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

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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?"

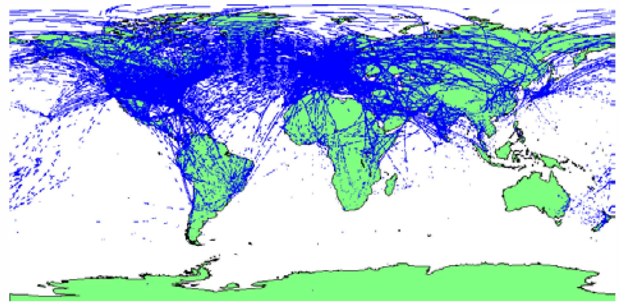

Figure 1. 62 Hours of Stitched Global Coverage

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

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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]

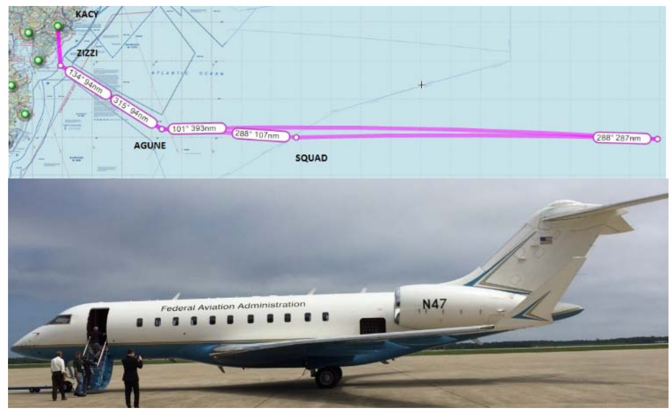

Figure 3. FAA Flight Test Plan and Aircraft[2]

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

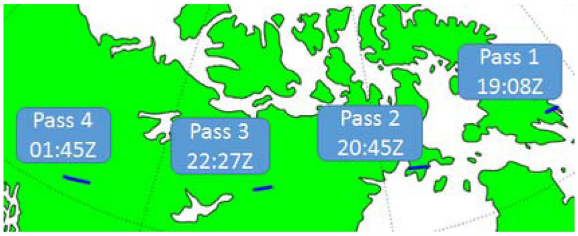

Figure 4. Overview of the Passes

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.

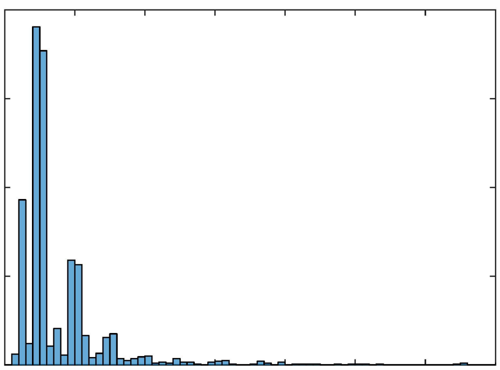

Figure 5. Measured UI for NAV Aircraft

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.

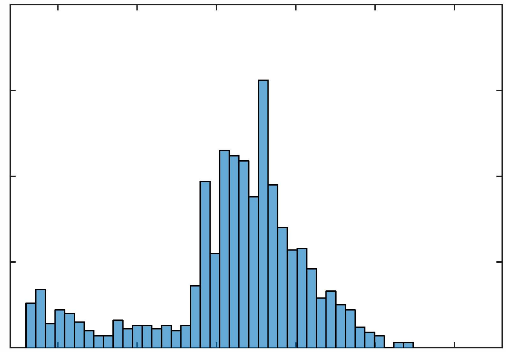

Figure 5. Measured Slant Range for NAV

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.

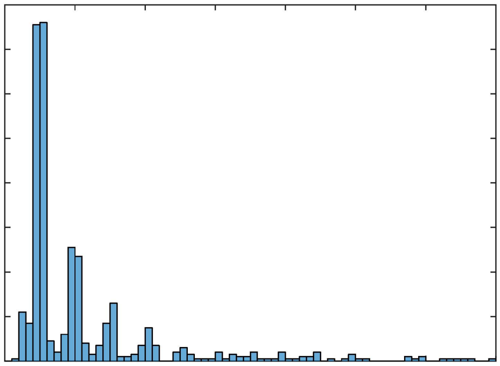

Figure 6. Measured UI for FAA Aircraft

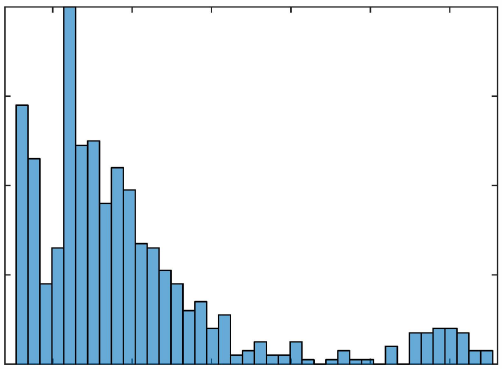

Figure 7. Measured Slant Range for FAA

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 8. 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.

[3] Photo Credit: Polaris Flight Systems

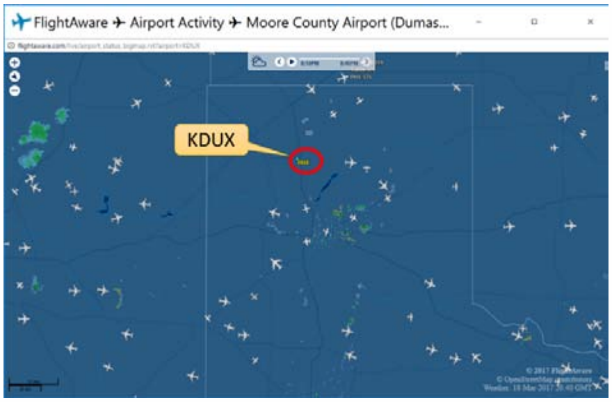

Figure 91 Example Aircraft Density near KDUX[4]

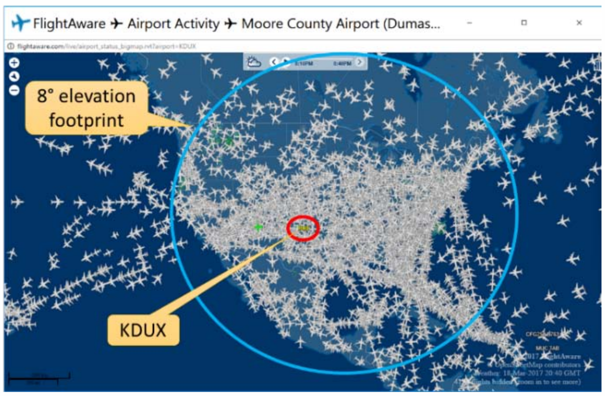

Figure 10. Aircraft Density over North America[5]

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 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 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.

[4] Figure Sourced from FlightAware
[5] Figure Sourced from FlightAware

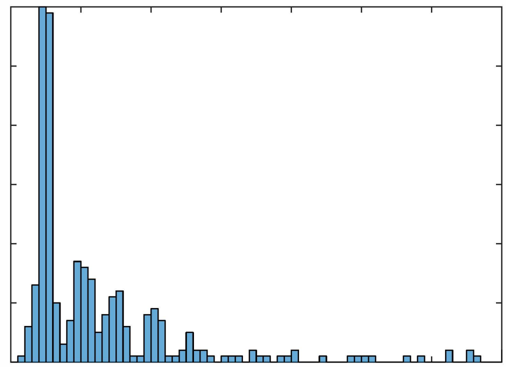

Figure 11. Measured UI for Polaris Aircraft

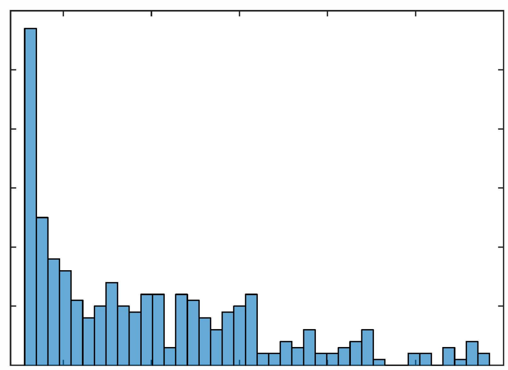

Figure 12. Measured Slant Range for Polaris

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].

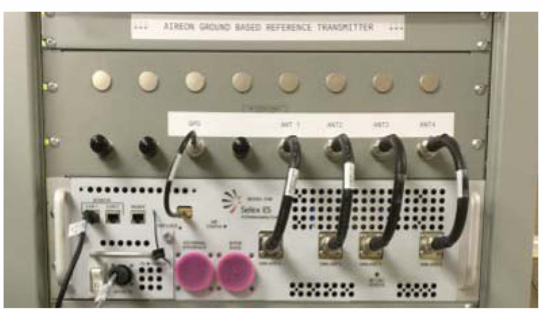

Figure 13. GBRT Selex ADS-B Radio Tx and Rx[6]

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.

Figure 14. GBRT in Iqaluit w/ 4 Tx Antennas[7]

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.

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

[6] Photo Credit: NAV Canada

[7] Photo Credit: NAV Canada

(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.

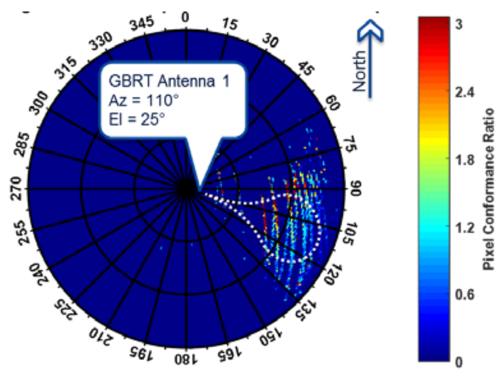

Figure 15. GBRT Spatial Conformance

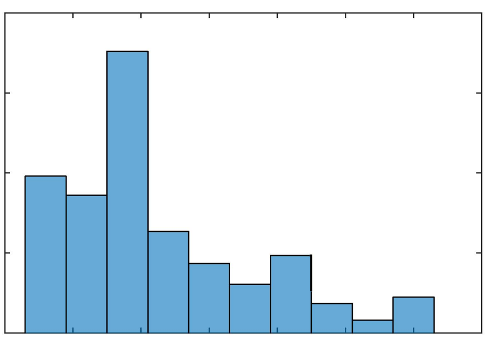

Figure 16. GBRT Pixel Conformance Histogram

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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