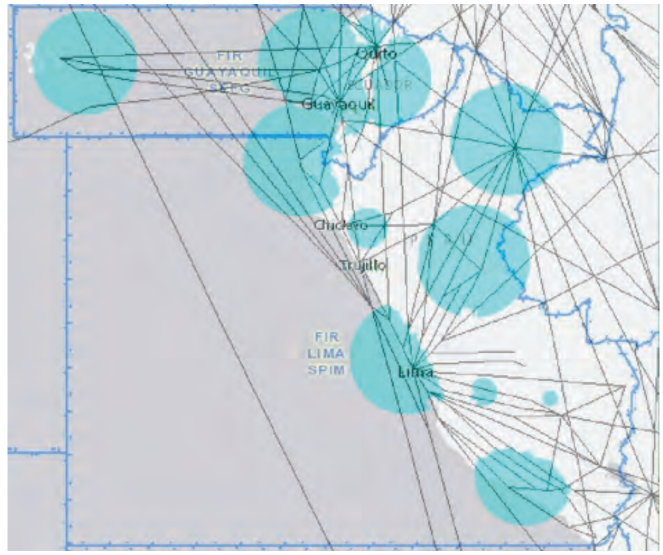
Peru. With reference to the geographical extension of the FIR, it has 1 radar for every 445,000 km2 and 1 radar for every 160,000 km2 in its continental area. Also, note that there is an oceanic area of 2,279,218 km2 where it is not feasible to install surveillance sensors on its surface.

10.000 feet
Ecuador: 27,45% coverage;
Perú: 13,14% coverage



Graphic 4: Ecuador - Peru 10.000 feet

15.000 feet.
Ecuador: 45,74% de cobertura;
Perú: 19,70% de cobertura



Graphic 5: Ecuador - Peru 15.000 feet

25.000 feet
Ecuador: 74,49% coverage;
Peru: 43,21% coverage

Graphic 6: Ecuador – Peru 25.000 feet

Remarks for Ecuador

- Low-altitude coverage (10,000 feet) is almost a quarter of the total FIR and continues to increase above the initial level, reaching up to approximately 75% at 25,000 feet.
- As explained in the previous item, full coverage in the FIR cannot be achieved due to the irregular orography of the land and the existing oceanic space, in which systems on its surface cannot be installed.
- The country is located at the interface of the CAR/SAM Regions with great operational responsibility for the two regions.
- There are important oceanic operational areas that cannot be covered with ground-based sensors.

Remarks for Peru

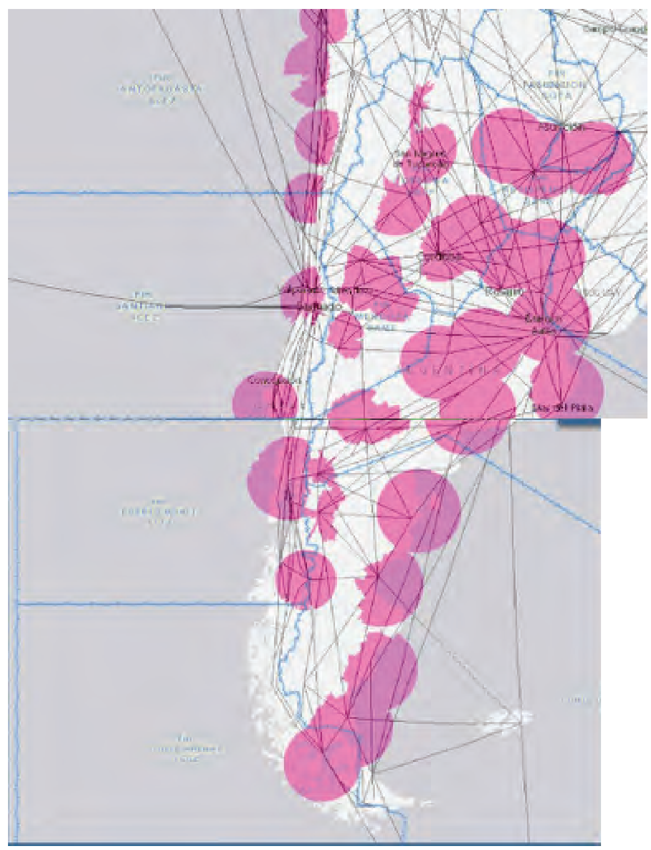
- Low-altitude coverage (10,000 feet) only reaches 13% of the total FIR. The resulting low value is explained by the large expanse of oceanic space that is part of the Lima FIR. And although it continues to increase above the initial level, it reaches up to approximately 43%, at 25,000 feet, which is an important value considering its oceanic part.
- As explained in the previous item, full coverage in the FIR cannot be achieved due to the large existing oceanic space, in which systems cannot be installed on its surface, and because of the irregular orography of the land in smaller proportion.
- There are important oceanic operational areas that cannot be covered with ground-based sensors.

Finally, the information provided from Argentina with 27 SSR sensors and Chile with 11 SSR sensors is the following:

Argentina. With reference to the geographical extension of the total FIR, it has 1 radar for every 716,000 km2 and 1 radar for every 112,000 km2 in its continental area. Also, note that there is an oceanic area of 15,115,501 km2 where it is not feasible to install surveillance sensors on its surface. The ocean area in charge of Argentina is one of the largest areas in the SAM Region of the data available.

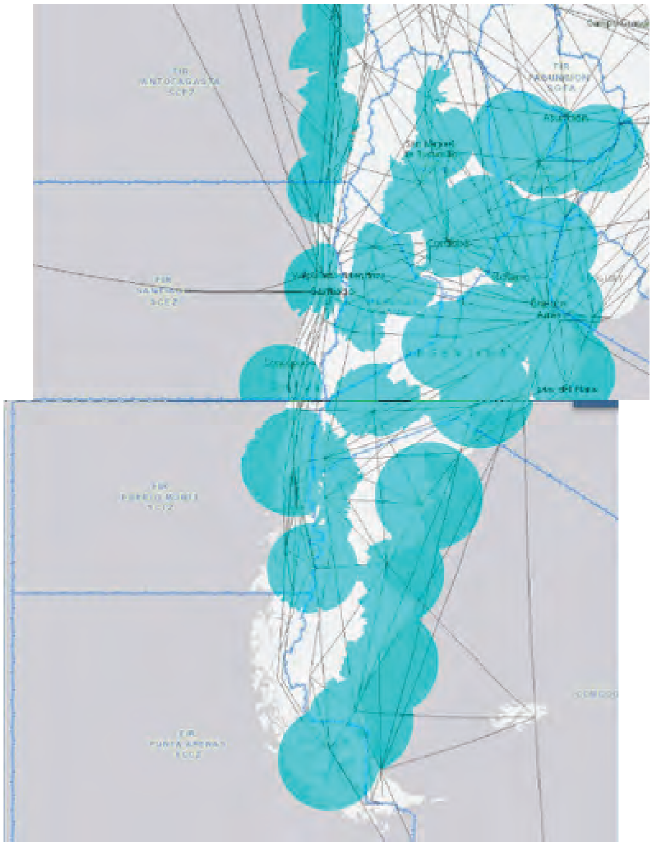
Chile. With reference to the geographical extension of the total FIR, it has 1 radar for every 912,000 km2 and 1 radar for every 68,000 km2 in its continental area. Also, note that there is an oceanic area of 9,282,669 km2 where it is not feasible to install surveillance sensors on its surface. The ocean area of Chile is also extensive, although smaller than that of Argentina.

10.000 feet
Argentina: 12,73% coverage;
Chile: 8,96% coverage



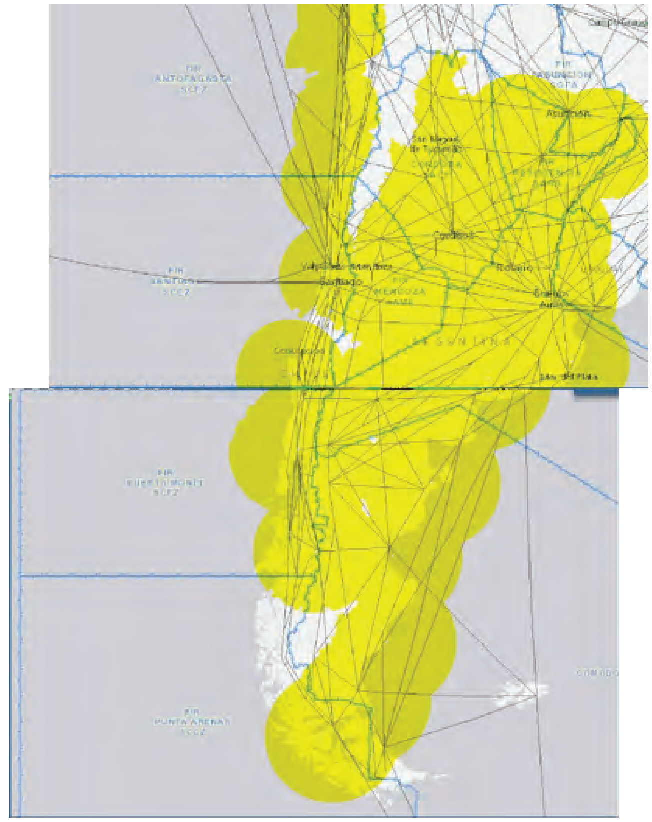
Graphic 7: Argentina - Chile 10.000 feet

15.000 feet
Argentina: 15, 27% coverage;
Chile: 11, 66% coverage



Graphic 8: Argentina - Chile 15.000 feet

25.000 feet.
Argentina: 18,58% coverage;
Chile: 17,55% coverage



Graphic 9: Argentina - Chile 25.000 feet

Remarks for Argentina

- Argentina. With reference to the geographical extension of the total FIR, it has 1 radar for every 716,000 km2, and 1 radar for every 112,000 km2 in its continental area. Also note that there is an oceanic area of 15,115,501 km2 where it is not feasible to install surveillance sensors on its surface. The ocean area in charge of Argentina is one of the largest areas in the SAM Region of the data available.
- Chile. With reference to the geographical extension of the total FIR, it has 1 radar for every 912,000 km2, and 1 radar for every 68,000 km2 in its continental area. Also note that there is an oceanic area of 9,282,669 km2 where it is not feasible to install surveillance sensors on its surface. The ocean area of Chile is also very large, although smaller than that of Argentina.

Remarks for Chile

- The coverage at low altitude (10,000 feet) is less than a tenth of the total FIR, despite the significant number of sensors, however, and like Argentina, it should not be forgotten that the coverage is on the FIRs of the whole country. The value continues to increase above the initial level, reaching up to 18% approximately, at 25,000 feet, which is still low, but consider the same reference for the percentage obtained.
- Due to what is stated in the previous item; it will not be possible to achieve significant coverage in the FIR due to the extensive existing oceanic space, in which systems on its surface cannot be installed.

The following tables present a summary of surveillance referential coverage - SAM Region

Secondary Radar

No.	Country	SSR	Area(s) FIR (km²)	Area Continent (km²)	Relation FIR/Cont.	Coverage 10.000 feet	Coverage 15.000 feet	Coverage 25.000 feet
1	Argentina	25	17.908.074,62	2.792.573,00	6,41	12,37%	15,27%	18,58%
2	Bolivia	7	1.085.891,42	1.098.581,00	1	26,10%	40,85%	70,35%
3	Brazil	84	22.110.440,00	8.514.877,00	2,6	27,86%	35,01%	46,26%
4	Chile	11	10.038.771,54	756.102,00	13,28	8,96%	11,66%	17,55%
5	Colombia	15	1.648.431,14	1.141.748,00	1,44	37,37%	49,33%	77,73%
6	Ecuador	7	942.758,82	283.561,00	3,32	27,45%	45,74%	74,49%
7	French Gui.	-	1.383.199,17	83.534,00	16,56	n/a	n/a	n/a
8	Guyana	-	270.916,57	214.970,00	1,26	n/a	n/a	n/a
9	Panamá	3	621.464,86	74.177,00	8,38	33,70%	41,63%	59,48%
10	Paraguay	2	399.136,50	406.752,00	1	30,87%	40,39%	69,21%
11	Perú	8	3.564.434,95	1.285.216,00	2,77	13,14%	19,70%	43,21%
12	Suriname	-	262.126,10	163.820,00	1,6	n/a	n/a	n/a
13	Uruguay	2	2.326.000,97	176.215,00	13,2	3,18%	5,30%	7,43%
14	Venezuela	10	1.204.815,45	916.445,00	1,31	48,87%	65,23%	83,64%

Ground-based ADS-B

No.	Country	ADS-B	Area(s) FIR (km²)	Area Continent (km²)	Relation FIR/Cont.	Coverage 10.000 feet	Coverage 15.000 feet	Coverage 25.000 feet
1	French Gui.	5	1.383.199,17	83.534,00	16,56	11,67%	15,34%	16,56%
2	Guyana	5	270.916,57	214.970,00	1,26	91,86%	96,90%	100,00%
3	Paraguay	6	399.136,50	406.752,00	1	92,61%	99,50%	100,00%

General remarks on coverage

In general, it can be concluded that the coverage with ground surveillance sensors is not enough, especially for levels below 15,000 feet. Air operations are executed at all flight levels, so it is ideal to have full coverage at all levels.

In oceanic spaces, it is obviously not feasible to install sensors for surveillance, so there would be no coverage except in the part of the ocean where the sensors are located on the coast or an island, and, even so, the curvature of the ocean should be considered. the land to have reached by the line of sight from that coastal shore or island.

There are countries such as Argentina, Uruguay, and Chile that apparently have low coverage for surveillance in their FIRs. However, the enormous expanse of oceanic space explains these low percentages. It is also the case of Peru to a lesser degree and other countries that have oceanic airspace.

All ground surveillance systems play an essential surveillance role, but the coverage they have is not enough in almost all places (not 100%) where they are installed, it almost does not exist in other areas and in the ocean part, it is not counted with them.

The integrity of the information

The integrity of the information in the surveillance messages is defined by three types of errors that could arise: errors in the central process, correlation of faults and spurious errors.

There are no data about the errors described, since, considering that the ADS-B messages, since they are transmitted by the aircraft, are received, processed and transported by AIREON until they are delivered to the user through data channels, they have no change in its content, this type of parameter will not be applied in the present study.

Reception times or latency

The reception time required by the current surveillance service, to visualize the traces of the aircraft and make decisions on the control of traffic in real time, is from “1” to “4” seconds, as the refresh rate, depending on the technical characteristics of the sensor used.

Secondary surveillance radar (4 seconds) –This type of sensor requires that amount of time to update its data in detection (interrogation / response) by the associated antenna movement. This radar system has been in force for many years as the primary surveillance sensor for air traffic control centers, both approach and route, and the service has been satisfactory at all times. Therefore, its latency is acceptable.

Multilateration (1 second) – This type of sensor reduces to 1 second the update time in obtaining the data of an aircraft for the purpose of surveillance services (and MLAT an alternative system to the SSR). Therefore, it is determined that this Latency time is very acceptable.

However, from the above, and due to the short, defined latency time, it must be taken into account that the support systems of the MLAT have processing times (position calculation) that could add something more to the amount of 1 second of latency, for this reason, 0.5 or 1 additional second must be considered to obtain a more real latency.

ADS-B – This type of sensor also reduces the update time for obtaining the surveillance data to 1 second. This sensor being more efficient than the previous two, and considering that the future trend is to use it in a massive way, it is presented as the form of surveillance with the highest application potential.

Service availability

The availability of the service is the quality or condition of available, that is, usable at the time it is required, however, and as all the support systems are not infallible in time within their normal operation, there are two statistical parameters that they indicate the behavior of those systems over time.

Average time to repair faults (MTTR)

The average time between failures or faults will be used to establish the time it takes a service provider, **on average**, to rehabilitate the service if it has been interrupted by any circumstance. The parameter is closely linked to the speed and proper training of the maintenance team, and it is also essential, to have logistic support and the adequate policy of acquisition and management of spare parts

The value of this parameter serves for the ANSP to take the primary contingency measures and prepare for the longer duration contingency measures, although these are the same in some cases. Average MTTR of an ADS-B = 20 min.; a system with several ADS-B = 30 min.

Continuity of the operation to maintain the visualization

Although the MTTR parameter exists and the monitoring centers usually work 24x7, it is fundamental to know what the average value is at the time that technical failures occur that interrupt the service, therefore, it is necessary to know the value of the Mean Time between Faults Criticism (MTBCF) adequate, mainly in relation to the installation infrastructure (air conditioning, energy, and grounding system). The average MTBCF of an ADS-B = 25,000 hours; system with several ADS-B = 20,000 hours.

Remarks to MTTR and MTBCF parameters

By combining the two parameters, the total availability of the ADS-B message path is obtained, since it is emitted in the transponder until it reaches the data consumption center. An acceptable value is **99.98%,** not counting scheduled interruptions.

Space-based ADS-B

AIREON, provider of the Space-based ADS-B service, is a company created from a joint project of Nav-Canada (Canada), ENAV (Italy), Naviair (Denmark), NATS (England) and the Irish Aviation Authority (Ireland)), which are Service Providers for Air Navigation (ANSP), and the company Iridium Communications, which provides satellite telecommunications services. Its website is www.aireon.com, where you can get more information about the company and its system.

The objective of its service is to provide a global surveillance capacity to the Service Providers for Air Navigation, including surveillance in areas with limited, or absence of aeronautical surveillance coverage. The AIREON Space-based ADS-B System receives, processes, filters, formats and validates the received ADS-B messages, to be delivered to the Service Providers for Air Navigation (ANSPs), for use in Air Traffic Control centers (ATC)), for purposes of air traffic control and separation of aircraft in the airspace.

A scheme of the service is presented in the Figure below, which also illustrates the way in which the subsystems come together to form the complete network of AIREON.

Figure 5. Space-based ADS-B system of Aireon

Aireon segments

The Space-based ADS-B system of AIREON is autonomous from the general ground surveillance infrastructure and is composed of two segments: the AIREON satellite segment and the AIREON ground segment.

Space-based segment

The satellite segment contains the hosted payload (HPL - from the English Hosted Payload). The HPL is located in each of 66 satellites of the Iridium NEXT constellation, distributed in six polar orbital planes and offers the capabilities to receive the ADS-B signal from aircraft in the airspace. The HPL receives, decodes and transfers ADS-B messages from aircraft to the ground segment of AIREON, through an interface and the primary payload of the Iridium NEXT system.

The data sent by means of the AIREON hosted payload to the primary load of the mission are routed through cross-links, connecting the 66 satellites and via downlink to a redundant dual Iridium teleport. Upon reaching the teleport, the downlink data is routed through a ground-based network to the ground segment. Unlike traditional surveillance data transmissions, AIREON recognizes the criticality of flight data security and encrypts the signal as soon as it is transmitted outside the aircraft.

Ground segment

The AIREON Ground segment is made up of the Payload Operations Center (HPOC) and the Processing and Distribution Department of AIREON (APD), with interfaces to the AIREON Headquarters (HQ). The HPOC provides all the necessary functions to monitor and control the AIREON hosted payload, including telemetry monitoring, fault recovery, and remote configuration. The HPOC processes data from / to the Iridium teleport network and manages the link bandwidth.

The HPOC operates primarily at the Operations Center of the Iridium Satellite Network (SNOC) located in northern Virginia, with a disaster recovery location at the Iridium technical service center in Chandler, Arizona (the TSC). The main responsibility of the SNOC is to manage the performance and state of the satellites individually. All Iridium SNOC personnel are also trained to operate the HPOC.

The APD provides full processing of ADS-B data, mission planning and payload functions (such as antenna and target programming) as well as data delivery and status to ANSPs. The APD functions include the acquisition of ADS-B objectives and the verification of duplicates, the generation of reports of each ANSP, the calculation, and storage of Technical Performance Measures (TPM) and the archiving of system data. The APD Network Operations Center (NOC) also provides the operator interface for system monitoring, control, and analysis. The APD is operated in Northern Virginia, with a disaster recovery location at the Iridium Technical Service Center (TSC) in Arizona.

The surveillance data link requirements worldwide vary between countries and regions (DO260 versions 0, 1, 2). The AIREON system can accept all ADS-B 1090 ES messages since all ADS-B messages have the same basic structure; the payload (HPL) of each satellite receives them in the same way they are sent. The APD handles the differences between the versions, according to the EUROCAE ED-129B standard.

The APD will deliver all processed data from ADS-B to the ATM system of each ANSP, through a Service Delivery Point (SDP). The SDP (Figure 7) is the demarcation point between the AIREON domain and the ATC automation platform of the ANSP (tracker). The SDP records the number of messages received in the ATM system of each ANSP to generate a report. This feedback loop also allows AIREON to monitor the performance of the Service Level Agreement with each ANSP. The SDP is composed of redundant COTS servers and routers that enable the connection of an ASTERIX data flow to the automation and monitoring system of each ANSP.

Space-based ADS-B and validating the aircraft position and location

A risk that needs to be overcome in any ADS-B system is the ability to verify the quality of the data that is delivered. Incorrect or misleading surveillance information provides dangerous and deceptive information to air traffic controllers. The inability to reliably validate and verify that ADS-B data used for aircraft separation entails risks that have often hampered the adoption of ADS-B by controllers. Although validation is not currently a minimum requirement of ADS-B ED-129B systems, it is a feature desired by most ANSPs. For ground-based systems, validation can be done through comparison with radar, WAM or other surveillance sources. In the case of oceanic areas, this is not currently possible.

AIREON has developed a complete position validation method that will be used to authenticate the vector integrity of the ADS-B data sent to any ANSP. This utterly independent validation layer alleviates concerns about the use of ADS-B as a single source of surveillance and increases the ability to use the zero version.

The AIREON payload (AHP) in the Iridium NEXT satellite constellation provides global ADS-B coverage (automatic dependent surveillance - broadcasting) that is achieved for each payload that covers a portion of the earth's surface. The nature of polar-orbiting satellites and the size of payload footprints allow overlapping coverage between adjacent payloads.

This overlap creates regions where ADS-B transmissions are detected by more than one AHP and allow two or more measurements of the same information. These measurements can be used to perform arrival time difference calculations (TDOA) that AIREON has incorporated into a position validation algorithm that allows verification of the position of an aircraft independent of GPS.

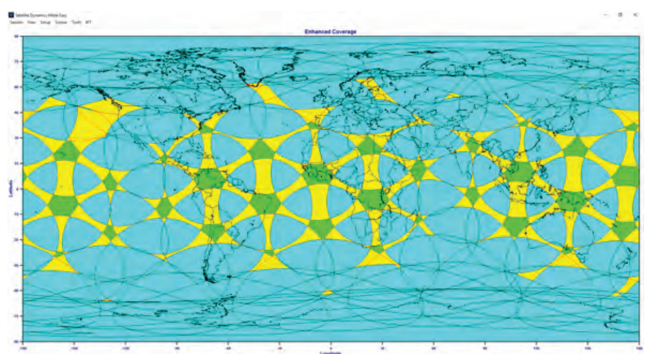


Figure 6 -

This independent validation algorithm increases the ability of the AIREON surveillance system to withstand counterfeiters (devices that are intentionally transmitting incorrect positions), defective avionics and GPS interruptions. This validated information allows AIREON to significantly improve the security and robustness of any system using its ADS-B data.

The validation algorithm uses two primary techniques: first, using two or more satellites to perform TDOA calculations and verify that the position of the reported aircraft is within a reliable distance from reality; second, it utilizes the aircraft's kinematics to persist and verify its validation status in regions where there is no overlap of satellites. Given the size of the AHP coverage footprint, the single satellite coverage regions exist only near the equator, in fact above 43 ° and below -43 ° latitude all airplanes are always covered by at least two satellites but even at the equator where coverage overlap is reduced, an aircraft still has an 80% chance of being covered by more than one satellite.

In the worst case, if an aircraft is only covered by a single satellite at the equator, it will reenter the redundant coverage in less than four minutes. During these times, the kinematic part of the validation algorithm will be responsible for ensuring that the reported data is correct.

In April 2018, AIREON began receiving Precision Timing Position (PTP) messages from Iridium, which provide the necessary precision in both synchronization and satellite positioning to perform the TDOA calculations. With these PTP messages, AIREON has begun to test the operational data validation algorithm with great success.

AIREON is the only surveillance provider positioned to perform this type of validation through ADS-B based on space or satellite and will deliver this new feature to subscribed ANSPs in the first quarter of 2020.

Other Aireon services

In addition to the surveillance signals for ATC purposes, AIREON will have, for different uses, the following services described in the table below:

Services	Features
Aireon ALERT	AIREON will offer the world aviation industry an excellent service without cost, called Aireon "Aircraft Locating and Emergency Response Tracking" (ALERT) for the location and tracking of aircrafts in emergency situations. The service will be available to ICAO, air navigation service providers, Civil Aviation authorities, air operators and rescue organizations The service will be offered to this aeronautical community through registration on the website: https://www.aireonalert.com/.
GlobalBeacon	In line with the procedures provided in the ICAO document "Global Aeronautical Distress Safety System (GADSS)", Aireon, in collaboration with the company FlightAware, will offer the GlobalBeacon tool, aimed at tracking aircraft by air operators. The service will exceed what is specified in GADSS, which provides for aircraft operators to track their fleet every fifteen minutes starting as of November 2018, and every minute beginning in 2019. The GlobalBeacon system will track aircraft every minute, as of December 2018.
Data to support air traffic flow management (ATFM)	Collaborative decision making among all stakeholders is an integral part of the ATFM and allows the aviation industry to collaboratively manage operational constraints in a way that balances operational efficiency with aviation security. The ATFM is based on the exchange of information and procedures throughout all phases of a flight. For efficient ATFM, many data flows are needed, such as flight plans, airspace restrictions, and weather forecasts. Monitoring information, flight information, and flow information are also an integral part of a successful ATFM system. It also requires a wide range of capabilities and information, including the accuracy of the data, which is key to supporting the operational decision-making process among interested parties.

Out of the services above- mentioned, ANSPs may make frequent use for the purpose of ATFM. Through AIREON's space-based ADS-B, reliable, accurate and real-time surveillance data can be provided to support today's ATFM activities and predict airspace and airport demand, as well as giving a migratory path to allow future concepts, Including trajectory-based operations (TBO).

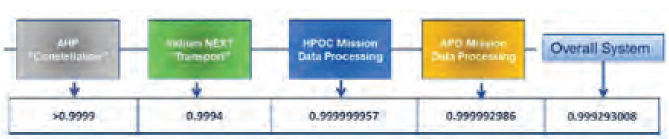
In addition, given that space-based ADS-B data is global, this could mean having a regional ATFM and enabling the sharing of information with other regions, achieving transparent airspace, interoperability between ATM systems and standardized procedures in support of the ICAO Global Air Navigation Plan (GANP).

Technical parameters that define the Space-based ADS-B service

According to the information sent by AIREON, it is observed that they have three main indicators that determine the quality of the service they provide: Availability, Latency, and Probability of Updating, which are the main parameters of the industry for any surveillance system.

Availability is calculated by dividing the number of status reports within the spatial volume of the service, during a period of time in which that service is running normally or degraded, by the total number of possible status reports in that same period of time. The planned maintenance periods are not taken into account in the availability calculations. The AIREON system values are presented in the Figure below.

ADS-B Sat. Availability (As reported by Aireon)



The table below shows the reference value and the availability value delivered by AIREON.

Availability compliance (As reported by AIREON)

Parameter	Source (Standard)	Required Value	Aireon Design Target
Service volume availability	ICAO Global Operational Data Link Document (GOLD); April 26, 2013	≥0.999	≥0.999

Latency is the amount of time necessary to deliver the user the data of interest, from the input interface of the AIREON System receiver to the Service Delivery Point (SDP), and corresponds to the duration of the internal processing and communication channels, to charge of the company.

The AIREON System is designed for a processing time of 1.5 seconds, which improves the 2.0-second requirement specified in the Eurocontrol documentation. When an SDP is implemented in a client's facility, AIREON contemplates the distribution of data to the user, resulting in a maximum total latency of ATC Surveillance Processing (1.5s maximum) + Surveillance Signal Distribution (0.5s maximum) ≤ 2.0s. The Figure below shows all the links and processing present in the transmission of the signal of space-based ADS-B.

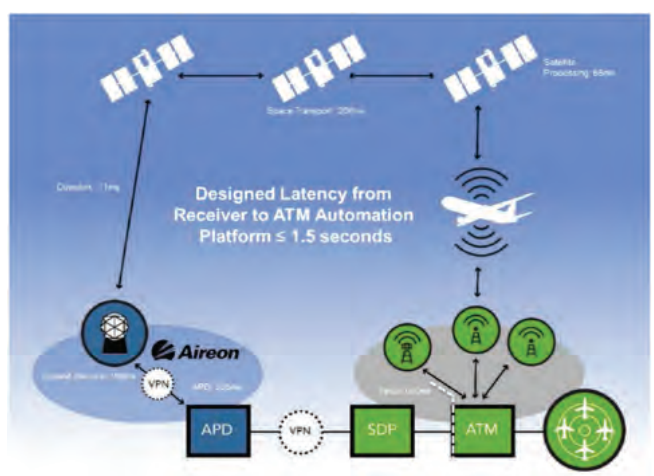


Figura 7 – Latency in the Aireon system

The latency of AIREON services is expected to be less than 1.5 seconds to provide ATC separation services en route and in oceanic spaces. The reference value and the latency value proposed by AIREON are presented in the table below.

Latency compliance (As reported by Aireon)

Parameter	Source (Standard)	Required Value	Aireon Design Target
Latency	Eurocontrol GEN SUR, Section 3.7.3.1.5	≥2.0s 99th percentile	≥1.5s 99th percentile Measurement to ATM Automation

The probability of update is the probability that at least one target ADS-B report will be received at the service delivery point, within a required period of time. The period of time required for this update interval is usually relative to an aircraft separation standard applicable to the volume of the airspace where the service is provided. The reference value and the Probability of Update value delivered by AIREON are presented in the table below.

The probability of Update compliance (As reported by Aireon)

Parameter	Source (Standard)	Required Value	Aireon Design Target
Probabiilty of Update	EUROCAE Technical Specification for an 1090MHz Extended Squitter ADS-B Ground System, ED-129B	≥96% for an Update Interval of 8 seconds (for low density en route airspace)	≥96% for an Update Interval of 8 seconds (for low density en route airspace)

Appendix A contains the test results developed by AIREON with FAA, Nav Canada, and Polaris, demonstrating the surveillance capabilities of the space-based ADS-B system.

Coverage

AIREON establishes that by virtue of the availability of a constellation of low-altitude satellites (780 km from Earth) that will circulate around the planet, with an ADS-B signal receiver, the geographic coverage under its services is of 100%, since the ADS-B signal transmitted from the aircraft at any point in the airspace to the satellites does not contain line of sight limitations as the ground-based infrastructure suffers. At the time of this study, AIREON has stated that although airspace coverage at the terminal level is guaranteed, the performance parameters of a surveillance system with 100% coverage of the airspace are guaranteed, starting at an altitude of 10,000 feet of height upwards and that once the constellation of satellites is completed and is operational, it will be possible to perform country by country and terminal analysis, in order to determine surveillance capabilities in terminal area below 10,000 feet, for the uses that each ANSP consider convenient.

For the above purpose, the company also determines the minimum technical characteristics that must be met by transponders with ADS-B Out capability.

Minimum conditions for onboard ADS-B

To determine the minimum technical requirements that transponders with ADS-B capacity must meet, AIREON takes into account the Latency and Probability of Update metrics, which have dependencies on the aircraft equipment and the level of flight:

- Avionics must comply with RTCA DO-260B/ EUROCAE ED-102A (Note: message formats from versions prior to DO-260 are compatible)
- Antenna mounted on the top and omnidirectional in azimuth. Any aircraft that has a TCAS antenna meets this condition.
- ADS-B Transponder equipment class (transmission power) A1, B1 or higher - Minimum 125W on the antenna

These three operational metrics are fundamental to provide ATC separation services using space-based ADS-B.

Telecommunications Network for the SAM Region

The South American Digital Network (REDDIG) is the support network for the Aeronautical Telecommunications Network (ATN) of the SAM Region. REDDIG supports the current fixed aeronautical voice and data requirements, the exchange of radar data and flight plans, as well as the new ATN applications, such as the case of the Space-based ADS-B.

Considering that part of the process of delivering ADS-B messages to users through AIREON, requires an adequate telecommunications network, and that the SAM Region has a data network called REDDIG that has significant coverage to reach the surveillance data consumption centers, AIREON estimates that the platform can serve within the space-based ADS-B process. To this end, it establishes minimum quality parameters:

- System Availability > 0.999
- Acceptance of Multicast Data
- Data delivery automatically with low latency
- Segregation of surveillance data for each ANSP connected

From the evaluation made to REDDIG II and analyzed by AIREON, REDDIG complies with these performance parameters.

With this, it is concluded that REDDIG could be used as an interface between the surveillance service provider (AIREON) and the SAM Region.

ADS-B data bandwidth estimated by AIREON for the Region

AIREON has also estimated the total bandwidth that might be necessary in case all States subscribe to space-based ADS-B data services, for complete use in both ground-based and oceanic airspace, lower and upper airspace. The table below shows the total potential bandwidth of the use of the system by the States, estimated in air traffic levels in the year 2030, and sum 2,061 Kbps during a period of 24 hours.

The potential bandwidth required by FIR for space-based ADS-B services

		CAT021		CAT025		CAT238		CAT253		TOTAL	
Country	FIR	Mean (kbps)	Max (kbps)	Mean (kbps)	Max (kbps)	Mean (kbps)	Max (kbps)	Mean (kbps)	Max (kbps)	Mean (kbps)	Max (kbps)
Argentina	SACF	8	21	0	1	0	19	6	32	14	73
Argentina	SARR	3	11	0	1	0	17	6	32	9	61
Argentina	SAMF	9	14	0	1	0	17	6	32	15	64
Argentina	SAEF	15	29	0	1	0	39	6	32	21	101
Argentina	SAVF	6	14	0	1	0	85	6	32	12	132
Bolivia	SLLF	6	16	0	1	0	21	6	32	12	70
Brazil	SBAZ	24	48	0	1	0	43	6	32	30	124
Brazil	SBRE	23	43	0	1	0	30	6	32	29	106
Brazil	SBBS	53	93	0	1	0	27	6	32	59	153
Brazil	SBCW	29	50	0	1	0	23	6	32	35	106
Chile	SCFZ	8	18	0	1	0	30	6	32	14	81
Chile	SCEZ	10	23	0	1	0	26	6	32	16	82
Chile	SCTZ	9	10	0	1	0	23	6	32	15	66
Chile	SCCZ	9	9	0	1	0	39	6	32	15	81
Colombia	SKEC	10	28	0	1	0	17	6	32	16	78
Colombia	SKED	26	51	0	1	0	23	6	32	32	107
Ecuador	SEGU	6	18	0	1	0	20	6	32	12	71
French Gui.	SOOO	9	9	0	1	0	23	6	32	15	65
Guyana	SYGC	9	13	0	1	0	16	6	32	15	62

The potential bandwidth required by FIR for space-based ADS-B services

		CAT021		CAT025		CAT238		CAT253		TOTAL	
Country	FIR	Mean (kbps)	Max (kbps)	Mean (kbps)	Max (kbps)	Mean (kbps)	Max (kbps)	Mean (kbps)	Max (kbps)	Mean (kbps)	Max (kbps)
Paraguay	SGFA	9	9	0	1	0	17	6	32	15	59
Peru	SPIM	19	34	0	1	0	36	6	32	25	103
Suriname	SMPM	9	11	0	1	0	16	6	32	15	60
Uruguay	SUEO	5	14	0	1	0	30	6	32	11	77
Venezuela	SVZM	10	24	0	1	0	22	6	32	16	79

In practical terms, the effective implementation of the surveillance service by REDDIG would need less bandwidth than what is reflected in the table.

Connection to the services of AIREON via REDDIG

The interconnection topology between AIREON and the ANSP, with the use of the REDDIG, will be evaluated over time among the members of the REDDIG with the support of telecommunications experts from the provider.

However, in order to present a basic architecture in this study, Figure 10 shows the main elements.

Note: A series of variations of network topology is possible, and all with technical and economically significant advantages, in relation to the architecture of the figure below. However, because it is not the main scope of this study, they will not be presented.

As shown in the Figure below, ADS-B messages, in any of the three versions, will be received (from the constellation of satellites) and processed by the Processing and Distribution Center of AIREON - APD. From this point, the messages corresponding to the ANSP of the SAM Region will be routed by two “Multiprotocol Label Switching – MPLS” networks, in parallel, with the use of Multicast, for two nodes (chosen by the members of the REDDIG). The routers installed in the two nodes will make the Unicast transmission for the ANSPs of destination.

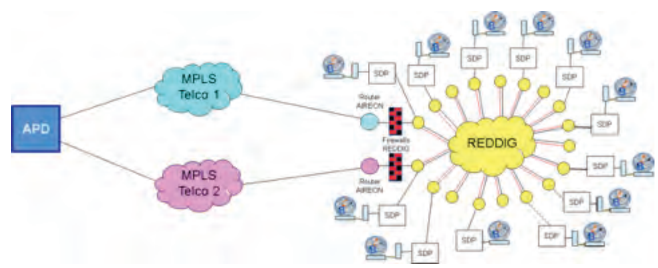


Figura 8 - Example of Network Topology with REDDIG

The feasibility of the previous architecture is being analyzed by Aireon along with other options for the distribution of the space-based ADS-B service through REDDIG, with the purpose of facilitating the regional implementation of space-based ADS-B in South America. The choice of the final platform will be a matter of discussion, opportunely, between the experts of the region and the engineering team of Aireon.

With the use of the REDDIG, Member States will be provided with:

- A reduction of telecommunications circuit costs; and
- The adoption of a standard message exchange platform for ATFM, SWIM and other applications.

Costs for ADS-B data distribution

AIREON charges for the delivery of ADS-B surveillance data to ANSPs, based on the following components:

- Flight hours over the airspace of the FIR that corresponds to an ANSP;
- The density of the traffic overflying the airspace in the FIR/ ANSP;
- Airspace area: oceanic or ground.

The flight charge, AIREON calculates it based on the time (flight hours) that an aircraft equipped with ADS-B crosses the volume of contracted services of the ANSP. Such service volume may be the entire airspace of ANSP, one or more FIRs within its controlled airspace or airspace defined by coordinates. The charge starts from the moment in which the aircraft enters the volume of service contracted until the moment in which the aircraft leaves the volume of contracted services.

Then, AIREON provides surveillance data services for the contracted service volume + 50 NM outside this airspace, for planning purposes. Costs vary between ANSPs since each airspace has its traffic volume and ANSPs may wish to subscribe to parts of the airspace or to all of its controlled airspace.

The rates per flight hour applied to each flight equipped with ADS-B are consistent worldwide and have been defined based on traffic density around the volume of service.

Feasibility of the use of the service

According to the minimum parameters required for surveillance systems and the data received from the AIREON service provider, it is possible to define the feasibility of using the space-based ADS-B service.

Provider of services and the SAM region

Surveillance services have a significant influence on the provision of services for air navigation, particularly in the operational safety and efficiency of air operations, therefore, it is imperative to ensure that the surveillance support of systems/ data providers for the visualization of air traffic situation has a level of service adequate to the requirements of control and guidance in each site and each region, or as it is in this case, the South American Region and in each member State.

In addition to the surveillance systems that are known and have been developed in the last 10 years, a new model of service provision has emerged to generate surveillance data that is based on ADS-B messages that are issued by aircraft that have this ability. This modality is the provision of data for surveillance when collecting ADS-B messages via satellite and delivering it to interested users through data channels. The company with this initiative is called AIREON. Currently, AIREON is the only company that offers this type of service and that has achieved the EASA certification as a Surveillance Service Provider for the aeronautical context.

The modality, after the technical analysis, is considered feasible by the tests carried out to date, and in fact, it is already being integrated into 11 ANSP. On the other hand, the last satellite launch will take place in December 2018, and the system must be operational by March 2019, together with the EASA certification. With this background, it should be noted that the service exists and that the company is available to interested users, so a comparative analysis of what ANSP requires and what is offered by AIREON will be done.

Capacity or service coverage in the airspace

A system that can detect all aircraft throughout the subcontinent and beyond, in addition to providing a continuous and quality service, would indeed be suitable for civil aviation and each country. Particularly in areas that currently do not have adequate coverage.

Response times in the process of information transfer or latency

The required information must be in a timely manner in the data consumption center, in this case, an air traffic control center. The report of the position of an aircraft must be presented in this center, practically in real time.

Information availability

All services/ systems must be available all time required by civil aeronautics (24x7), for operational safety. However, no equipment or system is infallible, and sometimes there are interruptions for scheduled maintenance or improvements to the system in use.

In the table below, expected parameters are shown and those that will be delivered by AIREON.

Values of the parameters considered as fundamental

No.	Description	Metrics	Expected value	Aireon compliance
1	Coverage 10.000	%	> 75	100
2	Coverage 15.000	%	> 85	100
3	Coverage 25.000	%	> 95	100
4	Latency	seconds	≤ 2	≤ 2
5	Availability	%	> 99,98	> 99,98

Benefits

With services provided by AIREON it is expected to have support for the development of the following aspects, in a regional implementation:

Operational safety – Effective surveillance in areas where there is no current coverage, undoubtedly contributes to the increase in operational safety.

Efficiency of flights – The capacity for adequate surveillance of ADS-B information provides means to optimize flights and increase the capacity of use of airspace.

Flexibility – The service provided by AIREON allows the ANSP to contract specific areas or volumes, at operational flight levels, as a single means of surveillance or augmentation of existing surveillance infrastructure, as well as redundancy in regions of critical operational interest.

Homogeneity – In regional implementation, with States obtaining information from the same source, with the same levels of parameters, it enables the homogenization of air navigation services throughout the region.

Environment – Improving flight management by increasing capacity, provides for more direct flights and reduces waiting times, as well as contributes to reducing the adverse impacts of aviation on the environment.

Profitability – With more efficient and economical flights profitability for aircraft operators becomes sustainable, with positive impacts for the end user. From the point of view of the ANSPs, the decrease in the infrastructure implemented and the maintenance required, have a significant effect on this aspect.

The AIREON experience has been confirmed by ANSPs from areas with considerable air traffic, such as the NAT Region. As a surveillance service provider for the ANSPs, AIREON will provide surveillance data (information) in the areas of operational interest of the clients.

It should also be taken into account that, the greater the airspace considered for coverage with space-based ADS-B, the greater the homogeneity of the information, although this must have very thorough experimental tests and nothing should be left unproven, in particularly regarding support telecommunications networks. In this sense, the use of the regional telecommunications infrastructure (REDDIG) can contribute to lower the costs of the distribution of surveillance data provided by AIREON.

Another important point is to perform the risk analysis, according to the peculiarities of each State and ATC control areas involved, taking into account the existing infrastructure, the current procedures and the service contracted to establish the mitigation measures.

If there is a country that starts the exploitation of this service, it will be essential that it shares its experience with the rest of the Region, providing solid comparative parameters.

Availability of avionics with ADS-B capacity

At the Twenty-first Workshop/ Meeting of the SAM Implementation Group (SAM/IG/21), the International Air Transport Association (IATA) presented a study note that points to a percentage higher than 90% (in some cases it reaches 99% or 100%) of aircraft, operated by the airlines, equipped with transponder with ADS-B Out capability.

Although the study only includes information from IATA member airlines and does not include aeronautical operators (aircraft in general) in a country, the information is important because it can mark the strategy of the CAA and ANSP in the SAM Region.

If aeronautical operators (aircraft in general) in a country, for the most part, do not have ADS-B capacity in their transponders, this condition would not allow taking advantage of the benefits of ADS-B (space- based or ground-based) in the short term, and there will be a lot of work to be done, and not postpone it for later, in order to have the benefits of ADS-B services and potentially, space-based ADS-B. This implies that secondary radars or multilateration would still have to be relied upon, even though these are not very efficient compared to ADS-B surveillance.

Regulations of the Aeronautical Administration

Efforts should be made to improve national regulations and demand plans for the use of ADS-B in aircraft, particularly in general aviation. A proper term of action to have the respective rules and requirement for the use of transponders with ADS-B capacity is 2 years.

Convenience on the use of the service

Referential costs

No disaggregated costs are available, but for the development of this study, some costs for the following countries have been provided: Chile, Colombia, Ecuador, Peru, by the Pacific coast that are presented in the table below.

Space-based ADS-B service costs with and without REDDIG

Country	annual total for 15 years (higher cost) US$	annual total for 15 years (lower cost) US$	Difference US$
Chile	2.022.467	1.915.776	106.690
Colombia	1.922.467	1.815.776	106.690
Ecuador	722.467	615.776	106.690
Perú	2.122.467t	2.015.776	106.69

Note 1. The costs of the Table above include the total airspace of the country (continental + oceanic), and its FIR (s) and the cost of telecommunications networks.

Note 2. The difference in costs only relates to using an independent telecommunications network (higher recurrent cost) or REDDIG.

Costs/ Space-based ADS-B coverage versus SSR costs

The costs provided by AIREON, related to each Km2 of the FIR and coverage are presented in the table below.

Cost of surveillance with space-based ADS-B services

Country	ADS-B Sat.	Cost of service (US$)	% Coverage FIR (10-15-25 thou. feet)	annual cost / Km2 FIR
Chile	1	2.022.467	100-100-100	0,20
Colombia	1	1.922.467	100-100-100	1,17
Ecuador	1	722.467	100-100-100	0,77
Perú	1	2.122.467	100-100-100t	0,60

The exercise of costs with SSR's - Ecuador

In this country there are 7 radars at USD 1,500,000.00 each (referential value), that sum up a total of USD 10,500,000.00 as an investment and, if we establish 20% maintenance throughout its lifetime, we have a total of USD 12,600,000.00.

The useful life of radar, with quality equipment, is 15 years. With this data and if we distribute these costs per year, the result is USD 840,000.00 per year. Taking coverage data mainly in the continental FIR, which are different for three altitudes, it is noted that this amount of financial resources reach to have a partial coverage and not total, and the oceanic area is not taken into account. Obviously this coverage is explained by the limitations of the line of sight and because the facilities are only located on the land surface.

On the other hand, if the service of the Space-based ADS-B has 100% coverage and the annual cost is of USD 722,467.00, it is appreciated that there is an advantage for coverage, and a lower recurrent cost for the service, without assuming maintenance costs, logistics of operation, technological updates and remote locations. A more detailed analysis of the subject is presented later.

The disadvantage that could arise is to depend on a single provider, and for what is known to date, there is no other provider of these services. However, mitigation measures can be taken or define very detailed contingency plans if there are service interruptions.

Another challenge right now that should also be taken into account is that there will be an initial cost for aeronautical operators that do not have transponders with ADS-B Out capability. This will take some time to resolve, either for ground-based ADS-B or space-based ADS-B. Below are tables with cases taken as reference:

Cost of surveillance service with sensors type SSR - 10,000 feet

Country	No. SSR	Cost equipment (US$)	Total Cost (+ 20%)	annual cost (15 years)	% Coverage FIR (10k feet)	annual cost/ Km2 FIR Cont.
Chile	11	16.500.000	19.800.000	1.320.000	8,96	19,48
Colombia	15	22.500.000	27.000.000	1.800.000	37,37	4,22
Ecuador	7	10.500.000	12.600.000	840.000	27,45	10,79
Perú	8	12.000.000	14.400.000	960.000	13,14	5,68

Cost of surveillance service with SSR type sensors - 15,000 feet

Country	No. SSR	Cost equipment(US$)	Total Cost (+ 20%)	Annual cost (15 years)	% CoverageFIR (15k feet)	annual/ Km2 FIR Cont.
Chile	11	16.500.000	19.800.000	1.320.000	11,66	14,97
Colombia	15	22.500.000	27.000.000	1.800.000	49,33	3,20
Ecuador	7	10.500.000	12.600.000	840.000	45,74	6,48
Perú	8	12.000.000	14.400.000	960.000	19,7	3,79

Cost of surveillance service with sensors type SSR - 25,000 feet

Country	No. SSR	Cost equipment(US$)	Total Cost (+ 20%)	Annual cost (15 years)	% CoverageFIR (25k feet)	annual/ Km2 FIR Cont.
Chile	11	16.500.000	19.800.000	1.320.000	17,55	9,95
Colombia	15	22.500.000	27.000.000	1.800.000	77,73	2,03
Ecuador	7	10.500.000	12.600.000	840.000	74,49	3,98
Perú	8	12.000.000	14.400.000	960.000	43,21	1,73

From the values of the initial AIREON table, and the values of the following tables, which include SSR sensors, it can be seen that the amount of the annual cost per Km2 of the FIR with ground-based systems is greater than the spatial value in all the heights considered and in all Countries. With this, we can conclude that the Space-based ADS-B service is convenient from the financial point of view, regarding the use of the SSR.

It should also be noted that the higher the analyzed coverage, the lower the value of the annual cost per Km2 of the SSR, as the percentage of coverage increases as a trend, however, the mentioned coverage cannot be expected. it reaches values higher than 85-90% at higher altitudes because ground-based systems have a significant dependence on the line of sight, geographical obstacles and power limits of support equipment, in addition to the curvature of the earth. Note then that the main impact of coverage is effectively at low altitudes, as can be seen from the tables presented.

Costs / coverage versus ADS-B Ground-based costs

The costs provided by AIREON, related to each Km2 of the FIR and coverages are:

Cost of the surveillance service with Space-based ADS-B service

Country	ADS-B Sat.	Cost of Service (US$)	% FIR Coverage (10-15-25 mil pies)	annual cost/ Km2 FIR
Chile	1	2.022.467	100-100-100	0,20
Colombia	1	1.922.467	100-100-100	1,17
Ecuador	1	722.467	100-100-100	0,77
Perú	1	2.122.467	100-100-100	0,60

Cost exercise with ADS-B land stations - Ecuador

Assuming that Ecuador had 7 ADS-B stations at USD 300,000.00 each, this gives us a total of USD 2,100,000.00 as investment, and if we establish 20% maintenance for its entire useful life, we have a total of USD 2,520,000.00. The useful life of an ADS-B team, with quality equipment, could be in 10 years. And if we distribute these costs per year, the result is USD 252,000.00.

If we take the coverage data, which would be similar to that of the radars, for the three altitudes, it is also noted that this amount of financial resources reach to have a partial coverage and not total, particularly in the ocean area. Obviously this is explained by the limitations of the line of sight and because the facilities are located on the earth's surface, just as in the case of having SSR systems.

On the other hand, if the service of the Space-based ADS-B has 100% coverage and the annual cost is of USD 722,467.00, it is appreciated that the annual financial cost is lower in all heights and there are other significant advantages such as coverage, and without assuming costs for maintenance, operation logistics, technological updates and remote locations. A more detailed analysis of the subject is presented below.

The other side of the case is to depend on a single provider, and for what is known there is no difference, however, you can take mitigation measures or define very detailed contingency plans if there are service interruptions.

The following tables present cases taken as reference:

Cost of surveillance service with ground-based sensors ADS-B / 10.000 feet

Country	No. SSR	Cost equipment (US$)	Total Cost (+ 20%)	annual cost (15 years)	% Coverage FIR (10k feet)	annual cost/ Km2 FIR Cont.
Chile	11	3.300.000	3.960.000	396.000	8,96	5,85
Colombia	15	4.500.000	5.400.000	540.000	37,37	1,27
Ecuador	7	2.100.000	2.520.000	252.000	27,45	3,24
Perú	8	2.400.000	2.880.000	288.000	13,14	1,71

Cost of surveillance service with ground-based ADS-B sensors / 15,000 feet

Country	No. SSR	Cost equipment(US$)	Total Cost (+ 20%)	Annual cost (15 years)	% CoverageFIR (15k feet)	annual/ Km2 FIR Cont.
Chile	11	3.300.000	3.960.000	396.000	11,66	4,49
Colombia	15	4.500.000	5.400.000	540.000	49,33	0,96
Ecuador	7	2.100.000	2.520.000	252.000	45,74	1,94
Perú	8	2.400.000	2.880.000	288.000	19,7	1,14

Cost of surveillance service with ground-based ADS-B sensors / 25,000 feet

Country	No. SSR	Cost equipment(US$)	Total Cost (+ 20%)	Annual cost (15 years)	% CoverageFIR (25k feet)	annual/ Km2 FIR Cont.
Chile	11	3.300.000	3.960.000	396.000	17,55	2,98
Colombia	15	4.500.000	5.400.000	540.000	77,73	0,61
Ecuador	7	2.100.000	2.520.000	252.000	74,49	1,19
Perú	8	2.400.000	2.880.000	288.000	43,21	0,52

From the values of the initial AIREON table, and the values of the following tables, which include ground-based ADS-B sensors, it can be seen that the amount of the annual cost per Km2 of the FIR with ground-based systems is, in its almost total advantage with the adoption of ADS-B Sat.

Also, it should not be forgotten, as in the case of the analysis of the SSR systems that the higher the height of the analyzed coverage, the lower the value of the annual cost per Km2 of ground-based ADS-B, as the percentage increases of coverage as a trend. However, it cannot be expected that the aforementioned coverage will reach values higher than 85-90% at higher altitudes, since the ground-based systems have a significant dependence on the line of sight, geographic obstacles and power limits of the support equipment, besides the curvature of the earth. Note then that the main impact of coverage is effectively at low altitudes, as can be seen from the tables presented. In addition, in the ocean region, coverage with ground-based ADS-B cannot be considered effective.

General remarks

- The costs, if SSR systems are used in relation to costs per space-based ADS-B, both globally and the cost per covered Km2 are higher with the ground- based systems.
- The costs, if ground-based ADS-B systems are used (if it is possible to install this type of sensors in the ocean) in relation to the costs per space-based ADS-B, globally would be higher than the costs of the satellite system. However, the cost per Km2 of FIR varies by height and Country, so it is necessary to make a particular analysis in each case.
- The table, to follow, reflects the comparison of costs between the Space-based ADS-B, ADS-B ground-based and SSR. As it is clearly observed, the Space-based ADS-B has a flagrant cost-benefit relation, in relation to the other technologies, without limitation of coverage in the levels used as a reference and other possible ones that are considered operational in each State.

The table, to follow, reflects the comparison of costs between the Space-based ADS-B, ADS-B ground-based and SSR. As it is clearly observed, the Space-based ADS-B has a flagrant cost-benefit relation, in relation to the other technologies, without limitation of coverage in the levels used as a reference and other possible ones that are considered operational in each State.

State (FL)	% FIR coverage Continental and Ocean (Space-based ADS-B)	% FIR coverage Continental and Ocean (SSR)	Space-based ADS-B (annual cost/km2 FIR)	SSR (annual cost/ (%Coverage x Km2 FIR)	Ground-based ADS-B (annual cost/ (%Coverage x Km2 FIR)
Argentina (FL 100)	100	12,37	0,15	8,68	2,61
Argentina (FL 150)	100	15,27	0,15	7,04	2,11
Argentina (FL 250)	100	18,58	0,15	5,78	1,73
Bolivia (FL 100)	100	26,10	0,57	2,93	0,88
Bolivia (FL 150)	100	40,85	0,57	1,87	0,56
Bolivia (FL 250)	100	70,35	0,57	1,09	0,33
Brasil (FL 100)	100	27,86	0,53	4,25	1,27
Brasil (FL 150)	100	35,01	0,53	3,38	1,01
Brasil (FL 250)	100	46,26	0,53	2,56	0,77
Chile (FL 100)	100	8,96	0,20	19,48	5,85
Chile (FL 150)	100	11,66	0,20	14,97	4,49
Chile (FL 250)	100	17,55	0,20	9,95	2,98
Colombia (FL 100)	100	37,37	1,17	4,22	1,27
Colombia (FL 150)	100	49,33	1,17	3,20	0,96
Colombia (FL 250)	100	77,73	1,17	2,03	0,61
Ecuador (FL 100)	100	27,45	0,77	10,79	3,24
Ecuador (FL 150)	100	45,74	0,77	6,48	1,94
Ecuador (FL 250)	100	74,49	0,77	t3,98	1,19

State (FL)	% FIR coverage Continental and Ocean (Space-based ADS-B)	% FIR coverage Continental and Ocean (SSR)	Space-based ADS-B (annual cost /km2 FIR)	SSR (annual cost/ (%Coverage x Km2 FIR)	Ground-based ADS-B (annual cost/ (%Coverage x Km2 FIR)
French Gui. (FL 100)	100	ADS-B 11,67	0,30	-	Nota b) 18,46
French Gui. (FL 150)	100	ADS-B 15,34	0,30	-	Nota b) 14,05
French Gui. (FL 250)	100	ADS-B 16,56	0,30	-	Nota c) 13,01
Guyana (FL 100)	100	ADS-B 91,86	1,26	-	Nota c) 0,91
Guyana (FL 150)	100	ADS-B 96,9	1,26	-	Nota c) 0,86
Guyana (FL 250)	100	ADS-B 100	1,26	-	Nota b) 0,84
Panama (FL 100)	100	33,70	2,29	14,40	4,32
Panama (FL 150)	100	41,63	2,29	11,66	3,50
Panama (FL 250)	100	59,48	2,29	8,16	2,45
Paraguay (Fl 100)	100	SSR- 30,87/ADS 92,61	1,31	1,91	Nota d) 0,57
Paraguay (Fl 150)	100	SSR - 40,39/ADS 99,5	1,31	1,46	Nota d) 0,53
Paraguay (Fl 250)	100	SSR - 69,21/ADS 100	1,31	0,85	Nota d) 0,53
Peru (FL 100)	100	13,14	0,60	5,68	1,71
Peru (FL 150)	100	19,70	0,60	3,79	1,14
Peru (FL 250)	100	43,21	0,60	1,73	0,52
Suriname (Fl 100)	100	-	1,23	-	-
Suriname (Fl 150)	100	-	1,23	-	-
Suriname (Fl 250)	100	-	1,23	-	-
Uruguay (Fl 100)	100	3,18	0,20	42,83	12,85
Uruguay (Fl 150)	100	5,30	0,20	25,70	7,71
Uruguay (Fl 250)	100	7,43	0,20	18,33	5,50
Venezuela (FL 100)	100	48,87	1,18	2,68	0,80
Venezuela (FL 150)	100	65,23	1,18	2,01	0,60
Venezuela (FL 250)	100	83,64	1,18	1,57	0,47

Remarks:

a) For most Countries, an imaginary number of ground-based ADS-B stations that would be with their matching location coordinates where currently SSRs are located was adopted.

b) French Guyana only has ground-based ADS-B (five sensors).

c) Guyana only has ground-based ADS-B (five sensors).

d) Paraguay has radars (two) and ground-based ADS-B (six). For this reason, the annual cost / (%FIR coverage x Km2 FIR) values take into account the actual amount of each sensor.

e) For SSR and ground-based ADS-B, the relations (annual cost/ (% Coverage x Km2 FIR) can be considered conservative with respect to the acquisition of the equipment and by the application of 20% for maintenance, operation, telecommunications, infrastructure costs and "spare-parts" throughout its useful life.

f) For calculations of SSR and Ground-based ADS-B, fictitious costs were considered if ground-based SSR and ADS-B sensors had 100% coverage in the entire FIR (oceanic and continental) of each State.

General considerations for contracting the service

It is necessary that all the Countries or the region in general, observe and analyze the significant change that is related to the 100% coverage offered by AIREON and in all the airspace considered, compared with the current service based on systems installed on land surfaces, which in the best case scenario reaches 80%.

It is also necessary to certify the service of the company from the technical point of view, in order to ensure the offered coverage, in particular, and compliance with latency and availability parameters.

Another fundamental condition is to consider the telecommunications networks that would take the surveillance data to the consumption centers. These should be redundant and demonstrate not only integrity but continuity in the service. It is known that AIREON provides channels with adequate availability and redundant for their services.

Level Service Agreement

The Service Level Agreement must be the primary document for contracting AIREON services, in its technical part. The document must include the following service premises as well as propositions (taken from Doc. 9883 "Manual on the Global Performance of the Air Navigation System" ICAO):

Operational safety

- Total airspace coverage to minimize the risk of incidents or accidents;
- Greater ease for air traffic control.

Capacity

- Theoretically, total coverage of the airspace, therefore, higher capacity of the tool for air traffic control

Flight efficiency

- Less time of airspace operation.

Services and procedures

- Better facilities for previously planning air operations, due to minimization of operations time.

Possibility of predicting

- Better coverage and reliability of the tool for air traffic control allows more significant use of airspace.

Flexibility

- Better coverage and reliability of the tool for air traffic control allows more flexibility.

Enviornment

- Less time of aerial operation and more direct routes;
- Less impact on the environment due to the reduction of emissions in the atmosphere.

Cost-effectiveness

- Fewer stations, equipment, and civil infrastructure;
- The contracting of the ADS-B signal would minimize (by the previous study) the costs and specific risks for managing the equipment;
- Less time in the operation, would make commercial exploitation more profitable or lower costs for services for air navigation.

Human Resources

- Fewer man-hours for technical activities.

Regulations and standardization

- Existing and available regulations

For the development of the document of Service Level Agreement (SLA), in addition to the premises of the previous list, information on the subject was requested from AIREON.

The information received does not detail the points of the agreement but the general information and principles such as:

Operational Service

o Detail of the characteristics of the service and its performance parameters;

o Reports of failures / interruptions, response times and those responsible for resolving faults;

o The communication protocols between user and management level;

o Coordination for routine revisions in anticipated times.

Quality of service

o Specific definition of service parameters and monthly statistics thereof;

o Remedies for parameters if they degrade;

o Procedure for changes in the level of service.

Obligations and Responsibilities of both the provider and the customer.

o Lists of people with their respective contact data, both the user and the provider, as responsible for the planned or random actions for the service to comply with the parameters of operation.

On the other hand, the company providing the service must go through the tests of coverage, latency, availability, in addition to supporting statistically and determine if the conditions of the ATC improved in each site where they provide their service.

Recommendations for the region

Technical Recommendations

The use of the AIREON services is feasible and would improve the current monitoring conditions due to the coverage that would be achieved and compliance with the minimum parameters of the proposed services, as well as the recovery of the ADS-B message at all times and in all places, as well as the transportation of this through reliable telecommunications networks.

It should be noted that areas with continental routes at low altitude (less than 15,000 feet) will not have good coverage with ground-based sensors, due to the orography, since there will always be a dependence of these on the line of sight to detect an aircraft. The practical needs of coverage must be analyzed by each sector and State.

This recommendation, in some cases, must also be analyzed for heights greater than 10,000 feet.

Regarding the oceanic spaces, it is evident the importance of having data from the aircraft operating on these areas, which can be provided by AIREON, improving safety and operational efficiency.

It should also be noted that AIREON can provide its services in specific airspaces defined by the ANSP, not necessarily in the entire FIR. This flexibility should also be analyzed by those responsible for air traffic control, jointly with those responsible for surveillance systems, to maximize the effectiveness of surveillance capacity.

The capacity of the space-based ADS-B system to validate the position of aircraft with respect to GPS is of great importance since, in case of GPS drops, it will still be possible to identify the actual location of the aircraft. Likewise, a validation of the integrity of the ADS-B data will be achieved.

Given the advantages of the space-based ADS-B service and in general for the implementation of a surveillance infrastructure with ADS-B in the region, it is necessary to motivate air operators to equip their aircraft with ADS-B transponders. According to the IATA survey, commercial aviation is fitted in the region by 90%, so it will be necessary to implement mitigation measures for general aviation, such as segregated airspaces, the policy of “better equipped, better served” or the establishment of regulations in each State.

Efficiency

Because there are no more accurate data available at the time, only one cost analysis test was done, and the results are the following:

With the tests carried out, it is convenient and reasonable to use space-based ADS-B services, in comparison with SSR and ground-based ADS-B sensors, mainly in the coverage parameter and most particularly in low altitudes (10 and 15 K feet).

Tests conducted evidence that the cost-benefit ratio is advantageous in almost all situations. Also, it should always be taken into account that coverage is a significant and very convenient parameter for operational safety.

Conclusion

ANSPs should consider space-based ADS-B services as it will significantly improve the safety, efficiency, predictability, and capacity of air traffic management (ATM), at the same time reducing the overall infrastructure costs.

Space-based ADS-B will generate immense financial, operational and security benefits. By having continuous surveillance of air traffic in real time, air traffic providers will have:

- Lower cost for implementation of the surveillance system
- Better awareness of the controller's situation through 100% surveillance in all sectors, FIR and beyond the limits of FIR
- Early detection of emergency transponder codes (in the current airspace of procedures)
- Standardization of FIR boundaries
- Reduced controller response time to abnormal situations and gross navigation errors
- Better search and rescue response
- Better awareness of the fluxes of air traffic
- Greater resilience since the service can serve as backup support for existing faults in the system
- Reduction of the risk of data loss through improved and continuous surveillance.
- Reduction of the risk of loss of separation.

List of acronyms

ADS-B	Automatic dependent surveillance—broadcast
ADS-C	Automatic dependent surveillance — contract
ANSP	Air navigation service provider
APD	Aireon Processing and Distribution Center
ASBU	Aviation System Block Upgrades
ASTERIX	All-purpose structured EUROCONTROL surveillance information exchange
ATM	Air traffic control
ATN	Air traffic management
ATS	Aeronautical Telecommunication Network
CAA	Air traffic service
CTA	Civil aviation authority
EASA	"European Aviation Safety Agency"
ES	"Extended Squitter"
FAA	Federal Aviation Administration
FIR	Flight information region
FMC	Flight Management Computer
FMS	Flight management system
GANP	Global Air Navigation Plan
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HPL	Hosted Payload
HPOC	Hosted Payload Operations Center
KPA	International Civil Aviation Organization
MLAT	Key Performance Areas
MSSR	Multilateration
MTBCF	Monopulse Secondary Surveillance Radar
MTBF	Mean time between critical failures
MTTR	Mean time between failures
NM	Mean time to repair
OACI	Nautical mile
PoD or PD	Probability of detection
PBIP	Performance-based air navigation implementation plan - SAM Region
PSR	Primary Surveillance Radar
REDDIG	South American Digital Network
SAM	South American Region - ICAO
SDP	Service Delivery Point
SMR	Surface movement radar
SNOC	Satellite Network Operations Center
SSR	Secondary surveillance radar
STCA	Short Term Conflict Alert
TBO	Trajectory Based Operations
TDOA	Time difference of arrival
TIS-B	Traffic information service – broadcast
TMA	Terminal control area or Terminal maneuvering area
TPM	Technical Performance Measurement
TSC	Iridium Technical Service Centre

AIREON'S INITIAL ON-ORBIT PERFORMANCE ANALYSIS OF SPACE-BASED ADS-B

Dr. Michael A. Garcia, John Dolan, and Andy Hoag, Aireon, McLean, VA

Abstract

On January 14th, 2017, the first SpaceX rocket launch of 10 of Iridium NEXT's satellites generated an exciting milestone towards the global coverage of Aireon's space-based Automatic Dependent Surveillance-Broadcast (ADS-B) system [1]. ADS-B is a cornerstone technology for the aviation industry that enables significant improvements in aircraft based travel efficiency and safety. Aireon's hosted payload ADS-B receivers have the potential to accelerate and extend the benefits of ADS-B to the entire Air Traffic Management (ATM) community by significantly expanding the boundaries of legacy infrastructure.

To evaluate the full extent of this potential, the Aireon team embarked on a series of functional and performance tests on the hosted payloads as well as integration with the operational system. About 2 weeks after the first launch, Aireon began to receive and analyze on orbit ADS-B data from equipped aircraft.

This paper describes the key test approaches, results, and analysis that were used to tune and verify Aireon's space-based ADS-B models to estimate the expected end-state ADS-B data service metrics when all 66 operational satellites have reached their mission orbit.

I. Introduction

In prior work, Aireon's methods for estimating performance and ensuring interoperability were described in detail [2] [3]. Once the satellites arrived in their respective mission orbit slots, the opportunity arrived to determine the accuracy of these performance estimates using measured data from the Space Based ADS-B receivers. Of the first 10 satellites launched, 8 went into the same orbital plane while 2 were commanded to drift to an adjacent plane. Iridium's satellite constellation has 6 polar orbiting planes with 11 satellites per plane [4].

During the initial on-orbit test campaign of the first Aireon payload, Aireon received ADS-B data from aircraft of opportunity (see Figure 1) and flight tests were coordinated with NAV CANADA and the Federal Aviation Administration (FAA) to validate aircraft detection and tracking in an operational environment. Furthermore, a ground-based reference transmitter (GBRT) was activated for in-depth calibration of Aireon's system performance models. The results from these tests go a long way to addressing the question:

"How does the measured performance compare to the expected?"

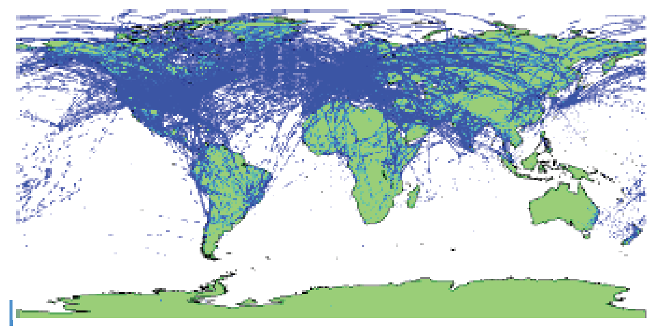


Figure 1: 62 Hours of Stitched Global Coverage

I. Clear Sky Environment

Background

ADS-B avionics are currently available in a wide variety of make, model, and transmitter power. In order to comply with most Air Traffic Control (ATC) airspace requirements, the minimum expected equipage for passenger-carrying aircraft is a class A1 transmitter which has an Equivalent Isotropically Radiated Power (EIRP) output of 125W (measured at the antenna connector) [5] [6] [7]. Furthermore, aircraft that exceed 5700 kg or plan to travel faster than 250 kt will need antenna diversity (top and bottom mounted antennas) [5]. Therefore, a class A1 diversity aircraft with 1090 MHz ADS-B is considered the minimally equipped aircraft that Aireon needs to support and became the "subject" of many test case scenarios.

Two challenges related to these low power aircraft tests became apparent early in the test planning phases:

1) Most ADS-B equipped aircraft transmit at a power ≥ 200W. This makes it difficult to find true 125W subjects for testing that are naturally part of the airspace.
2) The airspace is a busy place. An area needed to be identified that could more closely match the "Clear Sky" conditions (i.e. low interference environment) described in the performance models [2].

Once the Clear Sky model is tuned and validated then the High Interference portion of the model can be layered on top to analyze the aggregate system model.

The primary concept of operations for this GBRT was for it to be always on and transmitting 10 messages per second out of each antenna with approximately the same peak output power as the TLAT antenna model used in simulations at 25 degrees of elevation (51 dBm EIRP + 4 dBi TLAT antenna peak gain = 55 dBm) [16]. The gain roll-off from the GBRT boresight would be analogous to "walking down" an aircraft antenna's lower gain areas as the satellite passes over, capturing the near full range of the expected 125W aircraft output power profile.

Figure 14: GBRT Selex ADS-B Radio Tx and Rx[6]

Figure 15: GBRT in Iqaluit w/ 4 Tx Antennas[7]

6 Photo Credit: NAV Canada
7 Photo Credit: NAV Canada

Data from the GBRT was collected and analyzed from a single payload over a 6 day period. During this time period the satellite had many passes over the GBRT and collected 37,863 ADS-B messages. Figure 16 shows a spatial conformance plot from the GBRT perspective for a single antenna transmitter (i.e. a bird's eye view polar plot of conformance vs. elevation and azimuth). The conformance values are calculated simply by dividing the measured samples by the expected samples (based on the model in ASIM) for each "pixel" where a pixel represents the counts at each respective elevation and azimuth angle observed. A histogram of the pixel conformance counts is in Figure 17 with a distribution centered at approximately 1 (where 1 is the ideal and values greater than 1 indicate expectation exceedance).

Table 4 summarizes the expected versus measured performance with the measured clearly outshining the expected values in each category. However, given the mean conformance is at 1 in these results as well as others collected, the spatial gain and MER curves were considered tuned well enough for initial on-orbit analysis and within an appropriate range of error.

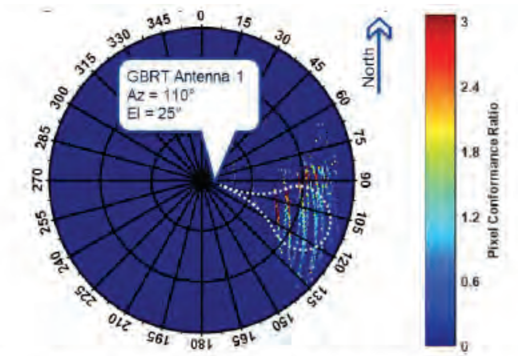


Figure 16: GBRT Spatial Conformance

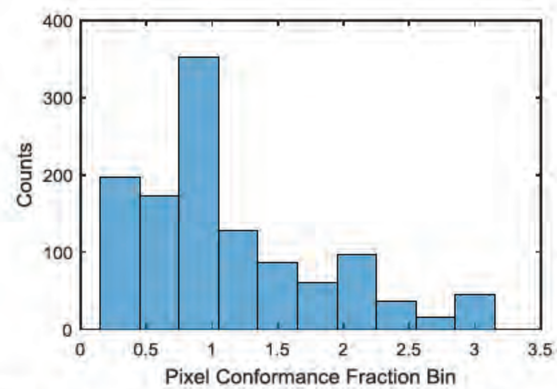


Figure 17: GBRT Pixel Conformance Histogram

Table 4: Summary of GBRT Results for 125W

From 1 Payload	Best Expected	Best Measured
Aircraft Elevation (deg)	7.00	0.70
Slant Range (km)	2550	3175
95th % Update Int. (s)	1.66	1.35
95th % Pixel Conform.	1.50	3.00

dissection of the measured impact of the interference environment will be more applicable when several additional orbital planes fill in later in the constellation deployment sequence. Naturally, the UIs will improve significantly when more Aireon payloads are in their mission orbit since overlapping payload footprint coverage mitigates many of the challenges associated with high density aircraft airspaces.

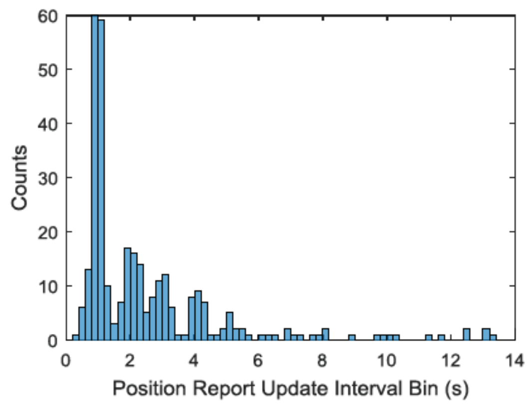


Figure 12: Measured UI for Polaris Aircraft

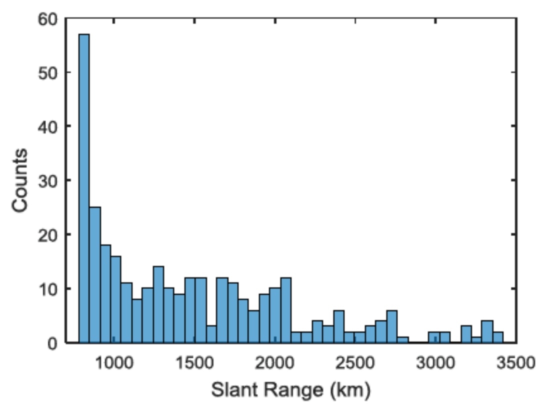


Figure 13: Measured Slant Range for Polaris

Table 3: Summary of Polaris Results for 200W

From 2 Payloads	Best Expected	Best Measured
Aircraft Elevation (deg)	4.00	-1.37
Slant Range (km)	2800	3392
95th % Update Int. (s)	15.00	9.97

IV. Reference Transmitter Calibration

Background

Below is a list of some of the uncertainties that can make it challenging to evaluate the performance model:

1. Aircraft TX power

2. Aircraft antenna gain pattern, orientation, and source (top vs. bottom)

3. Link budget

4. Payload receiver spatial gain

5. Payload receiver MER curve

6. Interference environment

One of the methods employed by Aireon to reduce the uncertainty for items 1-5 on the above list was to provision a Ground Based Reference Transmitter (GBRT). The role of the GBRT is to transmit ADS-B messages from a fixed ground location to the satellites using a carefully calibrated transmitter and antenna system. Since the GBRT is a calibrated transmitter operating from a controlled environment, the received signal level at the satellite can be known with a much higher degree of certainty than by using targets of opportunity. The GBRT was designed to have four calibrated antennas (from Til-Tek) with approximately 15 degree half-beam widths (similar to a radar beam shape), each pointed in a different direction with site surveyed information. The GBRT is driven by a Selex 4 channel radio (Figure 14), which is also used in several of the FAA's Wide Area Multilateration (WAM) systems [14].

Transmit power and attenuation were carefully measured and controlled to each antenna (which addresses items 1 and 2). The link budget is assumed to have the least amount of uncertainty considering how well-established Free Space Path Loss (FSPL) is calculated in the telecommunications industry [15]. To control the interference environment (item 6), the GBRT was located in an area with very low aircraft density in Iqaluit, Canada on a site owned and operated by NAV CANADA (Figure 15). The high latitude also increases the number of passes per day by the satellites. Given the reduction in uncertainty the GBRT provided, it allowed for analysis with this test asset to be focused on items 4 and 5.

III. High Interference Environment

Background

The estimated impact of in-band and near-band interference on the reception of ADS-B messages from space was the primary topic of prior publications by Aireon [2] [3]. A few years later it is exciting to test the methods outlined in those studies and compare measurements to the expected results. The plan for the high interference environment test was to have a dedicated flight test from a General Aviation (GA) aircraft flying near the “middle” of terrestrial US airspace.

The flight plan (shown in Figure 9) involved flying a Beechcraft Bonanza from the Moore County Airport in Dumas, TX (KDUX) to Show Low (KSOW) in Show Low, AZ.

Figure 9: Polaris Flight Test Plan and Aircraft[3]

Although the local environment of KDUX is not particularly high density on its own (Figure 10) one aggregate satellite footprint can cover most of North America. Using FlightAware to depict the aircraft density, Figure 11 illustrates the approximate size of an 8 degree elevation angle satellite footprint directly over North America (light blue outline). Therefore, it was agreed amongst the stakeholders to conduct the primary high interference test case in this region.

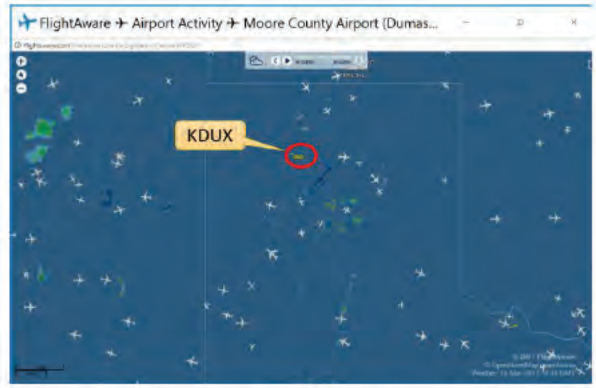


Figure 10: Example Aircraft Density near KDUX[4]

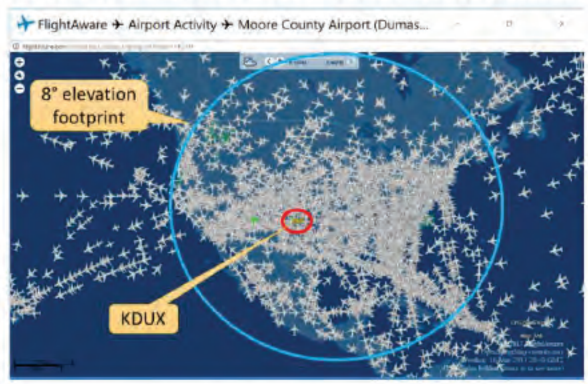


Figure 11: Aircraft Density over North America[5]

Polaris Results

The Polaris flight test took place on 3/20/2017 with three passes from two satellites collecting data for about 16 minutes each. Figure 12 and Figure 13 show the aircraft’s measured UI and slant range histogram, respectively. As indicated in Figure 13 and Table 3, the maximum slant range (and minimum elevation) has improved relative to NAV CANADA’s 125W clear sky test, which is likely due to the higher power transmissions (200W) on the Polaris aircraft. Additionally, the UI performance is shifted due to the high density of aircraft with 1090 MHz transmissions (ADS-B, Mode S, and ATCRBS). However, the 95th percentile UI is about 10s which is an improvement on the performance of the expected value of 15s for two payloads. Better receiver range performance comes with the counteracting Pd penalty of increased potential for overlapping message interference. A more detailed

The slant range histogram in Figure 6 shows excellent performance at long ranges and certainly exceeded expectations for a 125W aircraft. Over 13% of the measured elevation angles were less than the expected minimum of ~7 degrees. This is likely due to an overly conservative atmospheric attenuation model [13] and a receiver that surpasses its anticipated sensitivity (probability of detection versus signal strength). Table 1 summarizes expected versus measured performance for some key parameters.

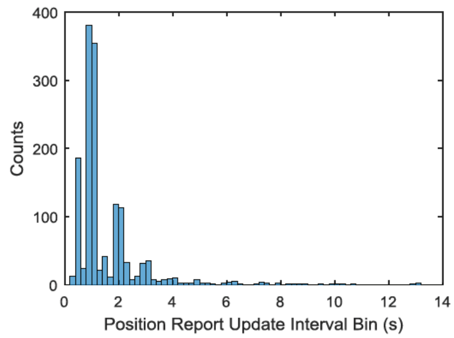


Figure 6: Measured Slant Range for NAV

Table 1: Summary of NAV Results for 125W

From 1 Payload	Best Expected	Best Measured
Aircraft Elevation (deg)	7.00	0.08
Slant Range (km)	2550	3229
95th % Update Int.(s)	8.00	4.09

FAA Results

The flight test for the FAA aircraft was on 3/30/2017 with a takeoff time from the FAA Tech Center airport at 17:40Z. During this flight test, three Aireon payloads were available to receive data, offering significantly more samples than if only one payload was in operation. Figure 7 shows the measured UI performance and the results look strikingly similar to terrestrial ADS-B coverage with the characteristic descending "harmonics" in the histogram at 1s intervals. Figure 8 reveals an impressive set of slant ranges, including a sizeable cluster near 3500 km. The differences in the slant range histograms from Figure 6 compared to Figure 8 are mainly due to variations in geometry from the payloads relative to the aircraft for a particular time period (as opposed to being an isolated measure of performance vs. slant range). Table 2 summarizes expected versus measured performance for some key parameters.

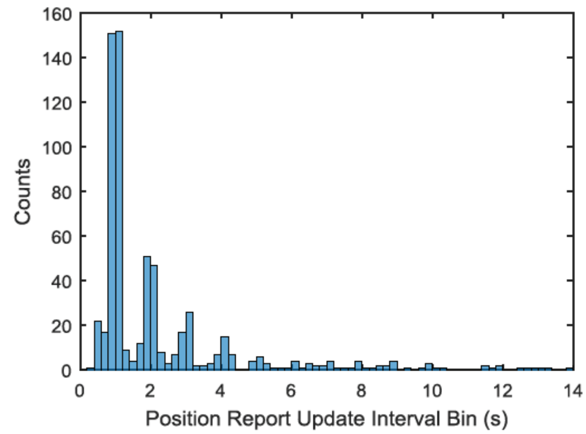


Figure 7: Measured UI for FAA Aircraft

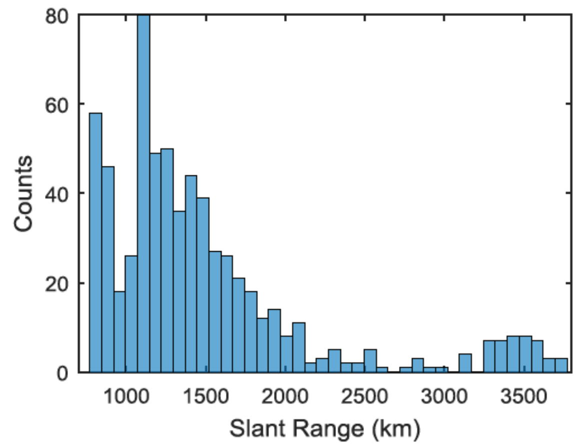


Figure 8: Measured Slant Range for FAA

Table 2: Summary of FAA Results for 125W

From 3 Payloads	Best Expected	Best Measured
Aircraft Elevation (deg)	7.00	-4.58
Slant Range (km)	2550	3768
95th % Update Int.(s)	15.00	10.02

One of the reasons why the UIs are distributed more towards higher values in Figure 7 than Figure 5 is that the NAV CANADA aircraft flew in significantly lower density airspace than the FAA aircraft. Even though the FAA aircraft was in an oceanic airspace, it is adjacent to one of the busiest airspaces in the world and the receiver beam footprints can cover over 1500 km in diameter. In order to more accurately portray this environment, the interference environment must be measured and tuned in the model.

Once the Clear Sky model is tuned and validated then the High Interference portion of the model can be layered on top to analyze the aggregate system model.

The first challenge was met by requesting and commissioning flight test aircraft from NAV CANADA and the FAA. Both Air Navigation Service Providers (ANSPs) have several aircraft that they use for specialized flight tests of equipment that supports their operations. Some examples of safety-critical equipment that ANSPs test with these aircraft are: ADS-B ground stations [8] [9], radars [10], multi-lateration systems [11], and navigation aids [12].

The use of controlled flight test aircraft allowed the uncertainties of the Clear Sky test to be significantly reduced. The FAA and NAV CANADA flight test crews are highly experienced in setting and calibrating the avionics and antennas as well as flying unique flight plans. This leads to resolving the second challenge. The NAV CANADA aircraft (a CRJ-200) was planned for a flight in the Northern Territories where the aircraft density is very low (Figure 2). The FAA aircraft (a Global 5000) planned a flight from the William J Hughes Technical Center (WJHTC) in Atlantic City, New Jersey (KACY) approximately 500 NM eastward into the New York Oceanic airspace (KZWY) and then returned (Figure 3)

Figure 2: NAV Flight Test Plan and Aircraft1

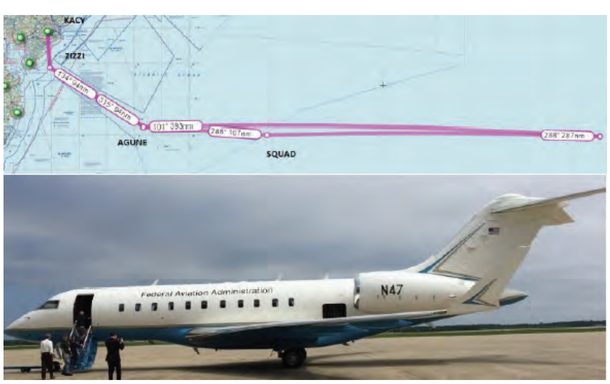


Figure 3: FAA Flight Test Plan and Aircraft2

NAV CANADA Results

During the time of this NAV CANADA flight test, 3/7/2017, only one Aireon payload was providing ADS-B data due to the stepwise schedule in gradually implementing the new satellites into the constellation. With limited coverage, bandwidth, and time due to the ~17,000 mph satellite orbit speeds, the flight tests had to be executed within a narrow window. Only less than or equal to 11 minutes of coverage is expected for each "pass" of the satellite relative to a given point on the earth over a 100 minute orbital period. The orbital planes are approximately "fixed" while the earth rotates underneath the planes which leads to the satellite coverage migrating westward. Given the westbound flight with a ground speed at about 320-420 knots, the NAV aircraft stayed in view of the satellite vehicle for 4 passes (see Figure 4).

Figure 4: Overview of the Passes

6935 ADS-B messages were received from the NAV CANADA flight test aircraft during this event with about 1500 ASTERIX CAT021 reports, which are triggered by position messages and filtered for duplicate messages from overlapping receiver beams. The histogram of Update Interval (UI) measurements is shown in Figure 5, showing a mean value close to 1s. Some of the outliers in this histogram is due to channel fading from a single satellite (near the edges of coverage) and will be further improved when the full constellation of 66 new satellites is operational.

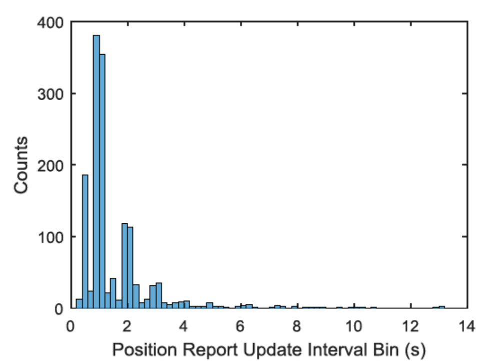


Figure 5: Measured UI for NAV Aircraft

[16]
Eurocontrol/RTCA, "Techinical Link Assessment Team (TLAT) Report," 2001.

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A COMPILATION OF MEASURED ADS-B PERFORMANCE CHARACTERISTICS FROM AIREON'S ON-ORBIT TEST PROGRAM

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Abstract

In just a few short years, space-based ADS-B has already transformed the roadmap for aircraft surveillance within the Air Traffic Management (ATM) industry. ADS-B (Automatic Dependent Surveillance – Broadcast) avionics is rapidly becoming mandatory aircraft equipage for many airspaces [1] [2]. ADS-B is ushering in a new era of flight tracking, surveillance, improved safety, and increased efficiency [3] [4]. Operational acceptance by Air Navigation Service Providers (ANSPs) of new technologies such as space-based ADS-B will depend in part on the outcomes of rigorous testing. Aireon conducted a series of on-orbit tests and characterizations to verify and validate key requirements and expectations of the system. The group of requirements with the highest priority for validation are known as the Technical Performance Metrics (TPMs) and are composed of Availability, Latency, and Update Interval.

Although initial results with a handful of payloads were shared in prior publications [5, 6], this paper will discuss results observed with 55 out of 66 payloads receiving ADS-B data. In addition, various constraints were removed from the system over time, leading to gradual improvements in all TPMs. Furthermore, certain classes of ADS-B transmitters (e.g. bottom-only antenna aircraft) were analyzed in isolation to better understand their performance profiles versus the general air transport population. The results contained in this work should help illuminate the key current capabilities of the Aireon system as well as the remaining expectations left to be demonstrated at the completion of formal Service Acceptance Testing (SACT).

I. Payload Coverage

One of the most pleasant surprises about analyzing the Aireon hosted payload's coverage of ADS-B equipped aircraft is that the range of coverage far exceeds the design target. As discussed in early on orbit results [6, 7] the design goal for the minimum elevation angle of coverage from a single payload is 8.2 degrees (range of 2465 km) and the actual measured minimum elevation often extends to -4.6 degrees (3800 km).

Figure 1 shows a 60s time-lapse coverage plot of the payload on Satellite Vehicle (SV) 164 with a zero-degree elevation footprint outline at the current time (solid) and 60s in the future (dotted). The bottom half of the figure is a range histogram showing high position message counts at 3400 km with a trailing edge towards 3800 km. Considering the satellites move fast (~17,000 mph towards the poles) this histogram will change its characteristics quickly based on the location of the satellite and the ADS-B aircraft density and distribution.

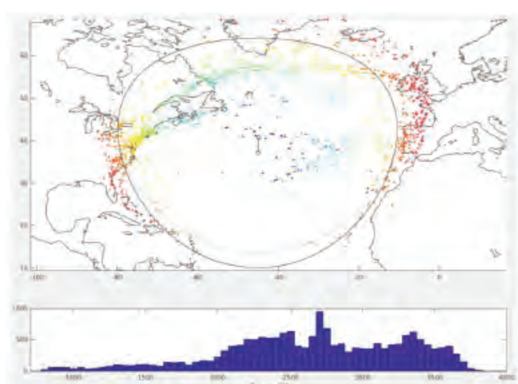

Figure 1: SV164 Coverage Plot and Range Histogram with a Zero Elevation Outline

Using an analog to the Minimum Trigger Level (MTL) of 90% of the nominal probability of detection (Pd), which is often used to define the edge of coverage for receivers, Aireon's MTL from an elevation perspective is measured to be approximately 0 degrees (3250 km). As will be discussed in the subsequent sections, the key TPMs of aircraft surveillance (Availability, Update Interval, and Latency) gain significant benefits from this extended payload footprint coverage.

II. Availability

Availability is the "promise" (and ideally realization) of meeting all the other TPMs. This can be calculated by:

$$A = \frac{MTBF}{MTBF + MTTR} \text{ or}$$

$$A = \frac{Uptime}{Uptime + Downtime}$$

Where A = Service Availability, MTBF = Mean Time Between Failure, and MTTR = Mean Time to Repair/Restore. For any surveillance system, there is typically the concern about losing one of the receivers and how it may impact operations. Redundant systems are commonly put in place to reduce the likelihood of such incidents (e.g. collocating two receiver devices at each site) and therefore increase MTBF. Aireon has taken a similar approach with redundant receiver subsystems onboard each SV. Each SV also has 4 crosslinks and 2 feederlinks (which is somewhat analogous to having 6 telco links per asset).

If those redundant critical systems fail on a given SV/payload, then a coverage gap may exist. The size and timing of the gap depends on how well neighboring payloads can cover the area for a failed payload. Since the Iridium constellation converges at the North and South poles, overlapping coverage increases the closer a region is to the poles. Figure 2 shows how single (green), double (yellow), and triple or higher (blue) coverage looks for an assumed minimum elevation of 8.2 degrees for a snapshot in time. If this was the range of the payload, a single SV/payload outage scenario would cause about 8 minutes without coverage for an equatorial service volume 2-3 times per day until it's resolved. Above about 60 degrees of latitude (or below -60 in the southern hemisphere) there's always at least double coverage and therefore 1 SV outage would have no impact there.

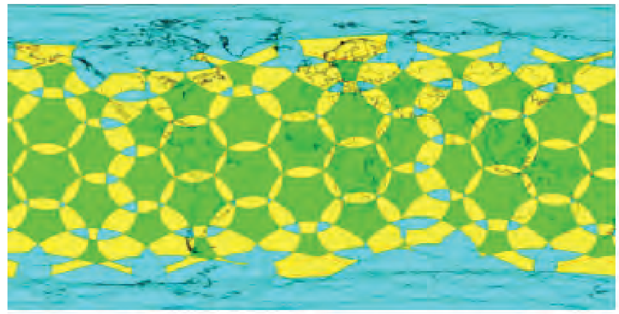

Figure 2: Coverage Overlap for Elev = 8 deg

However, if the minimum elevation coverage is closer to 0 degrees (as discussed in the previous section) then the areas of single-payload coverage shrink dramatically as shown in Figure 3. The latitudes of double or more coverage shift by 20 degrees to ±43 degrees. Additionally, the worst-case outage times for equatorial service volumes (such as Singapore FIR) reduce to ~3 minutes twice daily. Therefore, the MTBF (continuity of service) increased and MTTR decreased significantly, resulting in end-to-end service volume availability estimates above 0.9999.

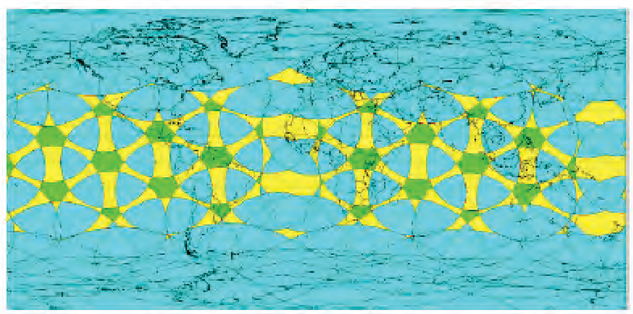

Figure 3: Coverage Overlap for Elev = 0 deg

Using a satellite dynamics simulation tool with Iridium's orbital configuration, test points were placed at latitudes of 0, 20, 30, 40, and 60 degrees. Over a range of minimum elevation angles (-5 to 8 degrees), the number of satellites covering each of these test points is calculated over a 24 hour period in 1 second time steps to determine the maximum duration that each of these points has single satellite coverage. The results from this simulation are summarized in Figure 4.

The observations of the results in Figure 4 indicate that the maximum coverage gap times decrease in nearly bilinear form for the latitude test points of 30 and 40 degrees with inflection points that have steeper slopes at 0 and 3.5 degrees, respectively. At the payload receiver MTL elevation of 0 degrees, latitudes above 40 degrees have no appreciable gap time, at 40 degrees it's just under 60 seconds, and for latitudes between 0-30 degrees the gap times are approximately 3.5 minutes. When there is a single payload outage, latitudes with gap times of 60 seconds or higher occur twice daily at the same longitude. For example, for a single payload outage, Singapore's airspace would experience a 3.5-minute outage in the first part of the day, then complete continuous coverage for 12 hours and then another 3.5-minute outage in the latter half of the day.

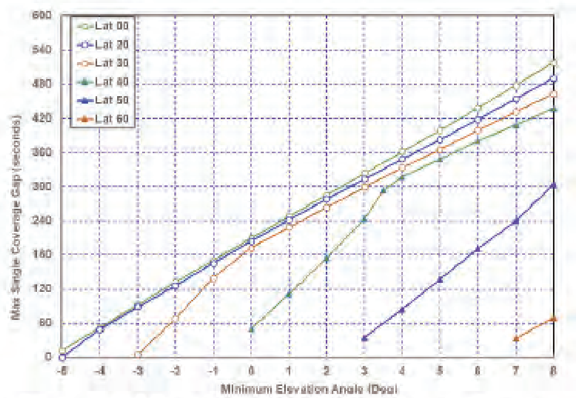

Figure 4: Maximum Single Coverage Gap vs. Elevation Angle in different Latitude Zones

Considering that most terrestrial surveillance systems have a MTTR of 30 minutes or greater, a worst-case "repair time" of 3.5 minutes is at least an order of magnitude better than the standard [8]. The anticipated outage behaviors related to the payload that would last greater than 24 hours have a MTBF of greater than 100,000 hours, which helps contain the overall risk such that a service volume availability of ≥ 0.9999 is achievable even for areas near the equator.

III. Latency

Latency is the delay measured from the time an ADS-B message is received at the hosted payload to the time an ADS-B report is delivered to the Service Delivery Point (SDP). The time of flight for a transmitted aircraft message to the reach the payload in space is less than 14 us and is rather insignificant when compared to the uncompensated latency of up to 400 ms within the ADS-B transponder. Since the ADS-B message is timestamped at the Aireon payload, uncompensated latency added to the transponder's budget is negligible, and the focus tends to be on the end-to-end latency (which can be compensated for by a tracker) within the Aireon system. The SDP is typically deployed at an ATC facility and locally networked to a tracker and automation subsystem.

The system latency budget required by ED-129B is 2.0s, which includes 1.5s to the edge of a distribution network and 0.5s within a distribution network to a tracker interface [8]. Aireon's design specification is for 1.5s (99%) to a SDP at an ATC site although a margin of about 200 ms is provisioned relative to this requirement. Figure 5 shows the results from a Monte-Carlo simulation estimating the expected system latency profile when aggregating the statistics from subsystem (e.g. payload, satellite segment, ground segment) latency requirements. Therefore, a design margin of approximately 700 ms is available relative to the ED-129B requirement.

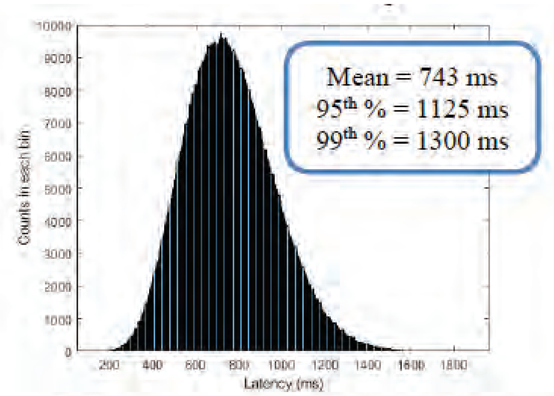

Figure 5: Requirements-based Model of Latency

As of Sept 2018, Aireon has 4 remote (at the customer location) SDPs deployed and 2 local (within the APD control station). Local SDPs should naturally have lower latency results than remote, but the observed results only show ~50 ms of difference between them. The measured results from the system can be visualized in Figure 6 with the aggregate statistics highlighted within the figure. These latency results, measured from the payload receiver to different end point locations, show an impressive 1655 ms of margin relative to the 2.0s requirement. Latency characteristics of 345 ms (99%) are clearly well within the same domain as terrestrial surveillance systems and in some cases faster.

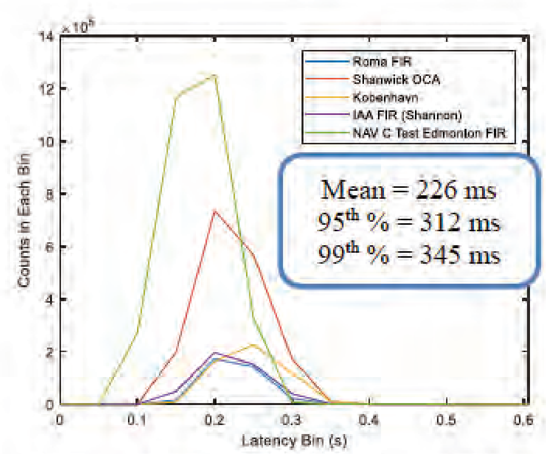

Figure 6: Measured Latency to 5 SDPs

There are slight dependencies of latency on geography wherein the more northern latitudes will tend to have lower latencies as shown in Figure 7 due to their closer proximity to a teleport site (such as Svalbard, Norway), but these variations are less than 50 ms at the 95th percentile.

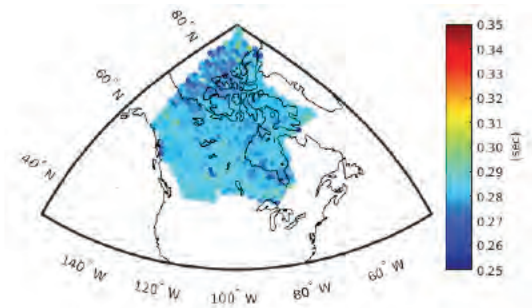

Figure 7: Edmonton FIR 95th % Latency Grid

IV. Update Interval

The update interval (UI), or more appropriately the probability of update (PUI), is measured at the SDP from a population of time intervals between sequential ADS-B reports for each respective aircraft. For low density en-route (5 NM separation) airspaces, the requirement from ED-129B is to meet a UI of 8s with a probability of 96% or higher. To achieve this level of performance, the mean aggregate Pd of the receivers needs to be greater than or equal to 18.2% [9].

Consistently achieving that degree of performance can be challenging when taking into consideration aircraft transmit power, additional attenuation to the bottom antenna, high interference environments, and limited bandwidth and power resources on the payload [9, 5, 7, 10]. However, since solutions to these challenges were developed early in the Aireon program along with the flexibility to adapt and tune post-launch, the results in this section will demonstrate the achievements made thus far to address these challenges.

One mitigation to the temporary limitations in bandwidth (which will be resolved by routing changes in Nov 2018) was to reduce the number of payloads providing service to 55 (only 5 out of 6 orbital planes) and allocate all available bandwidth to this "miniconstellation".

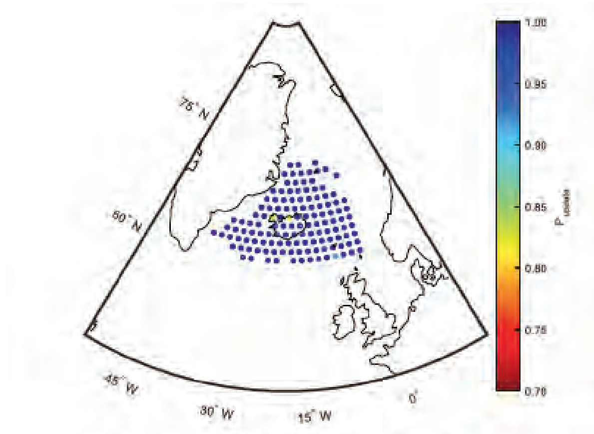

Figure 8: Reykjavik FIR P_{UI} Grid

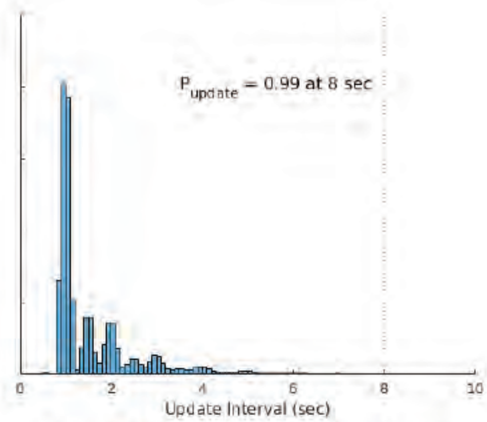

Figure 9: Reykjavik FIR UI Histogram

Update interval can also be viewed within various segments of the population to determine how they perform relative to the majority population or intended use. As an example, several aircraft types, such as the Cessna 402C, typically have bottom-only antenna transponders. In prior work, the relative attenuation from the top to bottom antenna over the elevation angle was estimated to be linear [9]. This means that reception of messages from a space-based ADS-B receiver to an aircraft's bottom antenna would be best at lower elevation angles (nominally below 20 degrees). However, given the extended range described in Section I, elevation coverage below 8 degrees offers additional detection opportunities that can lead to beneficial performance. Figure 10 shows a track from a bottom-only ADS-B aircraft flying from Puerto Rico SJU airport (latitude ~ 18.4°) to St. Thomas. Although there are a few gaps in coverage, the PUI over 30s intervals is 98.5%, which could be suitable for situational awareness and tracking applications. Additionally, this performance is expected to further improve with the additional 11 payloads of coverage and increased bandwidth. Performance is also expected to improve at latitudes closer to the poles due to the increase in low elevation angle coverage opportunities. By comparison, smaller satellites (e.g. cubesats, nanosats) would likely have more difficulty detecting bottom-only aircraft since their smaller aperture receivers would have more channel fading at lower elevation angles.

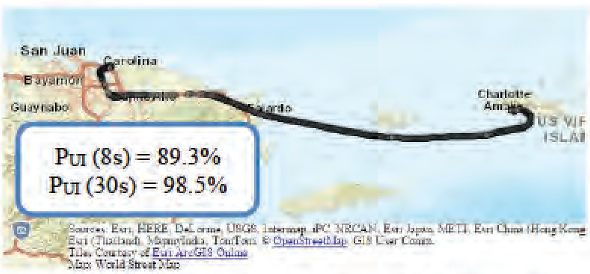

Figure 10: Cessna 402C Bottom-Only Reception from Puerto Rico to St. Thomas

Another example segment of the ADS-B aircraft population is that of aircraft that are on the surface of an airport. The airport surface can be a busy environment and there are often challenges for terrestrial systems with finding suitable sites to provide adequate coverage of the entire movement and non-movement areas. Considering the Aireon payload has an extreme bird's eye view at 780 km, building shadowing and link margin differences relative to 18,000' (5.5 km) are typically insignificant factors from space. Additionally, upon landing, most aircraft with diversity antennas will broadcast all messages out of their top antenna which is beneficial for a space-based receiver. Figure 11 shows an example of a coverage plot at Keflavik (KEF) airport in Iceland over a 24 hour period. The aggregate PUI (5s and 8s) is 99%, which is aligned with the results from the whole FIR shown in Figure 8 and Figure 9. The combined performance would provide a seamless continuity of service from en-route (8s) to terminal/approach (5s) to surface (although surface would require a UI of 1s).

With only 55 payloads in use, the UI was measured over the Reykjavik FIR showing near uniform results throughout the airspace at a PUI of approximately 99% for an 8s UI (see Figure 8). Figure 9 shows the full histogram of UI results as an aggregate over the 3-hour window the service volume had full coverage.

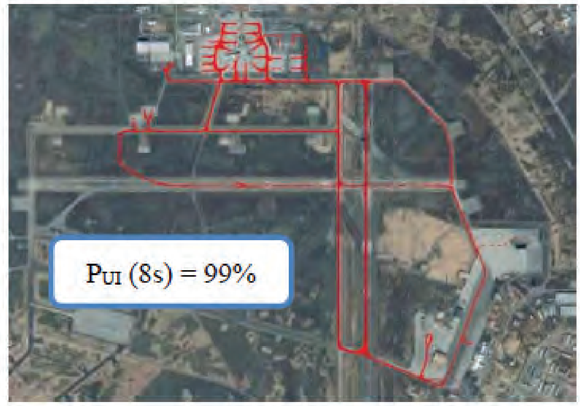

Figure 11: Surface coverage of Keflavik Airport

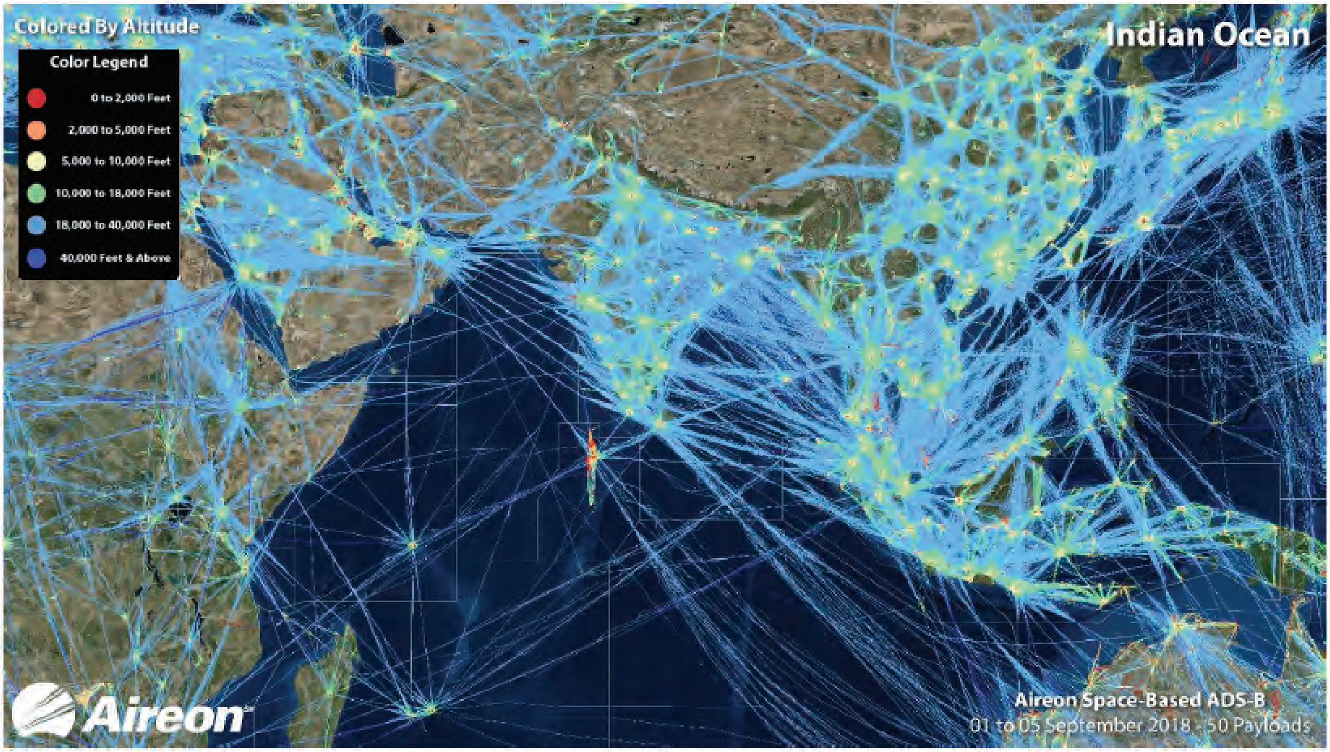

Figure 12: Aireon's ADS-B Coverage (Colored by Altitude) from Sept 1-5, 2018 with 50 Payloads

V. Conclusion

he key surveillance TPMs of availability, latency, and update interval were demonstrated in this paper from the Aireon system. In each case, significant margin was found in the measurements relative to the internal and external requirements. These results were achieved even with a partial constellation and other temporary constraints. Even in this state, Aireon receives about 10 billion ADS-B position messages per month and this number is expected to rise by several fold by the end of 2018. Figure 12 shows a depiction of the coverage over several areas in the southeast region of the world with altitude color contrast highlighting areas with terminal, airport, and helicopter operations. Clearly the potential of this system has only begun to be explored, giving rise to new metrics and a

VI. Acknowledgements

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V. Summary

Each test discussed in this analysis consistently shows the measured performance of the Aireon payload going beyond expectations. With over one hundred thousand unique ADS-B aircraft and hundreds of millions of messages observed from a few payloads in just one month, this is clearly only the beginning of discovering the system's full potential. More testing, analysis, and tuning will certainly be necessary for both the first set of payloads as well as the other payloads that are launched and placed into mission orbit. However, these initial results certainly increase confidence that, with a complete constellation, an 8s UI will be achievable by Aireon in the majority if not all airspaces.

These results would be difficult (if not highly unlikely) to be produced from prototype, experimental, novelty, or adoption-limited technologies for continuous ATC-grade surveillance and global flight tracking. For example, hundreds of small-sats/cubesats would be needed to generate global coverage without loss of continuity from a given aircraft. Geosynchronous satellites have a much higher latency and tougher link budget to overcome than low-earth orbiting constellations. As another example, although 15 minute updates can be provided by ADS-C, the platform does not readily support much higher update rates at the same aircraft capacity levels as an enterprise space-based ADS-B system.

Acknowledgements

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