April 2025

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Satellite wide area multilateration solution, applications, and benefits

Abstract— Wide Area Multilateration (WAM) surveillance systems provide a robust and effective means of surveilling aircraft; these systems can operate both actively (interrogating aircraft for necessary messages) or passively, using available messages of opportunity, to determine aircraft positions. WAM systems do not require any information from aircraft transmissions other than a form of identification to group multiple received messages from the same transmission together, resulting in a surveillance solution that is independent of any onboard aircraft systems, such as Global Navigation Satellite System (GNSS). The methods and calculations required to perform multilateration are standardized in the aviation industry and have been implemented by many systems around the world. What is not common for WAM systems is the use of extremely fast mobile and/or very distant receivers, such as satellites. Generally, most WAM systems, especially Air Traffic Control (ATC) grade systems, require highly accurate position and timing information for the receivers, typically done via site surveys and highly accurate clocks for the ground stations. When the receiver is mobile, this makes the receiver location uncertainty a problem for accurately solving for the transmitter's location. Aireon, working with Iridium, has access to Precision Timing and Position (PTP) data which enables the required accuracies on the receiving satellites to perform Time Difference of Arrival (TDOA) calculations, the staple of a WAM system.

Using the Iridium constellation's unique geometry, there are many areas of the world covered by the three or more requisite receivers to perform two-dimensional multilateration. One of these areas is the North Atlantic Tracks, which regularly has three or more Iridium satellites providing coverage. Building on the work done for a paper presented at DASC 2023, this paper provides analysis of the performance of a Satellite Wide Area Multilateration solution operating on thousands of aircraft as a proof-of-concept for widespread applications. Additionally, using this solution, this paper will also investigate the robustness of this style of surveillance against GNSS jamming and spoofing events which have become more common and affect more airspaces every day.

I. Introduction

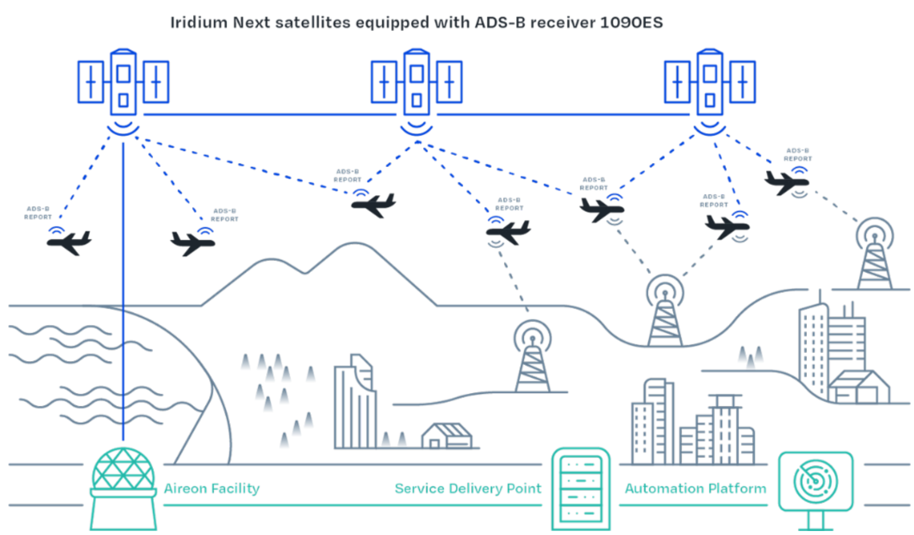
This paper describes the use of Wide Area Multilateration (WAM) techniques applied to satellite-based receivers and an evaluation of the performance of such a solution. Section II describes the Aireon system which is leveraged to accomplish this Satellite Wide Area Multilateration application to provide a foundation of how data is captured and analyzed. In Section III, a high level description of the solution is described as well as references to previous papers that have laid the groundwork for this next-level evaluation of the application. This solution uses commonly applied multilateration techniques and equations, but the unique challenges, and how they are overcome, are also described.

The solution and theory have been developed into a prototype that is outlined in Section IV. This prototype has been updated to evaluate against many thousands of aircraft and the results of this analysis are also presented in this paper to showcase the capability of this unique solution. From this data we can also evaluate the usefulness of a satellite-based WAM solution in mitigating common and growing issues in the Air Traffic Surveillance community such as GNSS jamming[1], which is discussed in Section V.

II. Aireon System

The Aireon space-based Automatic Dependent Surveillance Broadcast (ADS-B) system provides an aircraft surveillance service to Air Navigation Service Providers (ANSP) around the world. The system went operational in April 2019, and is supported by the Iridium NEXT constellation. Aireon has Hosted Payloads (HPL) that ride on each of the 66 Iridium satellites that are orbiting at approximately 780 kilometers above the Earth. Each of these satellites are linked to up to four others, creating a dynamic mesh network that ensures continuous availability. The signals transmitted by ADS-B-equipped aircraft are relayed from the Aireon HPL through the Iridium network to the ground in real-time[2].

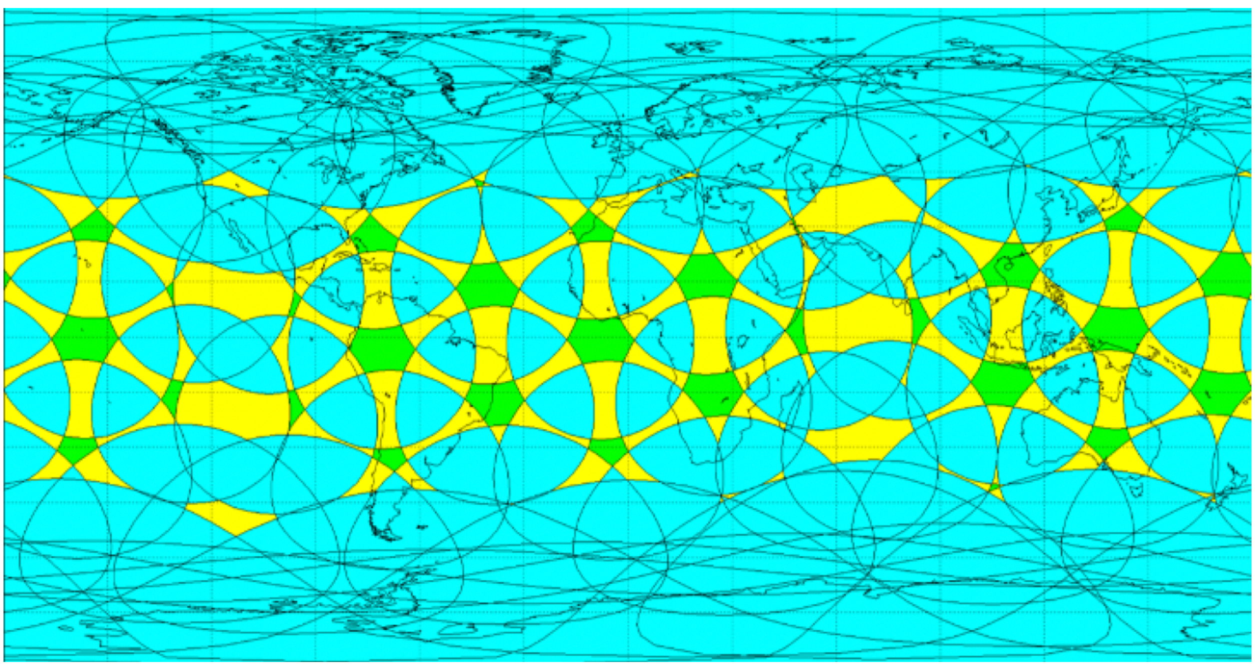
FIGURE 1
Diagram of the Aireon System[2]



The latency of the Aireon system, reception at the satellite to delivery to end user, is less than 400ms[3] and provides a high rate of detection across most of the world. In oceanic and more remote areas of the world, where there is reduced traffic density and low 1090MHz interference, the Aireon system can regularly deliver aircraft target reports at a median rate of once every 2 seconds[4]. This level of performance correlates to a high rate of detection as report updates are triggered by ADS-B position messages, which are sent twice a second[5].

The coverage for the Aireon HPL in clear-sky environments has been observed to be limited by the horizon, or the physical obstruction of the Earth. This equates to a zero-degree elevation angle from the aircraft's perspective; where elevation angle is the angle from the horizon measured upward. In some cases, the actual measured minimum elevation angle has been observed as extending to -4.6 degrees, approximately 3800 km in radius[3]. Using the more conservative estimate of a zero-degree elevation footprint shows significant overlap, especially as we approach the poles of the Earth. Fig. 2 shows a snapshot of the coverage of all 66 satellites in the Iridium constellation; the overlap is represented by different colors where the green is single satellite coverage, yellow is double satellite coverage, and blue is 3+ coverage. This overlapping coverage is what allows for a multilateration solution, as simultaneous detections of the ADS-B transmissions allows for the Time Difference of Arrival (TDOA) measurements.

FIGURE 2
Satellite Overlapping Coverage at Elevation Angle of 0°[6]



III. Satellite wide area multilateration solution

The equations and techniques used for a standard multilateration solution are not novel or new, but applying them to a mobile receiver is non-standard. Additionally, when that receiver is a satellite it adds a layer of complexity that requires solutions to problems presented by the large coverage and high speed. This section will cover the basics of multilateration as well as the specifics of the satellite-based solution and overall algorithm developed by Aireon.

A. Closed-Form Solutions

To independently determine an aircraft's full position, we need to solve for three unknowns, the x, y, and z coordinates. To find these three unknowns we need at least three observations. If we have exactly three observations, we can use a closed-form solution to solve for the aircraft's position. The equations described in [7] show the full derivations of how to solve for the three unknown closed-form solutions; it stands that we need a single transmitted signal to be received by four receivers to accomplish this. This is because we are using TDOA measurements, and each unique pair provides one observation.

In [8] we showed a rederivation of the equations in [7] as well as showed how they can be modified to solve for the two-dimensional position (if we accept the aircraft's reported altitude as an observation); in this paper, we will only summarize the closed-form equations. The TDOA measurements can be associated to the receivers using the speed of light by the following:

Transitions are then identified using the following algorithms, where $\underline{X}$ is used to identify the average value and $\|X\|$ represents the absolute value:

$$R_i = c(t_i - t_T)$$

$$R_j = c(t_j - t_T) \quad (2)$$

$$R_i - R_j = c(t_i - t_T) - c(t_j - t_T) = c(t_i - t_j)$$

B. Iterative Solutions

In most cases, the multilateration solution can be solved through an iterative method. This can be useful for a few reasons:

- More than the minimum required number of receivers is available.
- There is more than an insignificant amount of error in the receiver position or timing accuracy.
- It uses a more straightforward set of equations.

Using a set of linear equations to define the problem, an approximation method, such as the Gauss-Newton method, can be used to determine the solution. Defining our set of equations as:

$$\boldsymbol{S} = c\begin{bmatrix} T_1 - T_2 \\ T_1 - T_3 \\ \vdots \\ T_1 - T_n \end{bmatrix} - \begin{bmatrix} R_1 - R_2 \\ R_1 - R_3 \\ \vdots \\ R_1 - R_n \end{bmatrix}$$

This is very similar to the expression shown in (3) and we will use the Gauss-Newton method to minimize the ***S*** value in this cost function.

The Gauss-Newton method requires the Jacobian of our cost function. The Jacobian, ***J***, is a matrix of the partial derivatives with respect to each of our independent variables:

$$\boldsymbol{J} = \begin{bmatrix} \frac{\partial \boldsymbol{S}}{\partial x} & \frac{\partial \boldsymbol{S}}{\partial y} & \frac{\partial \boldsymbol{S}}{\partial z} \end{bmatrix} = \begin{bmatrix} \frac{\partial S_1}{\partial x} & \frac{\partial S_1}{\partial y} & \frac{\partial S_1}{\partial z} \\ \frac{\partial S_2}{\partial x} & \frac{\partial S_2}{\partial y} & \frac{\partial S_2}{\partial z} \\ \vdots & \vdots & \vdots \\ \frac{\partial S_n}{\partial x} & \frac{\partial S_n}{\partial y} & \frac{\partial S_n}{\partial z} \end{bmatrix}$$

With the Jacobian, the iterative update to the approximation is defined as:

$$\boldsymbol{\Delta} = -(\boldsymbol{J}^T \boldsymbol{J})^{-1} \boldsymbol{J}^T \boldsymbol{S}$$

The update, **Δ**, is used to repeatedly update the position estimate, until the change is negligible. This iterative method can be used for the two-dimensional solution, the difference being that the altitude is used for the z-value and that the Jacobian only has two columns.

C. Satellite Specific Challenges

There are a few key differences between a terrestrial WAM system and a Space-Based WAM system:

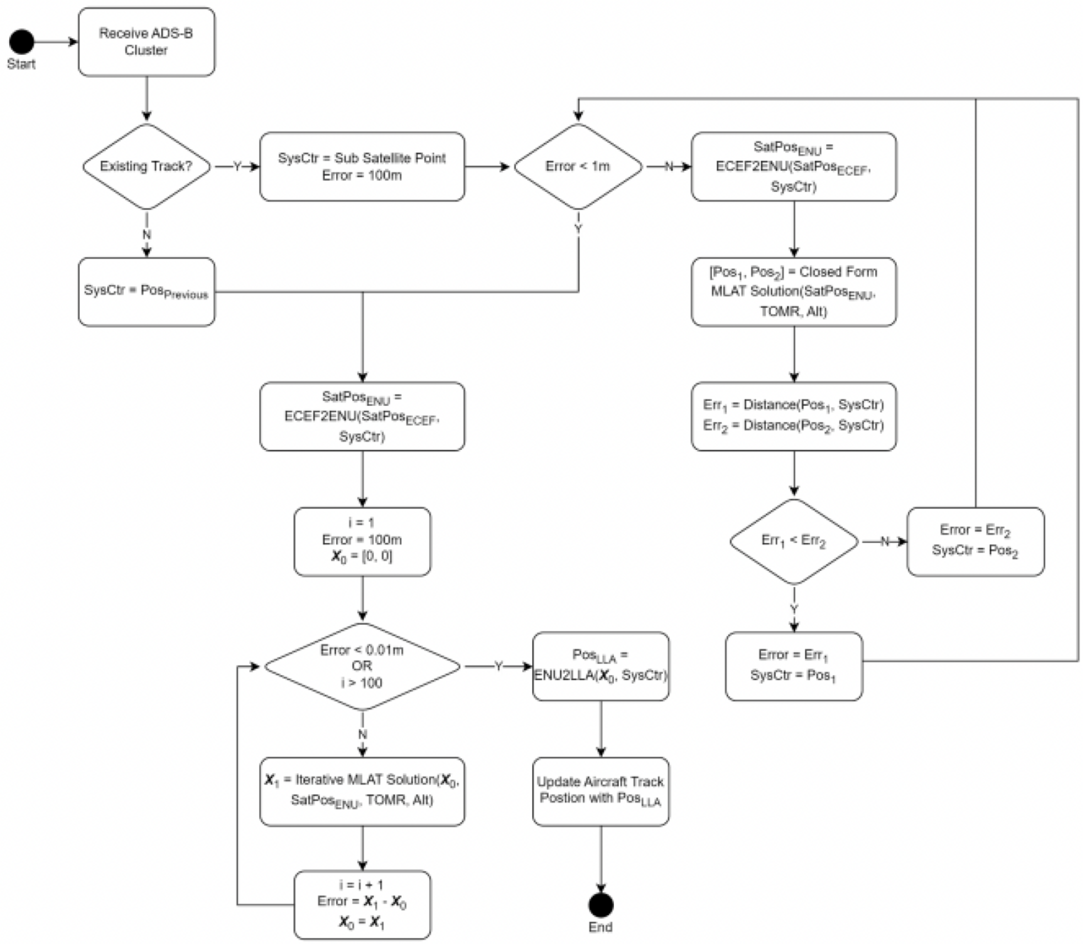
1. Stationary versus mobile receivers – A standard WAM system will use a set of stationary receivers that are sited and calibrated to support their mission and area of interest. For a space-based system the receiver is moving, which affects accurate measures of its location and the area it covers.
2. Receiver coverage – A ground station can only observe a limited area, whereas a satellite's coverage footprint is significantly larger. This results in more data to process as well as impacts to estimating the transmitter's location.
3. Operational area – A terrestrial WAM system is going to operate over a certain location on the Earth. This allows for certain assumptions, such as system center for coordinate conversions, and reasonable locations for calculated positions. In a spaced-based system the entire Earth is essentially the operational area.

Mitigating these challenges are key to developing a successful space-based WAM system and have been explored in the algorithm and prototyped developed for this paper.

D. Algorithm

In [8] a high level algorithm was developed to support an initial prototype of space-based WAM. The method employed was to use the closed-form method to determine the initial estimate of the aircraft's location and then to switch to the iterative solution to continue updating the aircraft's position. This algorithm is outlined in the flow diagram shown in Fig. 3. The first complication of this approach was to deal with coordinate conversions; the equations in the previous sections are all based on a cartesian East-North-Up (ENU) coordinate system, but our data is global and represented in Earth-Centered Earth-Fixed (ECEF) coordinates. Normally, one would use a system-center near the desired location to do the coordinate conversion, but given our global operating theater, this is less straightforward.

FIGURE 3
Space-Based WAM Algorithm



As described in [8] and shown in Fig. 3, if we have no existing aircraft position, the first step is to assume one of the receiving satellites' sub-satellite point as the system center. From there, the coordinate conversion is performed, the closed form multilateration solution is determined, and that position is used as a new system center. This process is repeated until the change in position is negligible, meaning we have a system center. As stated in Section III.A we will determine two possible positions every time the closed form solution is determined. While evaluating this algorithm, it was found that in some cases both solutions are "reasonable" whereas in most terrestrial based systems one solution is reasonable and the other is located very far away. To mitigate this, the solution closest to the previous system center is used as the update, this has resulted in successful solutions, even if at times it requires some additional repetitions.

Once an accurate system center is found, the iterative solution can be used to update the aircraft's position as TDOA clusters are received. As the position updates, the previous position should be used as the system center to prevent long-duration tracks from experiencing errors due to the curvature of the Earth affecting the coordinate conversions. This process can continue until the aircraft track terminates, due to landing or leaving an area of interest.

IV. Satellite wide area multilateration applications

In [8] the original prototype was tested on a single flight in northern Canada to assess feasibility in an area with significant satellite receiver overlap. This approach was scaled up and evaluated on a large scale sample of Aireon data over the North Atlantic. Using 24 hours of Space-Based ADS-B data from 2024-09-04, all aircraft that cross the North Atlantic (Gander and Shanwick Oceanic Flight Information Regions) was processed through this Space-Based WAM solution.

A. Closed-Form Solutions

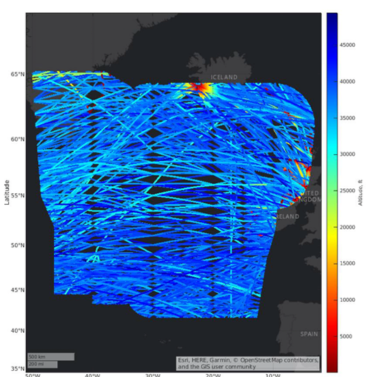
A prototype was developed that implemented the algorithm described in the previous sections. This prototype was written in MATLAB and was used to determine the WAM positions and evaluate the accuracy of the solution. In this case, the ADS-B data was assumed to be truth. This MATLAB prototype was used to evaluate the 24-hour recording of ADS-B data in a batch-processing manner, not real time. This prototype focused on the two-dimensional solutions and used the aircraft reported geometric height as the altitude component.

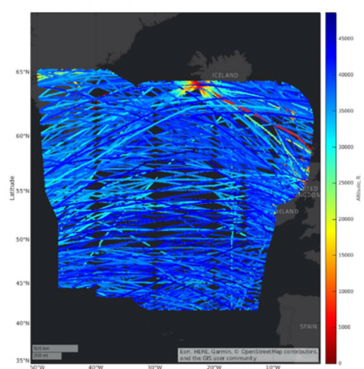
B. North Atlantic Analysis

The 24-hour sample of data over the North Atlantic accounted for a total of 1472 unique aircraft and approximately 8.5 million ADS-B clusters of three or more satellites. Fig. 4 below shows a geographic plot of all the ADS-B data colored by altitude. Fig. 5 shows the Space-Based WAM solutions calculated for that same dataset. Obviously, at this magnitude of a view any nuances cannot be observed, but this does show a strong correlation between the positions on a large scale. The next section details the accuracy and update interval performance of the Space-Based WAM solution.

FIGURE 4 & 5
North Atlantic Space-Based ADS-B Data Captured on 2024-09-04

North Atlantic Space-Based WAM Solutions for 2024-09-04

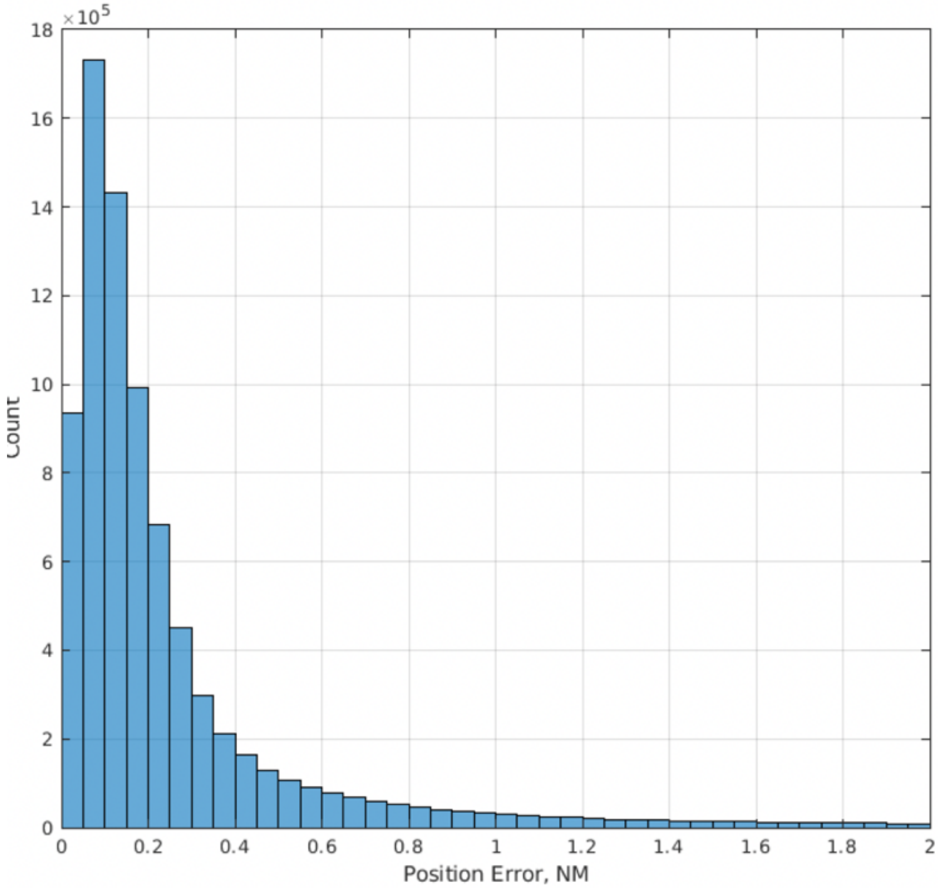




C. North Atlantic Performance

Looking at the entire sample of data and comparing the Space-Based WAM solutions to the ADS-B, one can calculate a position accuracy by assuming the ADS-B is truth. The ADS-B positions were interpolated to the times of the WAM solutions using a Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) for the latitude and longitude. A simple WGS84 distance calculation was used to compare these interpolated positions to the WAM solutions to get an error metric for each report which is aggregated into the histogram shown in Fig. 6.

FIGURE 6
Space-Based WAM Accuracy



The numbers are heavily weighted to the lower values, with a mean of 1.37s, a 95th percentile of 8.34s, and a 99th percentile of 10.22s. Calculating the Probability of Update (PU) using the methods described in [9] finds an 8s PU of 81.1% and a 60s PU of 92.7%.

Looking at the performance on an aircraft-by-aircraft basis can highlight good performance and show a promising use case. Fig. 8 shows a single flight in the North Atlantic, coloring the geographic plot by the position error, and showing two histograms (the position error and update interval). In the case of this individual flight, the position errors and update intervals are heavily weighted to the lower values. Most errors are less than 0.5NM and there are no update intervals greater than 8s. The flight does show various position outliers, but they are somewhat evenly distributed throughout the flight and could be compensated for via a tracker or other error-detection mechanism. These concepts will be explored in future work.

FIGURE 7
Space-Based WAM Update Interval

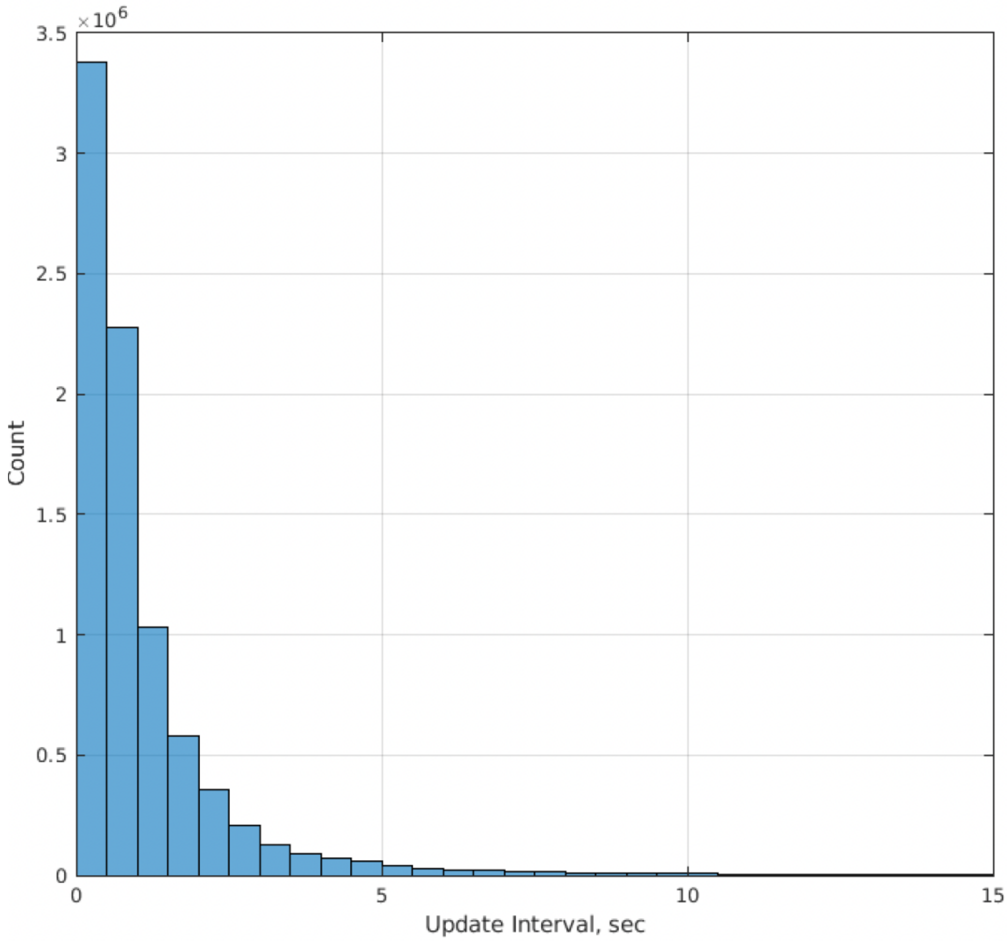


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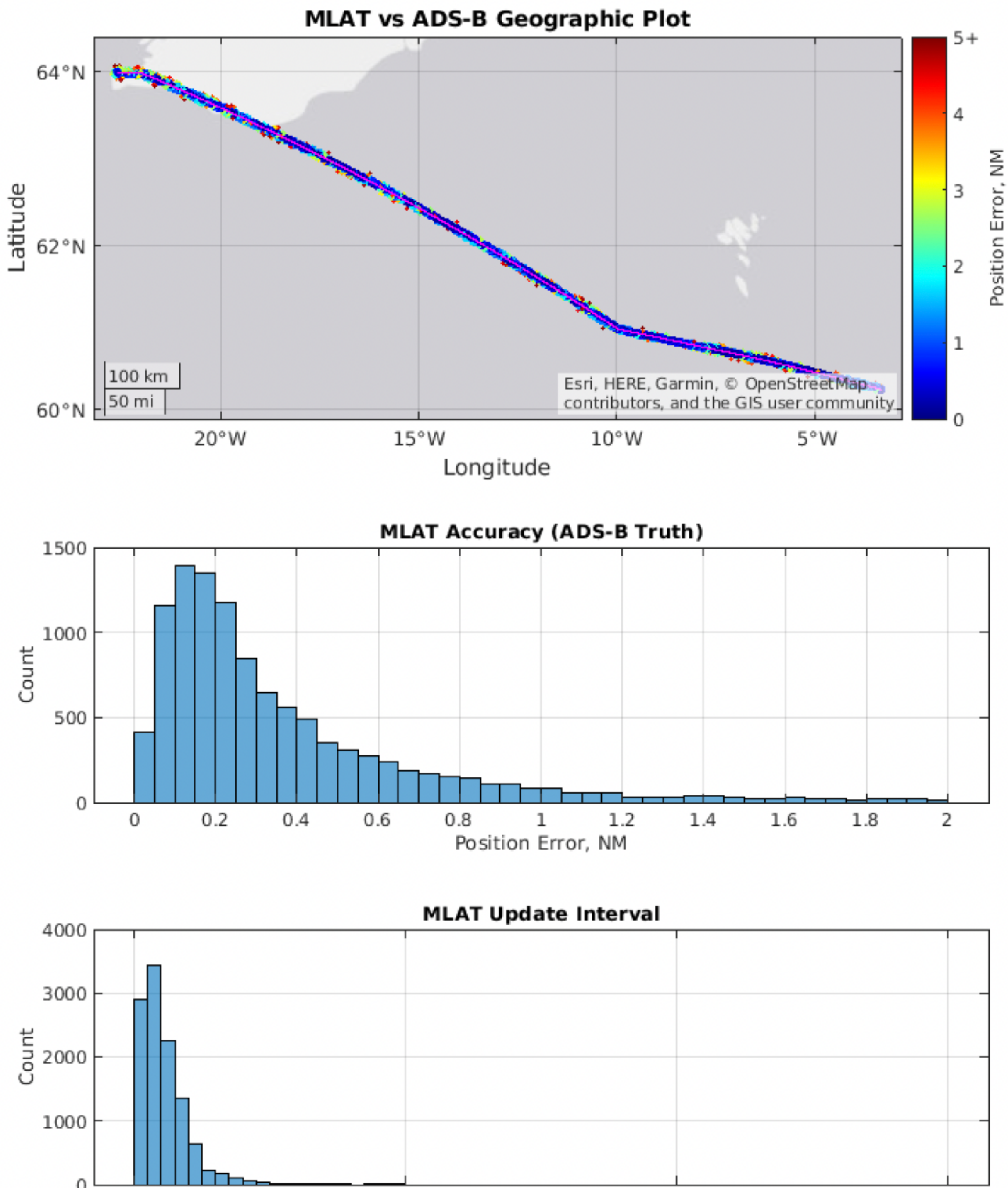
FIGURE 8
Single North Atlantic Space-Based WAM Flight Performance



V. Satellite wide area multilateration benefits

A Space-Based WAM solution can provide multiple benefits when it comes to air traffic surveillance, to both regions with existing infrastructure and into new areas. In this section, we discuss the predicted benefits of a Space-Based WAM solution as well as some observations from existing data. Three primary use cases are:

1. As a backup to ADS-B in areas that may already have existing ADS-B systems.
2. To provide GNSS resilience, noting that satellites are resilient to GNSS jamming, but ground stations can be targeted.
3. As an augmentation to existing terrestrial systems to provide a combined WAM solution that has better resilience to site failures, or could create a WAM system with no added terrestrial sites[8].

A. Backup to ADS-B

The most straightforward benefit to a WAM system, terrestrial or space-based, is the ability to provide surveillance during an ADS-B failure. This type of failure could come from a more systematic issue or individual aircraft. In either case, WAM systems can track aircraft as long as they can observe and cluster transmissions. The more likely failure mode is a single aircraft experiencing issues with its ADS-B equipment; in this case, as long as the ADS-B equipment transmits some messages, a WAM system can identify and track the aircraft. The unique benefit of a space-based solution is that it can provide this resiliency world-wide and in areas where ground stations cannot be deployed, such as oceanic or remote regions.

B. GNSS Resilience

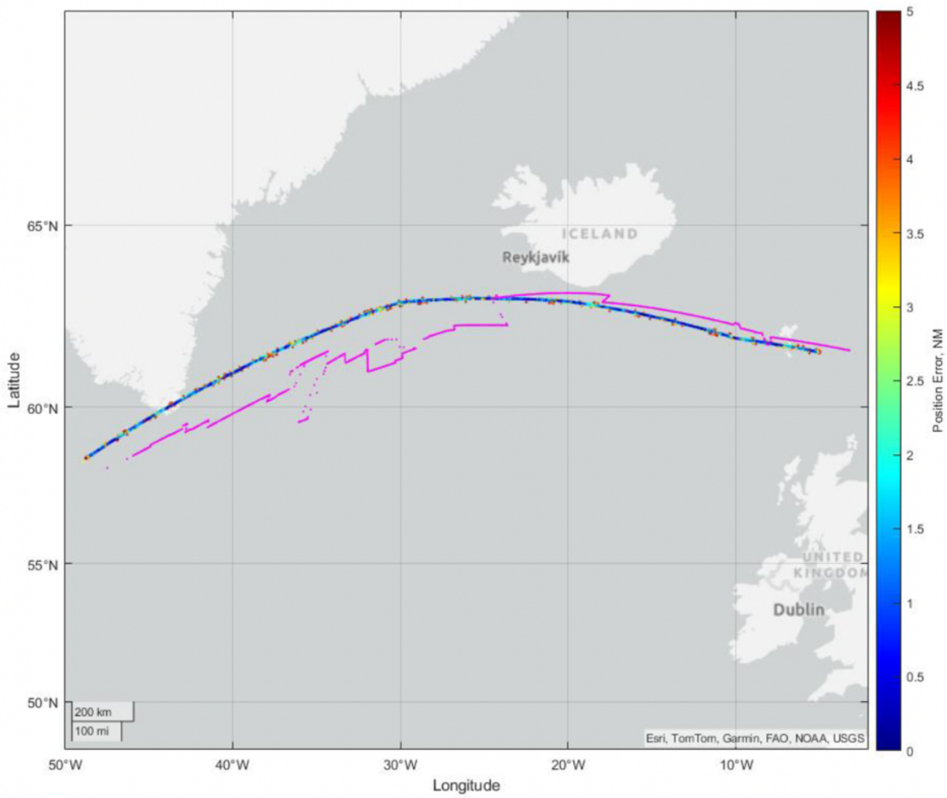
A growing concern in the air traffic world is GNSS jamming and spoofing[1]. ADS-B is dependent on GNSS to provide accurate position data and is suspect to forms of

GNSS interference. A benefit of WAM systems is that aircraft-centric GNSS jamming is not an issue, as long as the receivers can receive some messages from the aircraft a position estimate can be calculated. Even the two-dimensional solution can be determined using barometric altitude in lieu of geometric altitude, with some potential degradation to accuracy.

For a terrestrial WAM system, the ground stations themselves can be susceptible to GNSS jamming, as stated previously, all WAM solutions require accurate timing and position information at the receivers. If the ground-stations utilize GNSS to maintain accurate timing, they could be spoofed or jammed, which could result in biases that could influence the WAM solution. A benefit of a space-based solution is that it cannot be jammed in this manner; the Iridium satellites do not rely on GNSS for timing, and any satellite system that did would be too far away from a jamming source to be affected.

Looking at data from 2024-12-14, a flight that was experiencing GNSS jamming and was reporting poor ADS-B positions was evaluated against the Space-Based WAM solution. This aircraft was reporting a NIC of zero, meaning the positions were not to be trusted, and this data would be removed from any ATC display. In this case, the aircraft would have to be tracked via an alternative surveillance method such as radar or WAM; over the oceans this requires a space-based solution. Fig. 9 below shows both the ADS-B data (in magenta) and the Space-Based WAM solution colored by the error; in this case the error was calculated against a post-processing smoothing on all the WAM data. It is clear that the ADS-B data is incorrect, given the inconsistency and various jumps in position; alternatively, the WAM solution is smooth and follows a reasonable flight path.

FIGURE 9
Flight Experiencing GPS Anomalies Tracked via Space-Based WAM



C. Terrestrial Augmentation

In [8] work was done with a single ground station and a collections of satellites to show a proof-of-concept for a combined terrestrial and space-based WAM solution. In this case, the same process is used as a purely space-based solution, but there are added benefits of more overlapping coverage or the ability to create a WAM network from existing terrestrial receivers with no added ground stations. Furthermore, the algorithm described in this paper could see some benefit with track initialization, where the ground stations can help constrain the starting location and system center for a more straightforward starting point.

VI. Acknowledgment

The authors of this paper would like to thank the Modeling & Analysis team of Aireon for their continued support of this and other research and development projects, allowing for continued growth and innovation. A special thanks is extended to Valerie Cox for her review of this paper and attention to detail on this work.

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