AIREON INDEPENDENT VALIDATION OF AIRCRAFT POSITION VIA SPACE-BASED ADS-B

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Abstract

The Aireon Hosted Payload (AHP) on the Iridium NEXT satellite constellation provides global ADS-B (Automatic Dependent Surveillance – Broadcast) coverage that is achieved by each payload covering a portion of the Earth's surface. The nature of the satellites' polar orbits and the size of the payload's footprints allows for coverage overlap between adjacent payloads. This overlap creates regions where ADS-B transmissions are detected by more than one AHP and allows for two or more measurements of the same information. These measurements can be used to perform Time Difference of Arrival (TDOA) calculations that Aireon has incorporated into a position validation algorithm allowing for verification of an aircraft's reported position independent of GPS. This independent validation algorithm augments Aireon's surveillance system to be resistant to spoofers (devices that are intentionally transmitting incorrect positions), faulty avionics, and GPS outages. This validated data allows Aireon to greatly improve the safety and robustness of any system using its ADS-B data.

The validation algorithm utilizes two primary techniques: first, using two or more satellites to perform TDOA calculations and verify the aircraft reported position is within a configurable distance from truth; second, use of the aircraft's kinematics to persist and verify their validation state in regions where there is no satellite overlap. Given the size of the AHP's coverage footprint the regions of single satellite coverage only exist near the equator, in fact above 43° and below -43° latitude all aircraft 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. The regions where TDOA calculations cannot be performed change rapidly due to the procession of the satellite constellation around the Earth. In the worst case if an aircraft is only covered by a single satellite at the equator it will re-enter redundant coverage in less than four minutes. During those times the kinematic portion of the validation algorithm will take over to ensure the reported data is correct.

Aireon has been receiving operational ADS-B data from the available satellites in orbit for over a year. Using recent data while 47 satellites were in operational orbit showed that there were over one million TDOA opportunities in sixteen million total reports collected in a single hour. In April of 2018 Aireon began receiving Precision Timing and Position (PTP) messages from Iridium which provides the necessary accuracy in both timing and satellite position to perform the TDOA calculations. With these PTP messages Aireon has begun testing the validation algorithm on operational data with great success. Figure 1 shows the results of successfully validating the position of transmitters in the Azores that are part of the ERA surveillance system to within 0.5NM via TDOA opportunities. Furthermore, Aireon has identified multiple cases of faulty avionics that are reporting incorrect positions in their ADS-B data and have successfully invalidated them using this algorithm.

This paper will outline the validation algorithm at a high level and show measured results of the algorithm from data recorded by the Aireon system.

Figure 1: TDOA Results on ERA Ground Transmitters in the Azores [1]

I. Overlapping Coverage & TDOA

The primary component to the validation process is the ability to perform TDOA calculations which requires coverage by more than one satellite. In the context of the Aireon system coverage is defined by the elevation angle of the aircraft, Figure 2 shows the angular relationship between the satellite, target, and Earth. In this context the target is the aircraft of interest with ε representing the elevation angle [2].

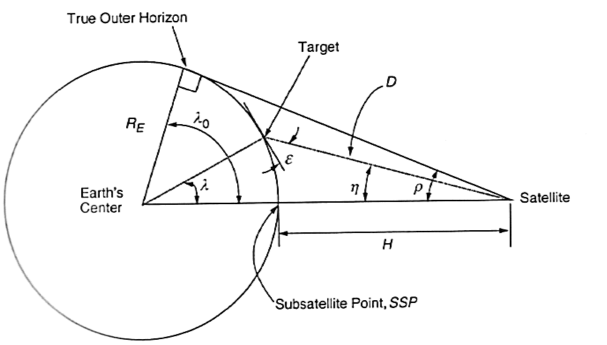

Figure 2: Definition of Angular Relationships [2]

The original design target of the Aireon hosted payload's coverage was 8.2 degrees of elevation [3] from the aircraft perspective, shown in Figure 3. It was immediately clear upon receiving data from the first Aireon payload that the actual performance far exceeded that objective. The measured elevations have been recorded as low as -4.6 degrees for some aircraft and it has been concluded that a more realistic coverage elevation is 0 degrees [4].

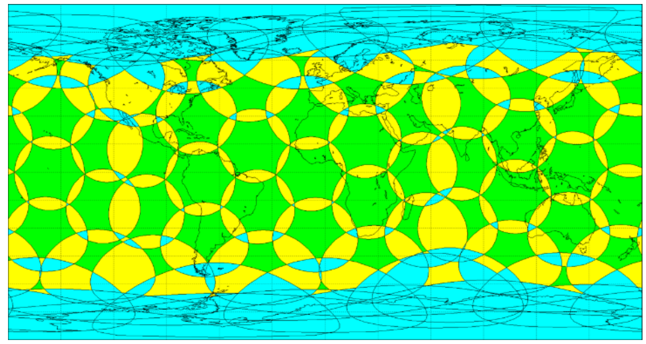

Figure 3: Satellite Overlapping Coverage at Elevation Angle of 8.2°

This new information opened the possibility for a heavier reliance on TDOA in the validation process which would be far superior to earlier design ideas such as pure range checking, beam-based, and probability-based validations. The new footprint size changes the predominant coverage type from single satellite to triple (or greater) satellite coverage. Figure 4 shows the updated overlapping coverage using the 0-degree footprint which provides for:

1. Persistent overlapping coverage at ±43°
2. Global overlapping coverage roughly 94% of the time
3. 80% probability of overlapping coverage at the equator (worst case)

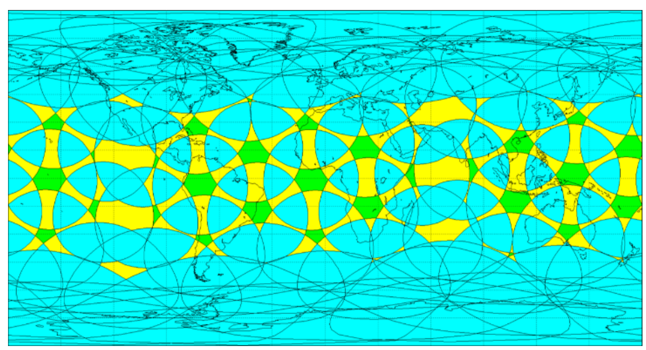

Figure 4: Satellite Overlapping Coverage at Elevation Angle of 0°

Figure 5 shows the difference between the peak time of single satellite coverage using the original 8.2-degree design and the 0-degree footprint observations for given latitude values calculated via a three-hour simulation. These values are averaged across multiple single satellite coverage events which can vary in time but gives a representative of how much time an aircraft can expect to experience inside a single satellite coverage event.

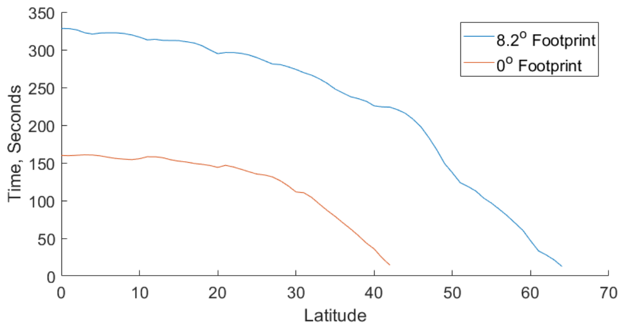

Figure 5: Peak Single Satellite Coverage Durations by Latitude

This improved duration of TDOA opportunities from the 0° satellite footprint leads to a high probability and average number of satellites in view of any given location. Figure 6 shows the probability of being under two or more satellites at any given time at any given location. This value bottoms out at about 80% meaning there is a very high probability, even at the equator, of having a TDOA opportunity. Figure 7 presents this information differently and shows the average number of satellites covering any given point, with the lowest value being two.

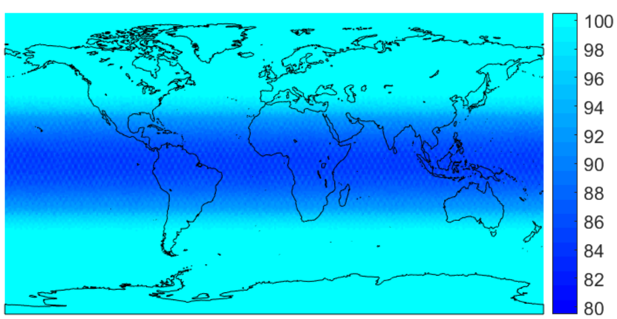

Figure 6: TDOA Probability

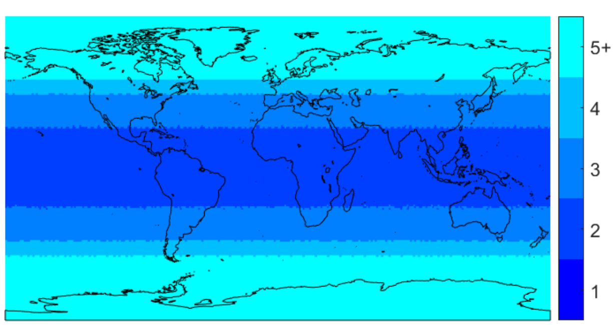

Figure 7: Average Satellite Overlap

The impact of this redundant coverage has been seen in the operational data with over one million TDOA opportunities observed in sixteen million reports collected in a single hour shown geographically in Figure 8. In this test we are checking for any messages that are seen on two satellites and contain the same information and are spaced by less than 20 milliseconds.

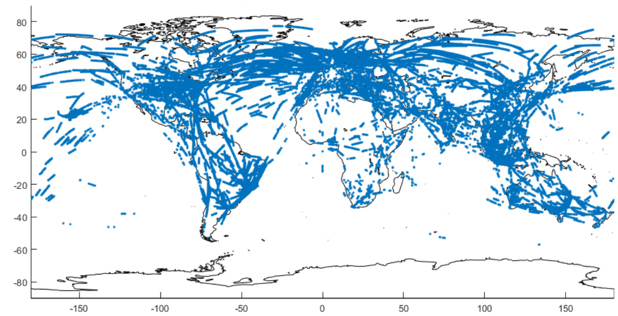

Figure 8: Example of Global TDOA Measurements in 1 Hour

The importance of the TDOA is that it provides an independent measurement that can be compared against the position data provided by the target aircraft, which in a noiseless environment would be calculated as:

$$TDOA = (TOMR_1 - TOMR_2) = (TOMR_1 - T_{TX}) - (TOMR_2 - T_{TX})$$

$$\Delta r_{obs} = c \cdot TDOA = |\boldsymbol{r}_{sat1} - \boldsymbol{r}_{acft}| - |\boldsymbol{r}_{sat2} - \boldsymbol{r}_{acft}|$$

Where $TOMR_1$ and $TOMR_2$ are the Time of Message Reception at each satellite and T_{TX} is the time of transmission, which is unknown. The ***r*** values indicate the position of the two satellites and the aircraft as vectors.

II. Validation Methods

Validation as described in this document is the indication that a position can be trusted to within a certain distance. It is the intent of Aireon to validate all ADS-B data delivered regardless of the type of satellite coverage. The previous section described the use of the overlapping satellite coverage to get TDOA calculations, but data will still need to be validated during the single satellite coverage periods.

There are three possible validation states, each of which can be broken down into further levels of granularity: Valid, Invalid, and Unknown. After TDOA validation has been performed the validity of an aircraft's position information will be known: either that it's invalid beyond a configurable distance threshold or valid within some quantized distance (e.g. 1.9 NM). Once the aircraft exits overlapping satellite coverage the validation state can be updated using the reported velocity. ADS-B velocity does not use GPS position but instead utilizes doppler shift calculations using the relative motion of the GPS satellite with respect to the aircraft. This method of calculation makes the GPS derived velocity, in a way, independent from the ADS-B position, therefore will not need to be independently validated.

Given the duration of single satellite coverage and requiring a TDOA validation to initiate any validation state using the velocity introduces a very low risk to report false validation information. Provided with two possible scenarios: a malicious spoofer or an unintentional piece of faulty avionics. In either case the goal is to report when the reported position does not correspond to the actual.

In the first case the spoofer can be eliminated using several techniques, first and foremost is a simple range check; if the aircraft is outside the maximum possible range of the satellite it is clearly a bad position. When the spoofer is detected by more than one satellite the TDOA calculation will prove that it is invalid.

In the second case, unintentional bad data, the procedure is the same unless the issue is sporadic. In that case an aircraft can start as valid and then begin reporting bad data at any time. In this case if observed by two or more satellites the TDOA will invalidate the aircraft position and if under a single satellite the "bad" position will not line up with any previously validated positions and the velocity.

Finally, the validation metrics must be reported. In the CAT021 ASTERIX report there is a field that indicates if an Independent Position Check has been performed and failed [5]. Aireon intends to use this field to indicate if a CAT021 report is suspect (validation distance is beyond a configurable value). To augment the single bit reporting, there is currently work ongoing in ED-142A with proposals on how to output the comparison of ADS-B to WAM with more granular containment distance information, including a partial (two receiver) WAM position which includes containment, ADS-B/WAM Integrity Category (AWIC), and position difference/distance [6]. These same outputs, intended for use in terrestrial systems, could also be used for Aireon's validation results.

III. Timing Accuracy

The TDOA calculation is dependent on two variables: the accuracy of the timestamp, and the accuracy of the receiver position. In terrestrial systems the receiver position can be surveyed via high accuracy GPS measurements but in the Aireon system the receivers are constantly moving. Additionally, a terrestrial system can receive highly accurate time from GPS sources, which creates a dependency on the very system that is being independently validated.

To achieve the necessary timing and position accuracy Aireon receives Precision Timing and Position (PTP) messages from Iridium which include precise satellite positions with accuracy within 240m and timing adjustments which allow for 200ns of accuracy. With these PTP messages, analyses have been conducted using a Ground Based Reference Transmitter (GBRT) located in Iqaluit Canada to verify and quantify the timing and satellite position accuracy.

The GBRT possesses four antennas that each transmit an ADS-B message at 10Hz. This ADS-B message has been formatted to contain the time of message transmission with an accuracy of ±30ns. Given the Time of Message Transmission (TOMT), the measured Time of Message Reception (TOMR) at the satellite, and the provided satellite position one can easily calculate the timestamp accuracy:

$$TOF = |\boldsymbol{r_{sat}} - \boldsymbol{r_{GBRT}}|/c$$

$$TOMR_{err} = TOMR_{meas} - (TOMT + TOF)$$

Where the ***r*** values represent the positions of the satellite and the GBRT, c is the speed of light, and the TOF is the time of flight from the GBRT to the satellite.

Evaluating 24 hours of data across the available satellite constellation has shown that most of the satellites have a time accuracy within the desired 200ns bound. Some initial results from this analysis are shown in Figure 9 which shows a heatmap of the timing error in nanoseconds across one plane of the satellites. A few of the errors exceed the 200ns value and are attributable to the experimental nature of the data, but most of the results are contained within the 200ns bounds. This accuracy is a combination of the satellite position accuracy and the timestamp accuracy, if either has significant errors the resulting calculation would reflect this. This timing accuracy allows for accurate TDOA calculations and subsequently accurate validation calculations.

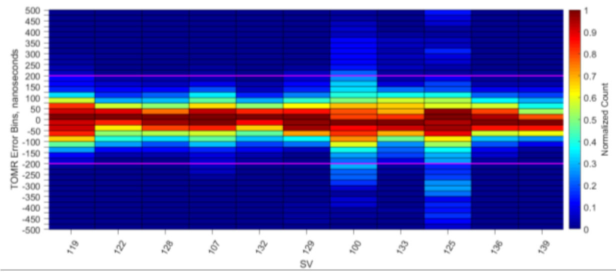

Figure 9: Initial Time Accuracy Results for One Plane

A further investigation of the TDOA accuracy using targets of opportunity was done using ground transmitters in the Azores. These radios transmit DF17 messages and being stationary made them excellent test targets to confirm the TDOA performance. Figure 1 shows the results of successfully validating the position of these transmitters to within 0.5NM via TDOA opportunities using the reported position, verified via Google Earth, as the truth [1].

IV. Validation Results

The position validation algorithm can be evaluated on the abundance of ADS-B data collected by the Aireon system. In most cases aircraft are identified as valid throughout their flights but some cases have been identified where the validation algorithm has found what appear to be faulty avionics and properly labeled them as invalid. These events can be categorized into two groups: global jumps and small deviations. The global jumps report positions that appear in a random location on the Earth and are easily identified via a coarse range check. Small deviations in reported position are more difficult to properly flag. In these cases, the aircraft's reported position only differs just enough from the true position to warrant invalidation.

During an evaluation of the validation algorithm, using a 6-hour dataset while 45 Aireon payloads were active, it successfully validated 50 aircraft flying across the North Atlantic with 0.34% false invalid indications. In this test the algorithm was configured to maintain a validation state hysteresis to prevent validation states from rapidly toggling. It was also configured to allow longer than normal coasting to perform through the satellite constellation coverage gaps. Figure 10 shows the trajectories of all the evaluated aircraft along with their validation state.

This was not the full set of aircraft available but during the time of this evaluation the Aireon system

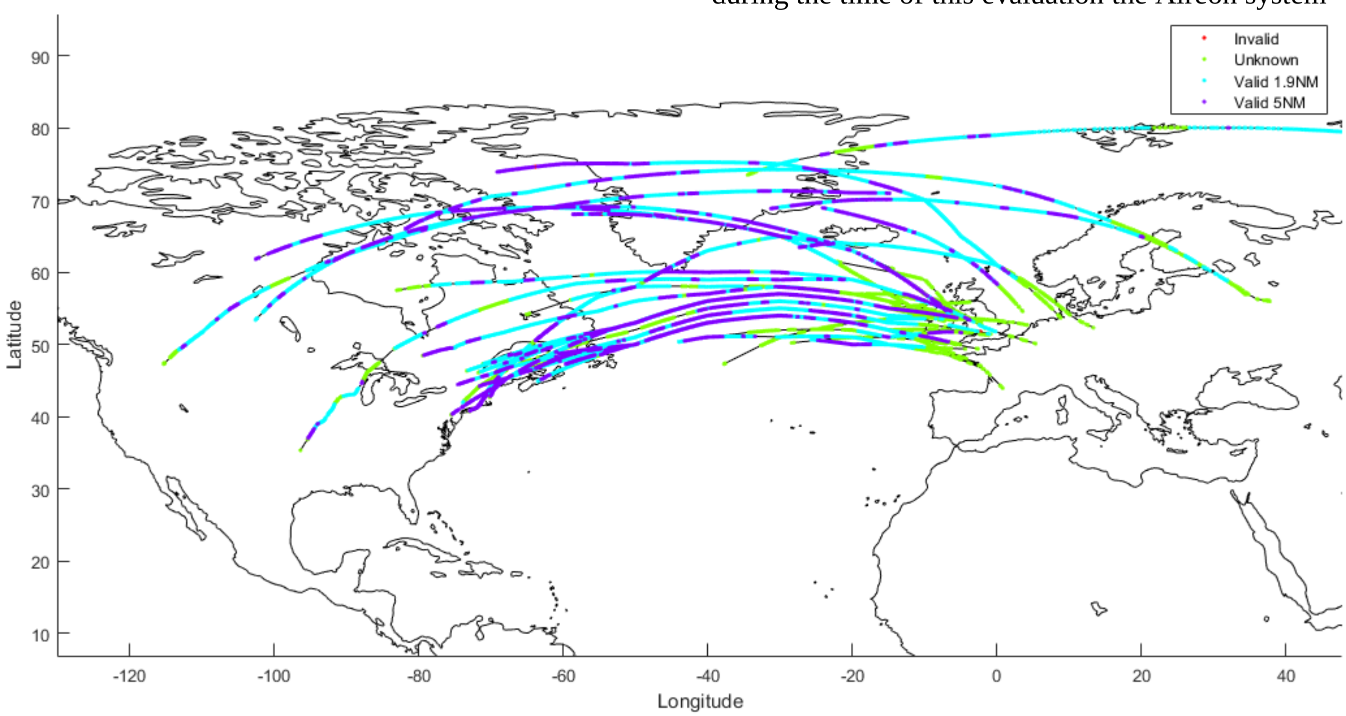

Figure 10: Example of North Atlantic Aircraft Validation with 45 Payloads and Reduced Bandwidth

was using experimental data to perform the validation and therefore not all aircraft were candidates for processing. Additionally, since the Iridium/Aireon system is in deployment the complete constellation has limited bandwidth and power configuration causing a reduced set of validation opportunities.

Figure 11 shows an example of an invalid aircraft, reporting a NIC of 8, whose position jump was approximately 13NM. In this case the jump was flagged by the kinematic portion of the algorithm. The reported position was beyond the maximum range from the propagated position and as such was labeled invalid. This functionality allows for validation of events that do not have TDOA opportunities.

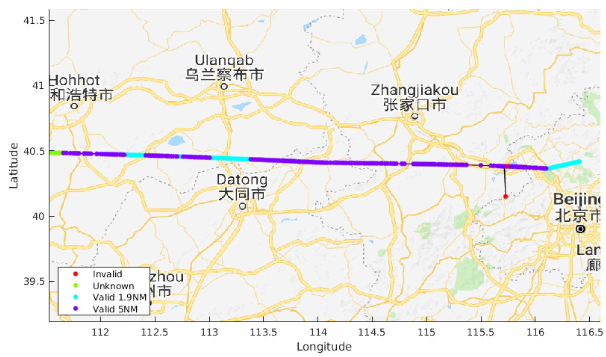

Figure 11: Small Distance Jump Invalidated by Kinematics

Figure 12 shows another example of an invalid aircraft who, in this case, had its position jump thousands of miles. These cases are easily identified by the range check component of the validation algorithm and are immediately flagged as invalid. These range outliers would be a nuisance to the region that they appear in as well as causing a loss of data in their "home" region.

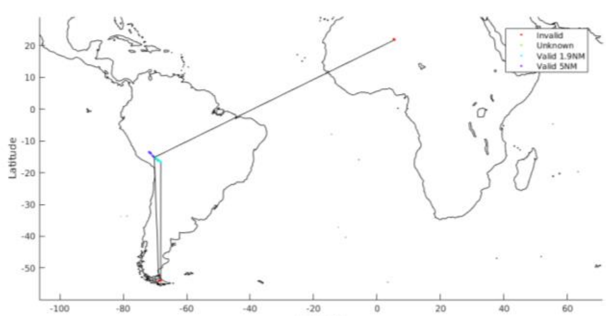

Figure 12: Jump Invalidated by Range Check

V. Upcoming Concepts

The current validation algorithm concept utilizes TDOA to determine if an aircraft's reported position is valid. Given more overlapping satellites the TDOA concept can be expanded to Wide Area Multilateration (WAM) which allows for the calculation of a completely GPS independent position suitable for air traffic control surveillance services. WAM would require at least three satellites to observe a single ADS-B message although the solution could be propagated by only two satellites in certain conditions. As discussed in Section I, the higher and lower latitudes have more satellite overlap. At approximately ±55° any aircraft would be under constant triple satellite coverage allowing for a constant full WAM solution with partial WAM solutions available at ±43°.

Comparing to the information provided in Section I and looking at the WAM capable overlaps it can be found that the Aireon system can produce WAM solutions at varying rates depending on the target aircraft latitude. The average and maximum time between WAM opportunities found during a three-hour simulation is shown in Figure 13. Based on these results Aireon can provide a fully GPS independent position solution for aircraft that rivals ADS-C's update rate of 10-15 minutes for any aircraft at ±28° or higher/lower.

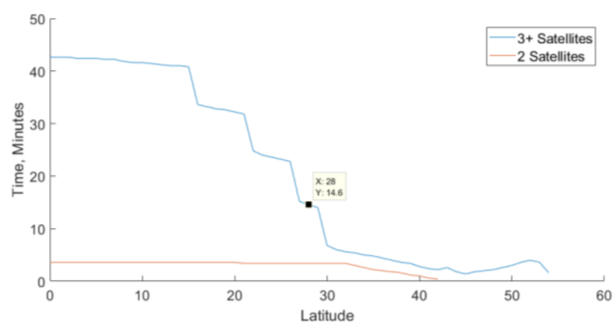

Figure 13: Simulated Maximum Time Between WAM Opportunities

To improve the time between updates Aireon can initialize an aircraft track using the full WAM solution and then provide a track propagation using two-satellite solutions. The position estimate of this partial solution is improved due to the rapidly changing geometry of the satellites with respect to the aircraft. Although not as accurate as a full WAM solution this partial solution can provide an interim track for more equatorial aircraft that can provide situational awareness in the event GPS is not available. For higher latitude aircraft this solution's error would be minimized as the gap duration shrinks and the position can be recomputed more frequently.

VI. Conclusion

"Doveryai, no proveryai (Trust, but verify)"

-Russian Proverb

A risk that needs to be overcome in any ADS-B system is the ability to verify the quality of the data being delivered. Incorrect or misleading surveillance information provides hazardous and misleading information to air traffic controllers. An inability to reliably validate and verify ADS-B data being used for aircraft separation carries risks that have often impeded the adoption of ADS-B by controllers. Although validation is currently not a minimum requirement of ED-129B ADS-B systems, it is a desired feature of most ANSPs, required by the FAA's systems [7], and may become a de-facto standard once EUROCAE's composite ADS-B/WAM guidance is published. For terrestrial systems, validation can be done through comparison to radar, WAM, or other surveillance sources: in the oceanic case this is not possible.

Aireon has developed a comprehensive method of position validation that will be used to authenticate the state vector integrity of ADS-B data delivered to any consumer. This fully independent validation layer alleviates concerns about using ADS-B as a single source of surveillance and increases the ability to use version zero. Aireon is the only surveillance provider positioned to perform this type of validation via Space-Based ADS-B and will be delivering this new feature to customers by the first quarter of 2020.

VII. Acknowledgements

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VIII. References

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