International Civil Aviation Organization
South American Regional Office
Nineteenth Meeting/Workshop of the SAM Implementation Group
(SAM/IG/19) – RLA/06/901 Regional Project
(Lima, Peru, 22 to 26 May 2017)

SAM/IG/19-WP/20
17/05/2017

Agenda Item 4: **Assessment of operational requirements to determine the implementation of improvements in communications, navigation and surveillance (CNS) capabilities for operations in route and terminal area**

SPACE-BASED ADS-B SURVEILLANCE DATA AND ITS DISTIBUTION VIA REDDIG II

(Presented by AIREON)

SUMMARY

The objective of this Working Paper is to present the progress on the analysis by Aireon about the potential use of REDDIG network to distribute Space-based ADS-B data to SAM States.

References:

- Meeting Report SAM/IG/18
- Meeting Report RCC/20

ICAO Strategic Objectives:	*A - Safety* *B – Air navigation capacity and efficiency*

1. Background

The Aireon program

1.1 Aireon is the only ATS Surveillance provider that from 2018 will offer worldwide coverage of ADS-B data. The company has been created by four ANSPs (NavCanada, ENAV, IAA, Naviair) and Iridium as technological partner, that together have realized a quite simple and efficient idea: install on each of the new Iridium NEXT satellites, flying in Low Earth Orbit altitude, a payload able to receive ADS-B messages sent on the frequency 1090Mhz. The constellation will be composed by 66 operational satellites, plus 6 spares on orbit and 9 spares on the ground. In January 2017, the first 10 satellites were launched and they are already receiving ADS-B messages, with excellent results. The first flight tests conducted by Nav Canada, FAA and Polaris have also been successful. Results are shown in Appendix A to this WP, titled “Aireon’s Initial On-Orbit Performance Analysis on Space-based ADS-B”. Many ANSPs all around the world are now planning a V&V activity that will prove the quality of the Satellite ADS-B data. Furthermore, the European Aviation Safety Agency (EASA) is in the process of certifying Aireon as a Pan European Surveillance service provider. This will be done based on EUROCAE/RTCA ADS-B performance criteria. The effect of this certification will be that Space-based ADS-B globally will be comparable to at least a Long Range Surveillance System supporting 5 NM En-Route Separation.

1.2 From 2018, the worldwide airspace will have another layer of ATS Surveillance, totally independent from ground sensors, which will be translated on the fact that in oceanic and remote areas, currently not covered by any ATS Surveillance technology, the ATCOs will have a real-time position coming from aircrafts, with a drastic increase of safety and possibility to adopt more optimized delivery of Air Traffic Services and revised remote location Separation Minima. Plus, for continental airspace, already covered by ATS Surveillance technology and DCPC (e.g. VHF), the ability to have another layer of surveillance can unlock further operational optimization (such as moving to 5NM in En-Route), as well as have a perfect solution for contingency in case of radar failures or problem on ground facilities.

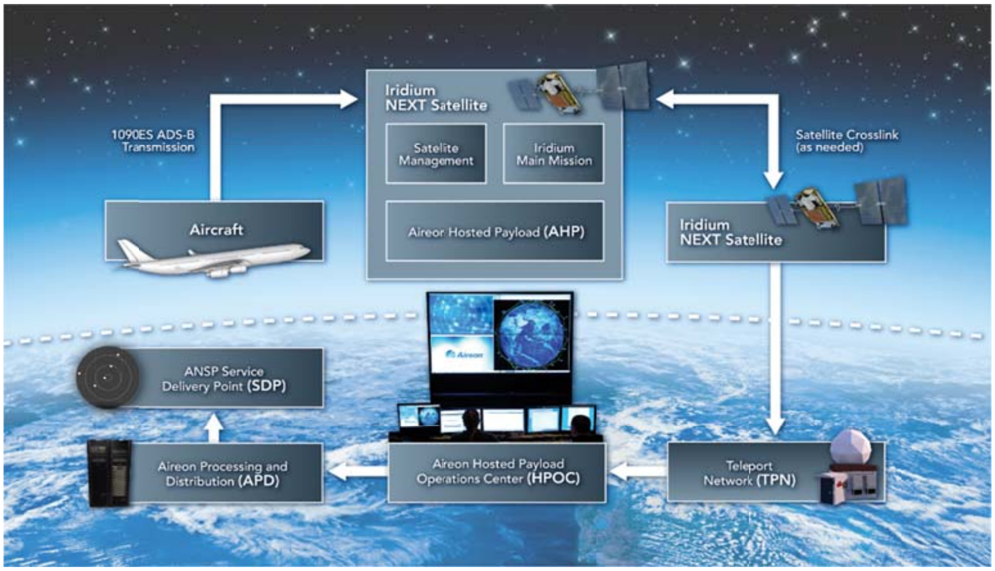

Figure 1 - Aireon Satellite ADS-B data flow

Aireon data distribution

1.3 As from Figure 1, the connection between the Aireon APD and the specific ANSP is typically done through a dual MPLS connection that will connect the APD with a Service Delivery Point (SPD) installed on the ANSP site.

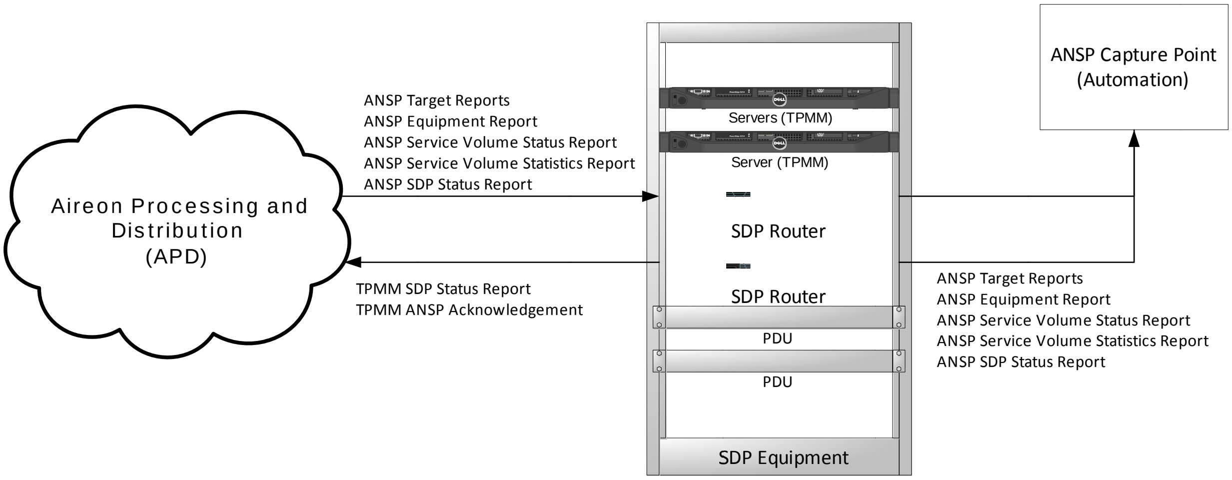

Figure 2 – Typical ANSP Service Delivery Point (SDP) hardware

1.4 The SDP (Fig. 2) is the real demarcation point between the Aireon domain and the ANSP domain: the outcome of the SDP is the surveillance data for that ANSP, ready to be integrated into the ATC automation platform (tracker).

1.5 Since ADS-B messages are small in terms of byte, the link between Aireon and the ANSPs does not require much bandwidth, but it is important to have a robust link. Since MPLS connections in some regions can be expensive and to optimize connections with the APD, as well as to optimize the use of SDPs in a region, Aireon aims to analyze the possibility to use regional networks already in place around the world, such as REDDIG, MEVA or PENS, for data distribution of the Aireon surveillance data in each region.

2. **Analysis**

REDDIG as SAM Regional Network

2.1 REDDIG is the Regional data distribution that ANSPs are using in South America. It is a combination of VSAT and MPLS connections and it is providing a very solid link and all 14 ANSPs are already interconnected with this network.

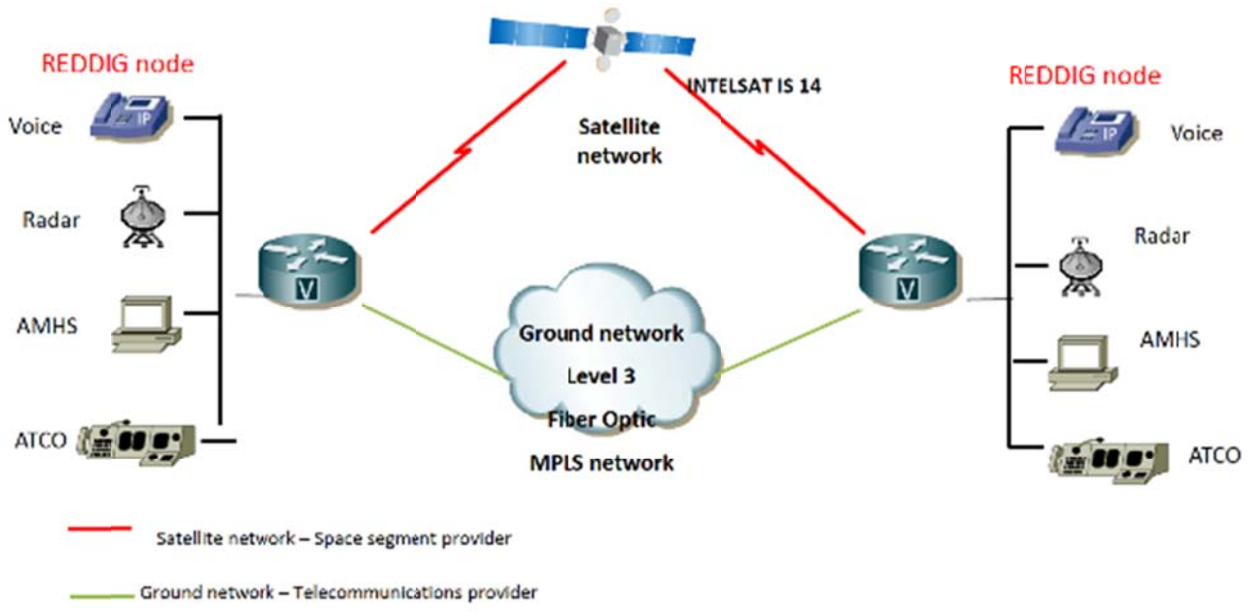

Figure 3 - REDDIG architecture

2.2 The network is owned by the States, and managed under the supervision of ICAO South America regional office.

2.3 By the usage of the REDDIG network to distribute Space-based ADS-B data, implementation and distribution costs could be minimized by those States interested in subscribing to the system.

Space-based ADS-B data distribution through REDDIG

2.4 With the use of REDDIG, Aireon could connect the APD located in Virginia (USA) to potentially two (2) or more Service Delivery Points (SDPs) strategically located in the South American Region, via MPLS connections and distribute the data to the entire region via REDDIG (Fig. 4).

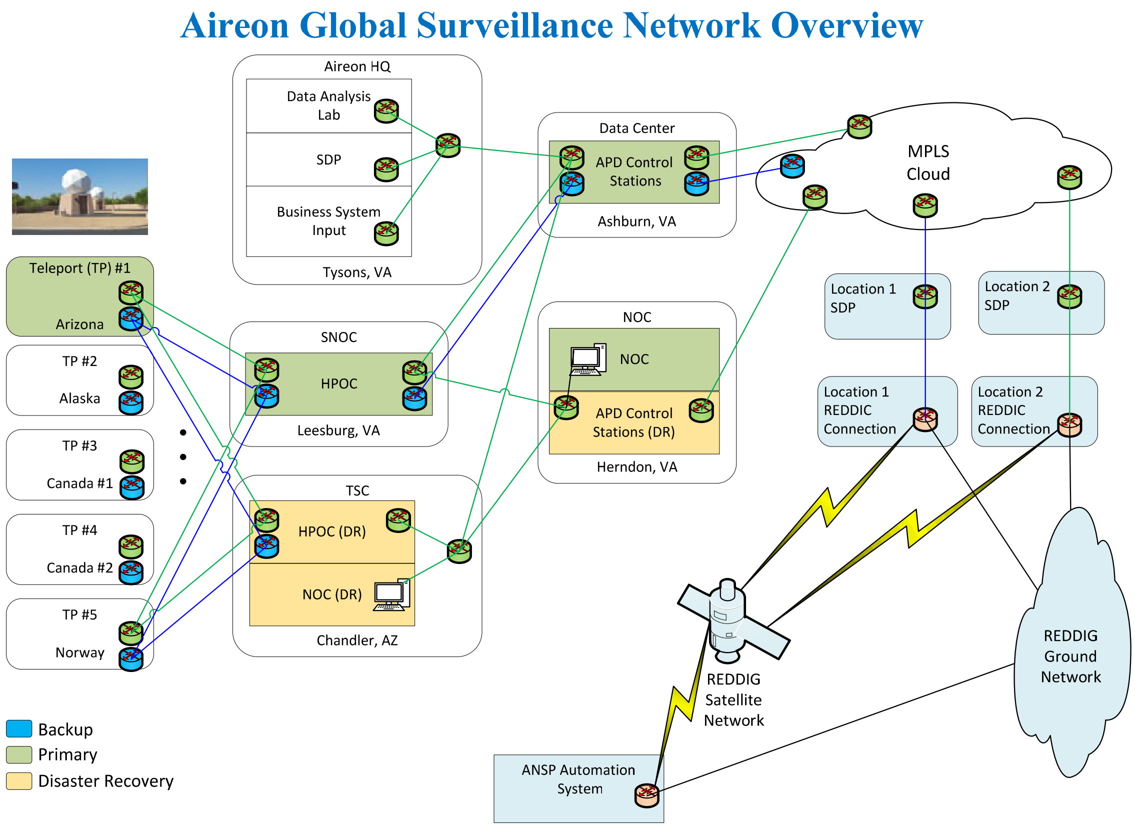

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Figure 4 – Regional Service Delivery Point (SDP) hardware

2.5 Each of the SDPs will be able to inject, as separate VPNs, the Satellite ADS-B data of each ANSP that would like to get those data. The demarcation point for Aireon will then be at the entrance of the REDDIG network, after which the REDDIG network manager will care about the data distribution. In this way, there will be only 2 solid MPLS connections between Aireon APD and REDDIG network, optimizing so costs and performances. This approach also provides geographical diversity of the SDPs in case of localized outage of service.

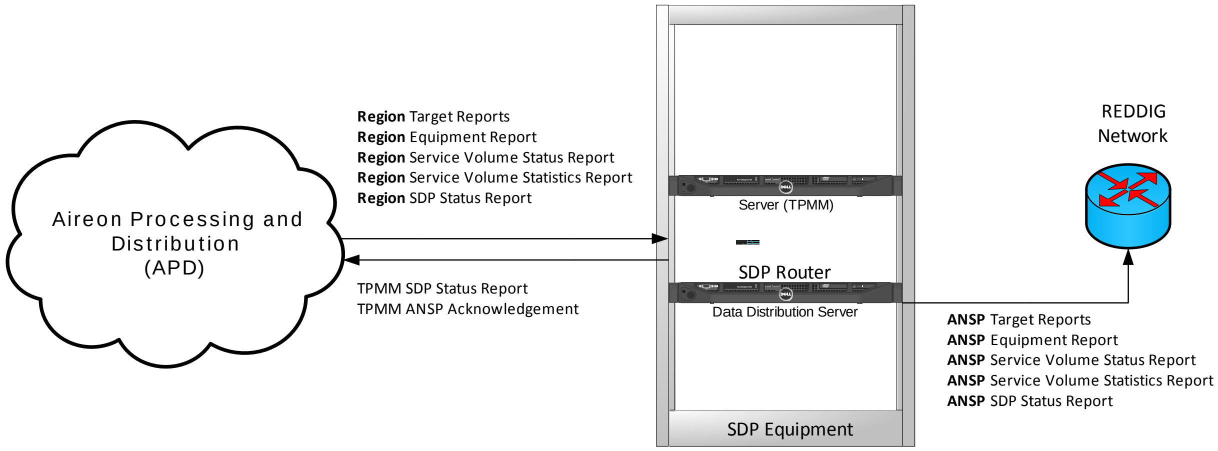
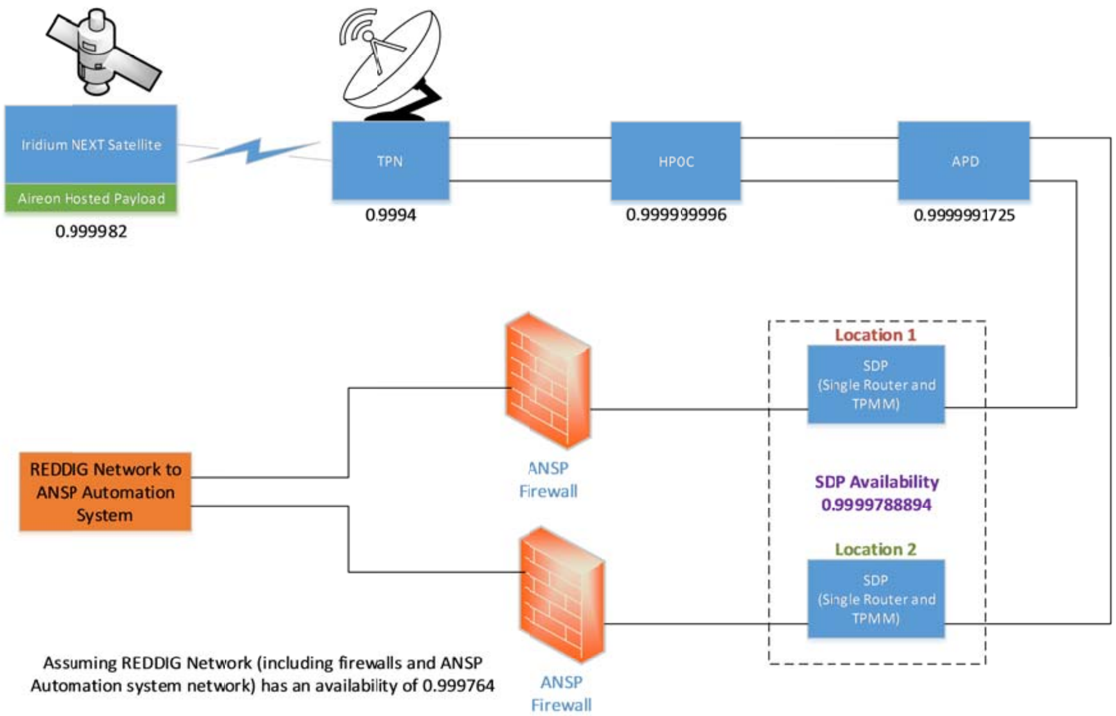


Figure 5 – Regional Service Delivery Point (SDP) hardware

2.6 With this configuration, the availability of the complete network from data reception at the satellites to the ANSP automation system will be greater than 0.999 assuming the REDDIG Network availability is greater than 0.9999 and the MPLS connection from APD to the SDP are at least 0.997.

Availability using two single string SDPs that feed a single Automations Systems



System Availability is 0.99912

2.7 REDDIG Network Requirements

- System Availability > 0.999
- Accepts Multicast Data
- Delivery to Automation system in low latency
- Surveillance data segregation for each of the connected ANSP

2.8 Bandwidth Usage from Aireon's Space-based ADS-B data

As per the request of the RCC/20 meeting, Aireon has estimated the total bandwidth that could be needed in the event all States were to subscribe to Space-based ADS-B data services, for full usage in both terrestrial and oceanic airspace, lower and upper airspace. Table 1 shows the total potential bandwidth from the full usage of the system by all States, estimated at air traffic levels in year 2030, which sums a total of 2,061 kbps for a 24-hour period.

Country	FIR	CAT021		CAT025		CAT238		CAT253		Total	
		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
Guyana	SYGC	9	13	0	1	0	16	6	32	15	62
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
French Guyana	SOOO	9	9	0	1	0	23	6	32	15	65

Table 1. Total potential bandwidth needed by FIR for Space-based ADS-B data services

Space-based ADS-B Data Distribution Implementation Costs

2.9 To determine the economic benefit for ANSPs to get Space-based ADS-B data through REDDIG, Aireon estimated implementation costs from the original design (Fig. 2) where ANSPs would receive the data directly from Aireon's Processing and Distribution Center (APD) in Virginia, and compared it with distributing the data through the regional network (Fig. 4 and 5). Results are shown in Table 2.

Estimated Cost using REDDIG	US$
a. SDP deployment and test costs (2 SDPs) – one-time cost	320,000
b. Telco Cost on 2 locations (single line in each location)/year – recurring cost	95,000
c. Implementation/service acceptance cost per ANSP – one-time cost	112,000

Estimated Cost per ANSP direct connection	US$
a. SDP at ANSP location-one-time cost	300,000
b. Telco Cost per ANSP (dual line)/year-recurring cost	95,000
c. Implementation/service acceptance per ANSP	112,000

Table 2. Cost Comparison of implementing Space-based ADS-B data through REDDIG and directly by each ANSP

Where:

SDP Deployment and Tests Cost

I. Using REDDIG: For Implementation at two REDDIG Nodes - This is a one-time cost to deploy a single sting SDP to two (2) REDDIG connection points. This will allow Aireon Global ADS-B data to be accessed from the REDDIG network by subscribing ANSPs. Cost includes hardware for two (2) single string SDPs (Fig. 5), a single MPLS 2MB Ethernet Point-to-Point circuit to each SDP; SDP Software, and Site Acceptance Test (SAT) (one trip to each location), to verify site is installed and functioning properly. The hosting ANSPs will need to do the installation of the SDPs in accordance with instructions provided by Aireon.

II. ANSP Direct Connection to APD: For Implementation at an ANSP - This is a one-time cost to deploy a redundant SDP at an ANSP facility to connect to the Aireon Global ADS-B data. Cost includes hardware for redundant SDPs (Fig. 2), two MPLS 2MB Ethernet Point-to-Point circuit to the ANSP's SDP; SDP Software, and Site Acceptance Test (SAT) to verify site is install and functioning properly. Each ANSP needs to do the installation of the SDPs in accordance with instructions provided by Aireon.

2.10 Telco Cost: This is a recurring yearly cost for two (2) MPLS connections established and tested during the SDP Implementation above. Cost shown on table 2 is an estimated cost, which may vary depending on the locations selected for the SDP(s) and the availability of MPLS connections in the selected regions.

2.11 Implementation Service Acceptance Test (ISAT) Cost: This is a one-time cost for each ANSP subscribed to receive the service. ISAT is conducted by Aireon prior to testing and assessment by the ANSP and is conducted on a single trip to the ANSP location and testing data relevant to the ANSP. The primary objectives of this test event include:

- Verifying Service target and status data is delivered to the ANSP in the proper format and with the required periodicity,
- Verifying the Service meets ANSP critical performance requirements,
- Verifying the Service coverage meets the service volume coverage requirements defined by the ANSP,
- Verifying the Service is ready for ANSP testing, regulatory evaluation and use.
- Computer-based training
- Engineers travel & living expenses during the duration of the assignment, estimated at 3 months.

2.12 Cost items a and b in Table 1 would be shared among States subscribing to the system, by using REDDIG, whereas they would have to be paid on a one on one basis, in the event each ANSP would install the system directly, with their own SDP and Telco Lines. This demonstrates a clear economic benefit to all ANSPs in the SAM region to use REDDIG as a means for receiving Space-based ADS-B data.

Space-based ADS-B Data Services Cost

2.13 Aireon charges the delivery of ADS-B surveillance data to ANSPs, based on a fixed cost per year that is calculated based on:

- Flight hours flown over the correspondent ANSP airspace/FIR(s)
- Density of traffic that overflies the correspondent ANSP airspace/FIR(s)
- Airspace area: Oceanic or Terrestrial

2.14 Costs will vary between ANSPs as every airspace has its traffic volume and ANSPs may wish to subscribe to portions of airspace or all its controlled airspace. Therefore, these costs have not been included as part of the scope of this WP.

2.15 States that wish to subscribe to Space-based ADS-B surveillance data services are invited to consider the economic benefits of distributing the data through REDDIG and potential economical and operational benefits of implementing such a system regionally, complementing the current surveillance capabilities in the SAM region and augmenting those capabilities by having full surveillance coverage in oceanic, remote and radar-only areas, among other applications as Air Traffic Flow Management (ATFM) and others.

3. Suggested action

3.1 The Meeting is invited to:

a) Take note of the information presented herein;

b) As per the request by States during RCC/20 meeting, continue with the development of the cost analysis to distribute Space-based ADS-B data to interested States through REDDIG; y

c) States to consider the implementation of Space-based ADS-B data services as a regional project.

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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?"

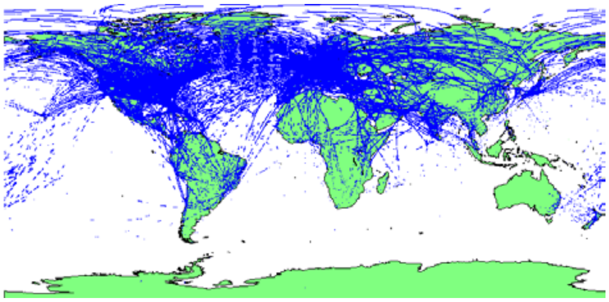

Figure 1: 62 Hours of Stitched Global Coverage

II. 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 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 Aircraft[1]

Figure 3: FAA Flight Test Plan and Aircraft[2]

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).

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[1] Photo Credit: NAV CANADA

[2] Flight Plan Provided by FAA: Source John Kimpton

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.

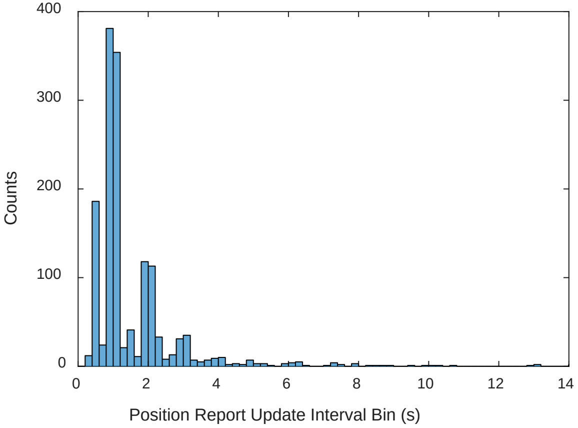

Figure 5: Measured UI for NAV Aircraft

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.

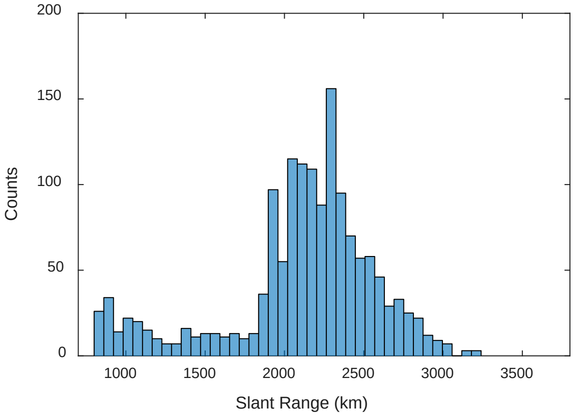

Figure 6: Measured Slant Range for NAV

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.

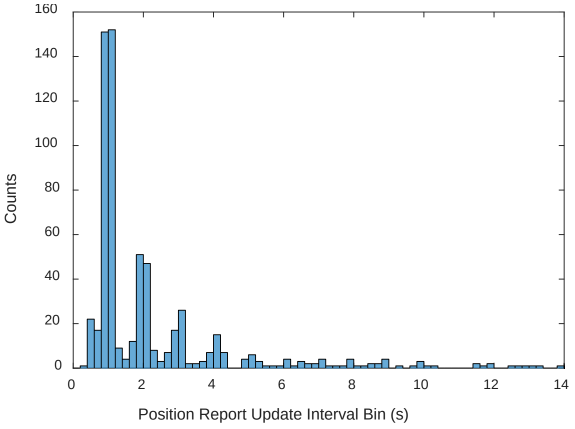

Figure 7: Measured UI for FAA Aircraft

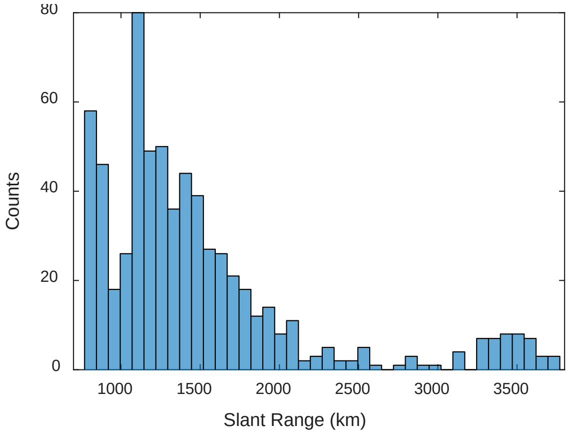

Figure 8: Measured Slant Range for FAA

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.

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.

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[3] Photo Credit: Polaris Flight Systems

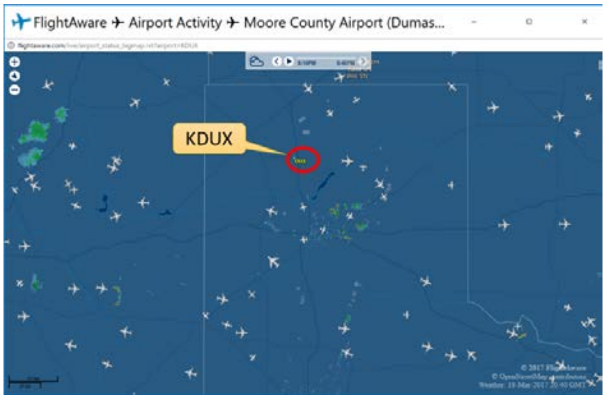

Figure 10: Example Aircraft Density near KDUX[4]

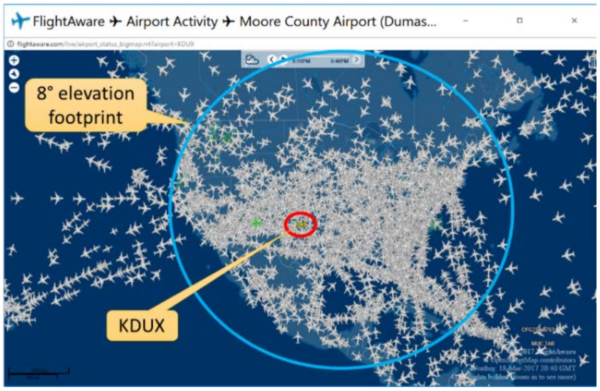

Figure 11: Aircraft Density over North America[5]

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 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 counter-acting Pd penalty of increased potential for overlapping message interference. A more detailed dissection of the measured impact of the interference environment will be more applicable when several additional orbital planes filled 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.

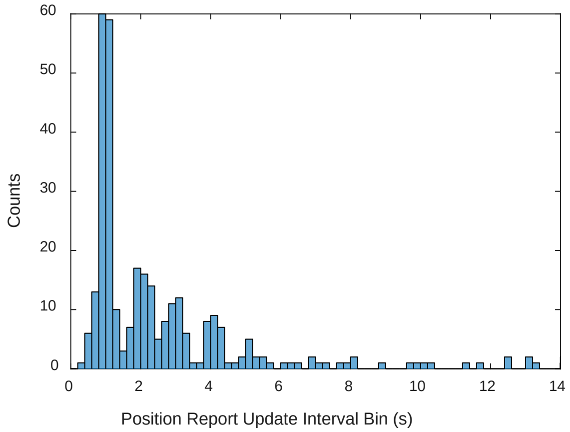

Figure 12: Measured UI for Polaris Aircraft

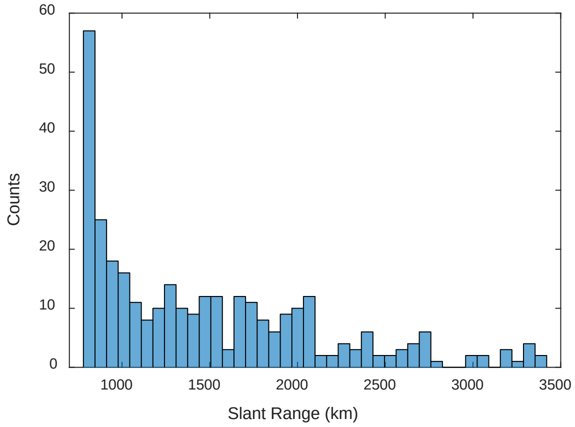

Figure 13: Measured Slant Range for Polaris

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

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[4] Figure Sourced from FlightAware

[5] Figure Sourced from FlightAware

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.

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]

Results

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.

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[6] Photo Credit: NAV Canada

[7] Photo Credit: NAV Canada

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.

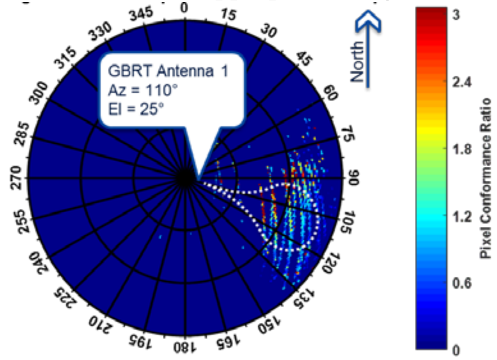

Figure 16: GBRT Spatial Conformance

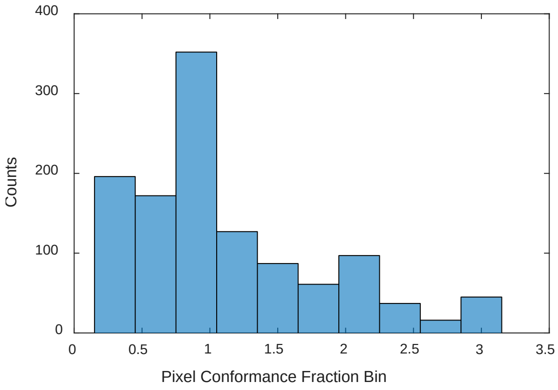

Figure 17: GBRT Pixel Conformance Histogram

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

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.

ANSPs will likely continue to choose a variety of surveillance technologies (as opposed to only one or two) to support separation services in their airspaces. Indeed, most aircraft surveillance systems are not mutually exclusive with each having tradeoffs in performance, operability, and cost. An ANSP is typically motivated to implement an ecosystem of solutions to solve different problems. As evidenced by this paper, once fully deployed, Aireon's Space-Based ADS-B system will be capable of meeting the same performance requirements as terrestrial systems for en-route (8s) and, by extension, oceanic airspaces. This increase in choice and capability for an ANSP is anticipated to bring tangible benefits for the airlines and air traffic community at large.

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References

[1] R. Mark, "Aireon Launch Begins New Era for Satellite-Based Aircraft Surveillance," 17 1 2017. [Online]. Available: http://www.flyingmag.com/aireon-launch-begins-new-era-for-satellite-based-aircraft-surveillance.

[2] M. A. Garcia, J. Stafford, J. Minnix and J. Dolan, "Aireon Space Based ADS-B Performance Model," in *ICNS*, Herndon, 2015.

[3] M. A. Garcia, "Aireon Space Based ADS-B Compatibility and Performance Analysis," in *ESAVS*, Berlin, 2016.

[4] K. Maine, C. Devieux and P. Swan, "Overview of Iridium Satellite Network," in *WESCON*, 1995.

[5] ICAO, "Annex 10, Vol IV, Surveillance and Collision Avoidance Systems," ICAO, 2014.

[6] RTCA, Inc, "Minimum Operational Performance Standards for 1090 MHz ES ADS-B and TIS-B," RTCA, 2009.

[7] EUROCAE, "Technical Specification for a 1090 MHz Extended Squitter ADS-B Ground System," EUROCAE, Malakoff, 2016.

[8] J. C. Moody, B. J. Lascara and W. J. Wilson, "Assessing flight information and traffic data services uplinked to flight test aircraft," in *ICNS*, Herndon, 2012.

[9] G. Wright, "NAV Canada Implements ADS-B," in *ICNS*, Arlington, 2009.

[10] C. Mayer and P. Tzanos, "Comparison of ASR-11 and ASR-9 surveillance radar azimuth error," in *DASC*, Seattle, 2011.

[11] A. Daskalakis, T. Hall and A. Mackey, "Colorado WAM Separations Standards Targets of Opportunity and Flight Test Analysis," in *DASC*, Orlando, 2009.

[12] L. N. Spohnheimer, "Navaids Testing Risks and Their Mitigation," in *DASC*, Indianapolis, 2003.

[13] ITU-R, "Attenuation by atmospheric gases (P.676-9)," ITU, Geneva, 2012.

[14] M. A. Garcia, R. Mueller, E. Innis and B. Veytsman, "An Enhanced Altitude Correction Technique for Improvement of WAM Position Accuracy," in *ICNS*, Herndon, 2012.

[15] ITU-R, "Reception of automatic dependent surveillance broadcast via satellite and compatibility studies with incumbent systesm in the frequency band 1087.7-1092.3 MHz," ITU, Geneva, 2015.

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

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