Placement Synergy: Bridging ADS-B Ground and Space Sensors for Secure Wide-Area Multilateration

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***Abstract*—The emergence of space-based air traffic surveillance systems, using Automatic Dependent Surveillance-Broadcast (ADS-B) receivers on satellites, has extended aircraft tracking to remote areas like oceans and polar regions. However, this increased coverage alone is insufficient to ensure system security and functionality. The openness of ADS-B communication exposes it to manipulation, allowing malicious entities to introduce false data into air traffic control (ATC) systems and disrupt tracking accuracy. Present ADS-B strategies focus on optimizing ground-based receivers without adequately considering space-based ones. This paper introduces an optimization solution that addresses this gap by strategically positioning ground sensors relative to space-based receivers. Our proposed method ensures that each message is received by at least four receivers, either on the ground or in space, enabling Multilateration (MLAT) for accurate location verification while minimizing the Geometric Dilution of Precision (GDOP) value. This integration strengthens global air traffic surveillance, significantly improving both the security and overall functionality of the system.**

***Index Terms*—ADS-B, Localization, Ground Receivers, Multilateration, GDOP, Space Receivers, Location Verification**

I. Introduction

Aircraft tracking is crucial for surveillance and accurate monitoring of aircraft positions. The Automatic Dependent Surveillance-Broadcast (ADS-B) protocol is employed to transmit and receive aircraft data, encompassing location details [12]. However, the open nature of this protocol creates opportunities for unauthorized tampering and cyber attacks. One significant issue is Location Spoofing, which compromises the credibility of received location data. Therefore, location verification becomes imperative to validate the accuracy of received information. Multilateration (MLAT) [25] stands out as a well-known technique for such verification, necessitating a minimum of four receivers to confirm a location.

The current deployment of ADS-B receivers, characterized by their random placement, does not achieve complete surveillance coverage, leading to the consideration of an alternative solution: the installation of ADS-B receivers on satellites. These space-based ADS-B receivers are located on the new Iridium NEXT low-Earth orbit (LEO) satellite constellation [9], comprising a total of 66 satellites. This innovation addresses the challenges faced by conventional aviation control systems by allowing broadcast messages to be received by the ADS-B receivers aboard satellites. A notable example of such a space-based global air-traffic surveillance system is Aireon [8]. Aireon has introduced space-based ADS-B receivers to overcome coverage gaps, utilizing satellites to extend surveillance coverage to previously unreachable areas. Other companies are initiating demonstration phases, such as Globalstar [1] and Gomspace [2], or transitioning to operational status, incl. Spire [5], Inmarsat [3], and Iridium [4].

With the emergence of space-based global air traffic surveillance systems [13], the installation of ADS-B receivers on LEO satellites significantly augments surveillance coverage, extending over oceans and deserts [18]. Yet, placing receivers in space does not necessarily fulfill MLAT's requirement for four receivers due to the challenge of achieving receiver beam overlap. Furthermore, the current sensor arrangement falls short in addressing regions lacking coverage by ground-based ADS-B receivers.

In this paper, we address the ADS-B Optimal Sensor Placement (OSP) problem by presenting an optimized approach for positioning ground-based sensors in coordination with space-based receivers. To the best of our knowledge, no paper has proposed a placement strategy to cooperate with space ones. The suggested method accounts for the fact that while ground receivers are stationary, space-based receivers are mobile, moving over time around the Earth. This integration aims to enhance message coverage of location verification by including uncovered areas in the current ADS-B network. Space-based ADS-B receivers play a crucial role in this approach by increasing the coverage and at the same time reducing the number of ground-receivers.

A. Problem Statement

Location spoofing is one of the most critical security challenges faced by the ADS-B protocol [28]. ADS-B messages are transmitted openly through the air without encryption, making it possible for an attacker to alter message content and mislead air traffic control systems or aircraft. While implementing cryptographic solutions could enhance message security, such measures are currently impractical due to the need for extensive modifications to the ADS-B protocol.

Despite these limitations, it remains essential to detect message alterations and confirm the authenticity of transmitted data to ensure the safety of air traffic. MLAT is an effective method for verifying the sender's location and ensuring message integrity. By using TDOA measurements from multiple receivers, MLAT can cross-check the reported position of an aircraft. However, MLAT requires simultaneous reception by at least four receivers to accurately triangulate the aircraft's location.

The effectiveness of MLAT is highly dependent on the optimal placement and density of ground receivers. This poses a significant challenge in remote or oceanic regions with a lack of ground-based infrastructure. In addition to that, for accurate MLAT, sensors must be strategically positioned in areas where the Geometric Dilution of Precision (GDOP) is minimized [35]. This ensures higher accuracy in determining the location of the signal source.

B. Research Questions and Contributions

Leveraging the space-based setup by Aireon, it becomes possible to optimize the placement of ground sensors to enhance MLAT's effectiveness. By exploring how space-based receivers can complement ground sensors, we aim to identify the optimal locations for ground sensors that would maximize the reception of ADS-B messages and make MLAT feasible in more areas. This paper addresses the following research questions:

- RQ1 How can space-based ADS-B receivers be effectively leveraged to optimize ground sensor placement for MLAT?
- RQ2 What are the optimal ground receiver locations to ensure the highest coverage and reliability of MLAT, especially in remote regions?
- RQ3 Can a combined approach using both ground and space-based sensors improve the detection of location spoofing attacks in ADS-B systems?

We make the following contributions to address these research questions:

1) We model the optimal sensor placement problem for ADS-B ground receivers, taking into account the presence of space receivers.
2) We enable location verification checks, such as MLAT with a low GDOP value, for all received ADS-B messages by providing a placement solution where each message is received by at least four sensors, either on the ground or in space, across the entire area to detect ADS-B spoofing.
3) We provide a set of optimal solutions for placing n sensors on the ground, considering the space receivers.
4) We determine the minimum number of sensors required to cover the land area, given the presence of space receivers in the LEO satellite system.

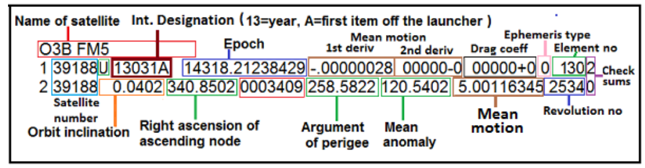


Fig. 1: An Illustration of a Two-Line Element (TLE) Set and the Explanation of Its Constituent Fields [6]

II. Preliminaries

A. Aviation and Space Network

ADS-B receivers function by capturing broadcasted information from aircraft, encompassing parameters like position, aircraft identification, velocity, and other pertinent ADS-B data. This information is subsequently transmitted to Air Navigation Service Providers (ANSPs). The data from space-based receivers is combined with inputs from ground-based receivers, resulting in a single representation of a given flight. This combined data helps Air Traffic Control (ATC) achieve increased accuracy in the management of aviation systems.

The Aireon Hosted Payload plays a pivotal role in collecting data broadcasted by aircraft. It relays this data from one satellite to another until it reaches Iridium's ground-based Teleport Network (TPN), from which it is conveyed to the Aireon Processing and Distribution Center (APD) system. Within the APD, the data is decoded and verified before being dispatched to ATC facilities subscribed to the Aireon service.

On the other hand, space-based receivers are in continuous motion, orbiting at a steady velocity, and are distributed uniformly. To ascertain the exact location of a receiver, Two-Line Elements (TLE) are utilized, as outlined in [24]. This TLE data, is regularly updated and released by organizations such as NORAD (North American Aerospace Defense Command) [27]. Fig. 1 explains the structure of TLE code and defines the meaning for its fields.

We obtained the TLE data for all 66 Iridium NEXT LEOsatellites and utilized this information to determine their positions on the sphere over time.

B. Optimal Sensor Placement (OSP) Problem

The OSP problem is an optimization challenge that focuses on determining the optimal configuration of sensor locations within a given domain. The objective is to optimize a specific function, or a set of functions, and identify solutions that satisfy these criteria. Essentially, the OSP is achieved when the chosen configuration aligns the best with the defined objective function.

There are several optimization algorithms that can be applied to this problem; however, in this paper, we utilize the Genetic Algorithm (GA) [22] as a tool to achieve our objective. A GA is a metaheuristic method used to solve constrained and unconstrained global optimization problems. The algorithm continues until either the fitness of the best individual no longer improves or a predefined number of generations have been evaluated.

C. Signal Propagation Model

Ground-to-Air Signal Propagation Model: ADS-B messages, transmitted by aircraft, are received by ground-based receivers within the Line-of-Sight (LOS) range [28]. The transmitted radio messages experience power reduction due to tropospheric reflection. The maximum reachable range for ground receivers is determined by the following formula [30]:

$$r_0 = 3.57\sqrt{k_e}(\sqrt{h_1} + \sqrt{h_2}), \tag{1}$$

where k_e denotes the effective earth-radius factor, and h_1 (resp. h_2) represents the height of the transmitter (resp. receiver) antenna in meters. As per linear approximation of the refractivity gradient, documented in [11], k_e is approximately 4/3.

Air-to-Space Signal Propagation Model: In scenarios incorporating space-based receivers, the propagation model evaluates the communication capabilities between aircraft and space-based receivers using fundamental geometric LOS calculations. This approach determines the maximum direct communication distance (horizon distance), which is computed using the following formula:

$$d = \sqrt{2 \times R \times h_{sat} + h_{sat}^2}, \tag{2}$$

where R is Earth's radius (approximately 6,371 km), and h_{sat} is the satellite's altitude above Earth's surface. This horizon distance calculation [7] is pivotal for identifying satellites within a viable communication range excluding Earth's interference. While the current model emphasizes geometric considerations, it lays the groundwork for integrating atmospheric effects in future enhancements. These will include free-space path loss, ionospheric propagation, rain attenuation, and gaseous absorption, following established guidelines such as the ITU-R P.618 model [34], to provide a more comprehensive analysis

D. Time Difference of Arrival (TDOA)

MLAT relies on the TDOA of signals from an aircraft to multiple receivers. Timing factors present a significant challenge that must also be taken into account. The varied altitudes of receivers in a mixed network affect the signal travel time, and these differences must be accurately accounted for in the calculations. The ToA from aircraft $\mathbf{p}$ to ground receiver $\mathbf{s}$ is given by this formula

$$t = \frac{1}{c}\|\mathbf{p} - \mathbf{s}\| + \tau + e, \tag{3}$$

where τ is the signal transmission time, c the speed of light, and e the measurement error.

E. Threat Model

Aircraft transmit ADS-B messages, which are designed to be received by any receivers within their Line of Sight (LOS).

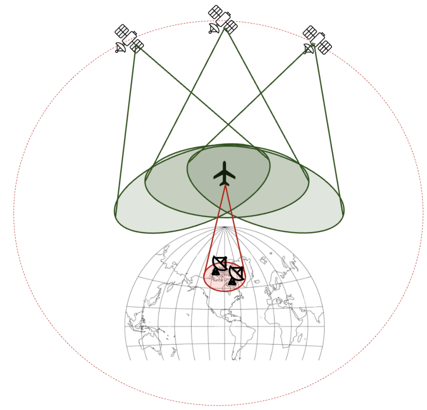


Fig. 2: Overview of the system approach, illustrating how the integration of space and ground receivers expands ADS-B coverage area while enabling MLAT execution using both types of receivers within the aircraft's line of sight.

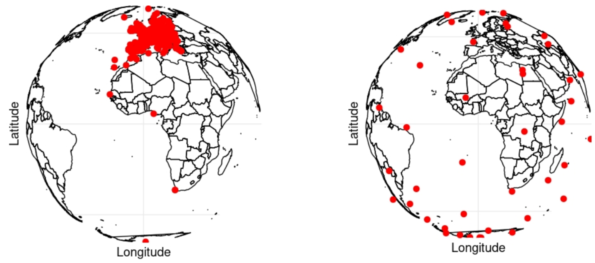
However, the messages are unencrypted, creating a vulnerability that attackers can exploit to intercept and alter the content. Our threat model focuses on ADS-B location spoofing attacks, where an attacker captures an ADS-B message and substitutes the actual location coordinates (latitude, longitude, altitude) with fake data, resulting in incorrect location reporting. This paper outlines the following types of attacks based on the attacker's position:

1) **Ground-Based Spoofer:** Situated near ground receivers, the attacker sends a fake signal that closely resembles the positioning of a legitimate aircraft. This deceptive signal can trick ground ADS-B receivers into recording an incorrect position for the aircraft, based on the altered data in the message.
2) **Space-Based Spoofer:** In this scenario, the attacker either operates from space or uses a drone capable of intercepting ADS-B signals from aircraft. These signals are then retransmitted to be picked up by both ground and space-based receivers.

These attack scenarios highlight the vulnerabilities in the ADS-B system, especially concerning the integrity of location information, and underscore the need for enhanced security measures in air traffic communication systems.

III. Proposed Solution and Strategy

Our proposed approach handles the placement of ADS-B receivers as an optimization challenge, which we tackle using a genetic algorithm. This method enhances MLAT by integrating space-based sensors with existing OpenSky [28] ground receivers. As depicted in Fig. 2, this integration not only increases the number of receivers able to detect a message but also extends coverage to remote areas like oceans. While ground receivers are predominantly located in Europe, space-based sensors are evenly distributed around the globe. Fig. 3 illustrates the distribution of sensors across the sphere and Fig. 5 explains the expanded horizon of space receivers over



(a) Ground Receivers **(b)** Space Receivers

Fig. 3: Spatial Placement of ADS-B Receivers on the Global Sphere

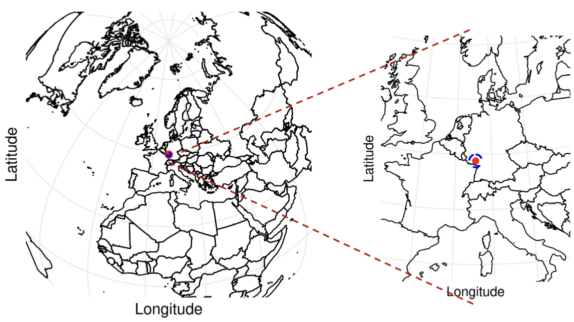
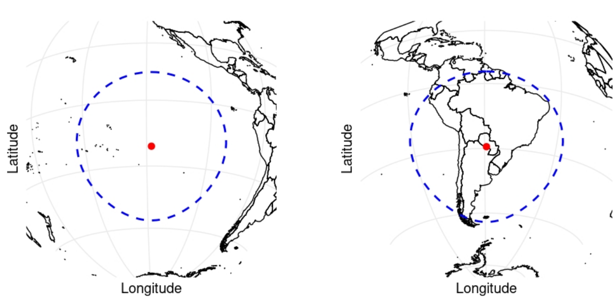


Fig. 4: Sensor Beam Horizon - Ground Receiver

ground ones (Fig. 4), which allows a single receiver to cover broader areas.

Our approach is designed to assess the existing configuration of receiver deployment and explore potential enhancements. It is essential to identify the optimal placement of receivers, concentrating on minimizing the number required on the ground compared to those in space, to facilitate MLAT verification. We also evaluate the cost implications of achieving this optimal setup, considering the current deployment of ground receivers.

Moreover, recognizing that the geometry of receiver placement significantly influences MLAT accuracy, our method examines how the integration of space-based receivers impacts this accuracy and the associated GDOP noise. This analysis aims to provide insights into the balance between receiver distribution and operational effectiveness in terms of both accuracy and cost.



(a) Over Oceanic Region **(b)** Over Land Region

Fig. 5: Sensor Beam Horizon - Space Receiver

A. Approach Direction and Methodology

This paper evaluates the described sensor placement problem using the following approaches:

1) **Assessment of Real-World Space-Based Reception:** This step evaluates the coverage provided by current satellite systems equipped with ADS-B receivers to establish a baseline understanding of the existing surveillance environment. Specifically, we determine the percentage of regions where four or more satellites provide coverage, enabling the application of MLAT. This assessment is crucial because it allows us to identify how close the current system is to the optimal surveillance scenario and highlights where improvements or additional resources may be needed. By understanding the existing gaps and limitations, we can better design strategies to enhance coverage and improve system performance in regions where aircraft operations are permitted.
2) **Examination of Ground and Space-Based Fusion in Real-World Scenarios:** We investigate the effect of combining the ground-based and space-based receivers to enhance the MLAT approach as follows:
   - Employing MLAT using positional information from both receiver layers.
   - Providing a comparative analysis against the scenario where only ground-based receivers are employed.

   We thus aim to answer the question: *How does the fusion of ground- and space-based receivers affect the MLAT performance compared to ground-based systems alone?*
3) **Determination of Optimal Configuration:** We aim to establish the minimum number of required ground-based receivers, along with their optimal locations, to effectively implement MLAT-based location verification while accounting for the presence of space-based receivers. To achieve this, we use an optimization approach that balances coverage and receiver placement efficiency.
   - We compare the derived optimal configuration to the actual real-world setup.
   - Additionally, we quantify how many additional receivers would be required in the current deployment to approximate the optimal solution.

   We aim to assess the differences in positioning precision between the current ground- and space-based receiver setup and the optimal ground-/space-based fusion configuration.

B. Preliminary Steps

To achieve our objectives, we first perform a series of preparatory steps to characterize the receiver network and its coverage. These preliminary steps include:

1) **Existing Receiver Location Determination**: First, we collect the geographical coordinates of all participating receivers, comprising both ground and space-based receivers. Ground receivers, provided by users and totaling approximately 700 in Europe, are stationary and

randomly distributed. Their locations are obtained from OpenSky. Conversely, space-based receivers, which are in continuous orbital motion at a consistent velocity, are close to uniformly distributed [20]. To accurately determine the location of a receiver, denoted as r, at a specific time t, we utilize TLE, as improved by [24]. TLE data, regularly updated and published by organizations such as NORAD, is accessible through various online platforms, including Celestrak [14] and Space-Track [29]. These orbital parameters from TLEs are employed with tracking software like N2YO.com [26] and Heavens-Above.com [19] to monitor satellites in real time. For this study, we developed Python code that leverages the TLE data to track the space-based receivers at any designated time.

2) **Satellite Intersection and Overlap**: Next, we focus on identifying the overlapping regions within the satellite beams' coverage. Given the high altitudes at which these space-based receivers operate, their coverage areas are expected to be extensive. Consequently, there are likely zones that fall within the range of multiple receivers. Furthermore, the GDOP values for these receivers are anticipated to be relatively low, a benefit stemming from the strategic placement of the satellites by organizations to ensure they are adequately spaced apart. This arrangement enhances the optimization of their collective coverage and precision.
3) **Intersection Evaluation with Ground-Based Receivers**: Additionally, we examine the intersections involving ground-based receivers alongside those with satellites. As discussed earlier, the primary aim of this work is to evaluate how combining ground and space-based receivers enhances the feasibility of using MLAT on ADS-B messages. This integration is key to verifying the authenticity of the location claimed by the aircraft, demonstrating the potential improvements in location validation brought about by this hybrid receiver network. Therefore, we investigate regions where the integration of space and ground receivers can enhance the application of MLAT, particularly in areas where installing ground receivers is not feasible.

C. System Model and Node Representation

Within the designated airspace system $\mathcal{A}$, through which aircraft transit from their origin to destination, there is an established network of receivers. This network consists of ground-based receivers that are fixed on the Earth's surface and a mobile receiver installed within a satellite system.

- The airspace $\mathcal{A}$ encompasses a collection of uniformly distributed points, each denoted as a point $\mathbf{p_j}$. These points are characterized by their specific altitude, longitude, and latitude coordinates.
- The set of ground-based receivers, referred to as R_{ground}, are stationary and strategically positioned across the terrestrial landscape. Each of these receivers is defined by its geographical latitude, longitude, and elevation.
- The set of space-based receivers, designated as R_{space}, are equipped within satellites that we assume operate at a constant orbital velocity.

D. Objective Function

We aim to address the challenge of OSP on the ground, this time incorporating space receivers into the equation. Our primary objective is to attain optimal coverage, ensuring that each ADS-B message is received by at least four sensors, whether they are ground-based or space-based. Additionally, we seek to identify the sensor configuration that results in the lowest GDOP value.

Given the airspace $\mathcal{A}$, our task is to select n ground receivers alongside the space ones that are grouped as S, aiming for a minimal GDOP value. The ideal scenario would involve achieving a GDOP value of zero (a required condition). For every set of receivers, we assess the following condition:

$$\forall\ \mathbf{p_j} \in \mathcal{A},\ \ |\widehat{g_j} - g_j| < \delta.$$

Here, g_j denotes the *required* GDOP value, and $\widehat{g_j} = \text{gdop}_{\mathbf{S}}(\mathbf{p_j})$ represents the *achieved* GDOP value at location $\mathbf{p_j}$, which is a consequence of the specific geometry of S. This formula serves to ensure that the deviation between the achieved and required GDOP values at any given point $\mathbf{p_j}$ in airspace $\mathcal{A}$ stays within an acceptable margin δ.

E. Proposed Solution

To address the OSP problem, we propose utilizing the GA [22] as an optimization tool. Our goal is to ensure full MLAT coverage with the minimum GDOP value, requiring each message to be received by at least four sensors for location verification. The genetic algorithm will be used to integrate space-based sensors with existing OpenSky receivers, enhancing MLAT's effectiveness in aircraft tracking and surveillance.

- Select m uniformly distributed points $\mathcal{P}$ over the surface area $\mathcal{A}$. Let $\mathcal{P} = \{\mathbf{p_j}\}_{j=1,\cdots,m}$, where each point in $\mathcal{P}$ symbolizes a potential aircraft location. Represent these points as $\mathcal{P} = [(\theta_j, \mu_j), \cdots, (\theta_m, \mu_m)]$.
- Position n sensors uniformly, denoted as S, across the designated area $\mathcal{A}$. Define these sensors as $\mathcal{S} = \{\mathbf{s_i}\}_{i=1,\cdots,n}$, where $\mathcal{S} = [(\theta_i, \mu_i), \cdots, (\theta_n, \mu_n)]$.
- Specify the location of k uniformly distributed satellites in space covering the entire area $\mathcal{A}$ at a given time. Represent these as $\mathcal{J} = \{\mathbf{j_l}\}_{l=1,\cdots,k}$, where $\mathcal{J} = [(\theta_l, \mu_l), \cdots, (\theta_k, \mu_k)]$.
  Here, $\theta_{j,i,l}$ and $\mu_{j,i,l}$ represent the longitude and latitude of the j, i, l^{th} points, ground sensors, and space sensor nodes, respectively.
- For each $\{\mathbf{p_j}\}$ in $\mathcal{P}$, calculate the direction cosine from this point to all ground and space sensors and construct the Direction Cosine Matrix (DCM).

- Determine the objective functions (Minimum GDOP value), applying each step in every generation of the GA:
  (i) Identify the set $\mathcal{S}_{LOS}^{i}$ of all ground ADS-B receivers where the LOS condition is met. And the set $\mathcal{J}_{HD}^{l}$ of all space ADS-B receivers where the horizon distance condition is met.
  (ii) If $|\mathcal{S}_{LOS}^{i}| + |\mathcal{J}_{HD}^{l}| < 4$, assign $\widehat{g_j} = \infty$. (GDOP cannot be evaluated if fewer than 4 sensors are in LOS/horizon distance with the aircraft.)
  (iii) Otherwise, calculate the GDOP at $\mathbf{p_j}$ for all 4-sized subsets of $\mathcal{S}_{LOS}^{j}$ and $\mathcal{J}_{HD}^{l}$ together using the closed-form expression from [35]. Then assign $\widehat{g_j}$ to the lowest value found.

The formula for the Mean Squared Deviation (MSD) between the achieved GDOP of the optioned solution from GA and the required GDOP (here in the optimal scenario the required is zero, however, such a scenario is difficult due to path loss factories, so any solution that is close to it could be a valid solution) across the entire airspace in question is expressed as follows:

$$\text{MSD}((\mathbf{S}, \mathbf{J})) = \frac{1}{m}\sum_{j=1}^{m}(g_j - \hat{g}_j)^2. \tag{4}$$

In this equation, $\text{MSD}((\mathbf{S}, \mathbf{J}))$ represents the mean squared deviation for the sensor set $(\mathbf{S}, \mathbf{J})$, where m is the total number of points in the airspace, g_j is the required GDOP value at each point j, and $\hat{g}_j$ is the achieved GDOP value at the same point. This calculation provides a quantitative measure of the deviation between the desired and actual GDOP values throughout the airspace.

F. Case Studies

We are examining various scenarios, each with a constant number of space-based receivers that move over time. The specifics of these scenarios are as follows:

1) **Sensor Placement from Scratch**
   In this scenario, we consider the airspace $\mathcal{A}$ without any existing ground-based receivers. Our objective is to determine the minimal number of ground receivers required to cover the area, ensuring that each point in P is covered by at least four sensors, either in space or on the ground. The chosen set should yield the minimum GDOP values, as calculated by (4).
   This scenario represents an ideal situation where we have m sensors and aim to optimize their ground locations. When evaluating potential ground sensor placements, the existing space-based receivers must also be considered.
2) **Augment existing sensors with new placements to reach optimal coverage**
   Conversely, the optimal scenario might incur high costs. Therefore, given that there are already deployed sensors, our goal is to identify the minimal number of additional sensors needed to complement these existing ones. The cost-effectiveness of this solution will depend on the locations of the current sensors and their proximity to the optimal scenario.
3) **Optimal Deployment of a Fixed Number of Sensors**
   In the final scenario, if we have a specified number of sensors to deploy, we aim to find the best possible locations for these sensors to approximate the optimal scenario as closely as possible.

These scenarios provide a comprehensive approach to sensor placement, taking into account both new deployments and the integration of existing infrastructure to achieve optimal coverage and accuracy.

IV. Results

A. Evaluation Setup and Data

We assess our approach by initially obtaining the positions of the 66 Iridium LEO satellites using TLE data released by NORAD. We implement a Python script to track these satellites, which function as space-based receivers, either at specific times or continuously. For ground-based receivers, we utilize the OpenSky Network, which comprises approximately 7,000 receivers worldwide. However, we were only able to obtain the precise locations for 700 of these receivers, primarily located in Europe.

Subsequently, we employ this data to optimize the number and placement of ground sensor receivers, aiming to enhance coverage of the sphere or enable MLAT capability. All scripts, including those calculating direction cosine and fitness functions, are developed in R and utilized by the GA for optimization purposes. All scripts are publicly available. [1]

B. Evaluation Criteria

To evaluate the effectiveness of our solution and to ascertain how close the current deployment is to the near-optimal configuration, we employ the following two assessment criteria:

1) **K-coverage density:** This metric assesses the number of sensors $|\mathcal{S}_{LOS}^{i}| + |\mathcal{J}_{HD}^{l}|$ covering any point $\mathbf{p_j}$ within surface area $\mathcal{A}$. More sensors covering a point are advantageous for two main reasons: (1) if one sensor fails, another can still service that point; (2) accurate location verification, as necessitated by MLAT which requires at least four receivers, is more reliable with greater sensor coverage. We aim to maximize this criterion to an extent.
2) **GDOP value:** Conversely, placing too many receivers close to each other can lead to an increase in the GDOP, thereby introducing more measurement noise. Our strategy focuses on minimizing this value. The optimal or desirable GDOP is close to zero, with solutions nearing this value deemed most effective.

C. Experimental Results

We employ the following procedure for the area we are targeting. Initially, we assess a small region defined by a

[1] https://github.com/afd1479/sensors_placement

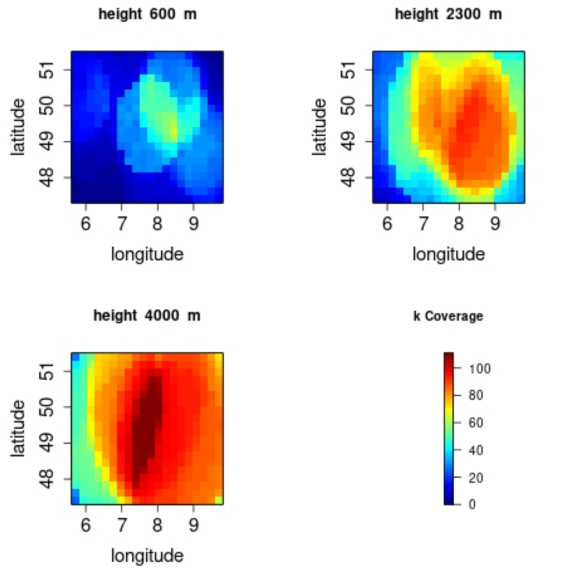


Fig. 6: k-coverage —Small Area — Ground Receivers

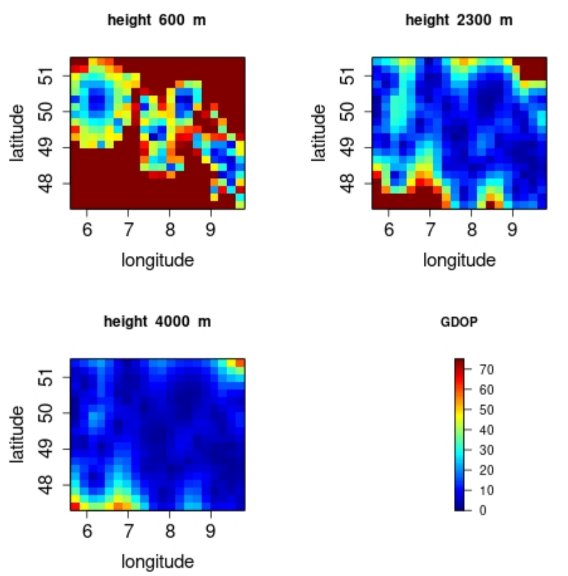


Fig. 7: GDOP —Small Area — Ground Receiver

longitude range of 5.71 to 9.71 decimal degrees and a latitude range of 47.4 to 51.4 decimal degrees. Subsequently, we expand our scope to test the entire Earth.

Fig. 6 illustrates the k-coverage provided by existing ground receivers from OpenSky for the targeted smaller area. As altitude increases, k-coverage expands due to a wider LOS. However, this arrangement can result in higher GDOP values because the triangulation among receivers to pinpoint locations via MLAT could lead to significant errors. Fig. 7 displays the GDOP values for the same area. Therefore, the objective extends beyond achieving robust k-coverage: it is equally crucial to maintain a low GDOP value.

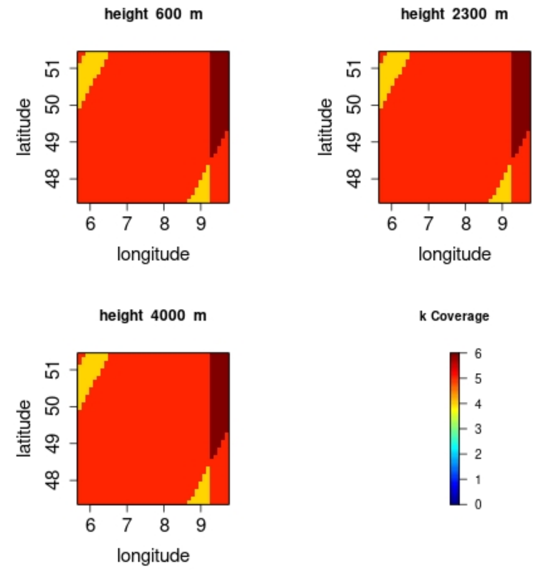


Fig. 8: k-coverage —Small Area — Space Receivers

We also tested the k-coverage of the same area, excluding consideration of ground-based receivers. Fig. 8 illustrates how the area is nearly uniformly covered by a similar number of receivers, providing evidence that LEO satellites are distributed almost uniformly. On average, all points within the surface area $\mathcal{A}$ are covered by five satellites (i.e., five space-based ADS-B receivers). Furthermore, we tested this coverage over several time snapshots as the satellites move, and we observed consistent coverage percentages.

Incorporating space-based receivers does not significantly alter the k-coverage heat map of the area, which is already densely populated by ground receivers. The addition of space-based receivers (five on average, as demonstrated) does not lead to a visible improvement in coverage. However, the GDOP is noticeably enhanced, as illustrated in Fig. 9. This improvement occurs because MLAT can now also utilize space-based receivers, which significantly refines the hyperbolic positioning necessary to pinpoint locations more accurately.

This does not imply that we are fully satisfied with incorporating only space-based receivers to enhance MLAT verification. As demonstrated, the current deployment of ground receivers is concentrated on a specific area, covering merely a small area of the Earth's surface, as illustrated in Fig. 10. This raises an important question: What about the remaining Earth's surface?

Space-based receivers provide an effective solution for covering areas not reached by ground receivers. Fig. 11 illustrates the k-coverage of the entire Earth using 66 Iridium satellites. However, relying solely on space-based receivers is impractical. As the transmission time for signals from space to Earth is longer, which can delay data reception. Therefore, we prefer to use space-based receivers selectively—primarily when the GDOP from ground receivers is high or in regions

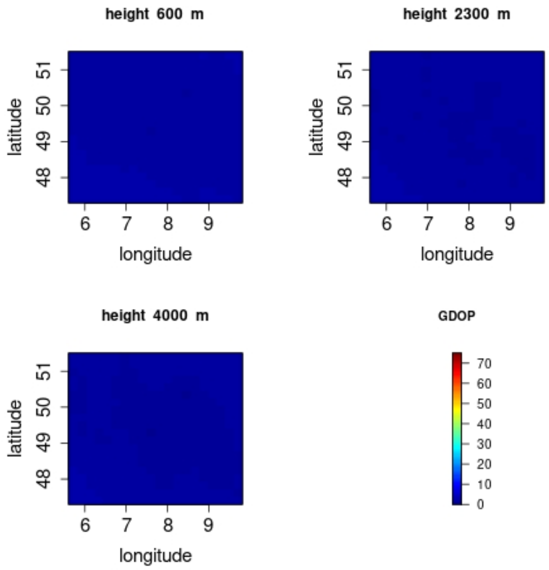


Fig. 9: GDOP — Small Area — Both Receivers

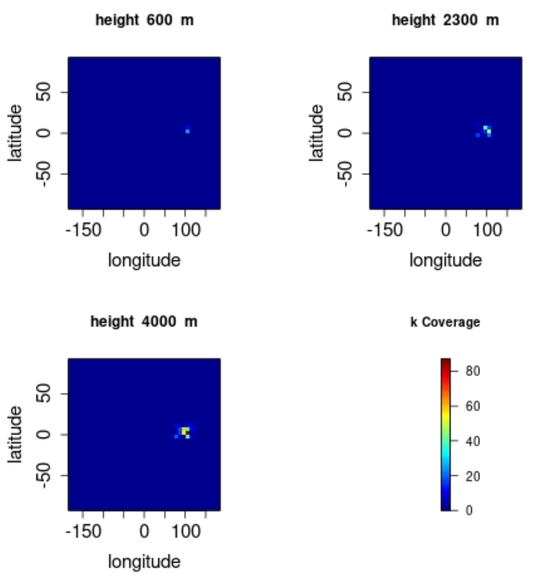


Fig. 10: k-coverage — Large Area — Ground Receivers

not adequately covered by at least four ground receivers.

Our approach evaluates the effects of integrating both ground and space-based receivers to enhance coverage and MLAT verification. Additionally, we explore near-optimal solutions for placing n ground receivers. Fig. 12a displays the proposed locations for 20 receivers within a selectively small area. It is important to note that in this test, we did not consider the approximately 100 already deployed ground receivers; we focused solely on the potential placements in relation to space-based receivers, aiming to identify the best-optimized locations. The GA was run for 50 iterations to achieve the optimal fitness value.

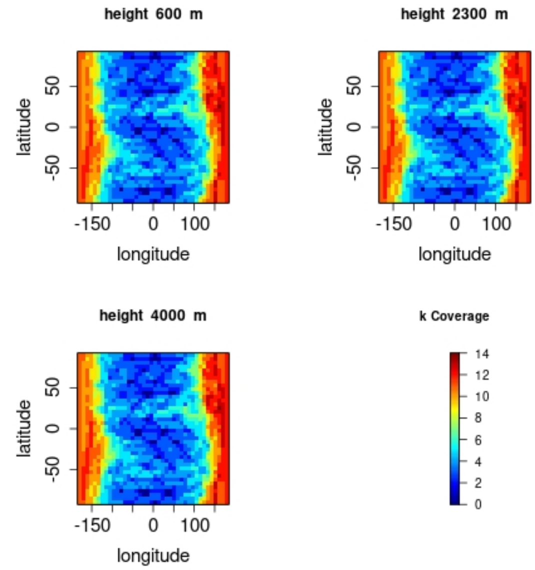
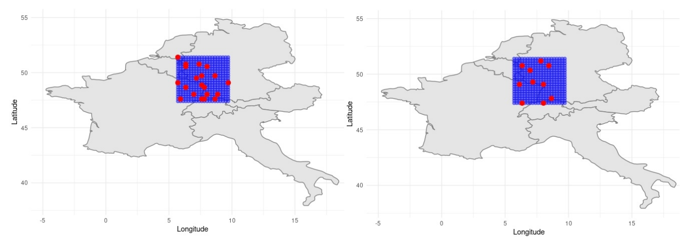


Fig. 11: k-coverage — Large Area — Space Receivers



(a) 20 Ground Receivers **(b)** 10 Ground Receivers

Fig. 12: Comparison of Optimal Ground Receiver Locations

Furthermore, we assessed whether these 20 receivers are sufficient or if more/fewer might be necessary for the same area. A subsequent GA run with fewer receivers (10 in this case) indicated that by iteration 20, the GA had already reached the optimal fitness value, suggesting that the specified area, detailed in Fig. 12b, could be adequately covered by only 10 receivers. The experiments reveal that the GDOP values in both scenarios approach zero. However, if the budget permits additional receivers for backup and redundancy, we would opt for 20 sensors. As shown in Fig. 13 and 14, the k-coverage is slightly improved with the higher number of sensors.

Since our goal is to cover the entire sphere, we replicated the process in another area of the same size but located in a different region, with longitudes ranging from 19 to 23 decimal degrees and latitudes from 41 to 45 decimal degrees. We found that 10 sensors are sufficient to cover this area as well.

Our placement procedure ensures a solution that guarantees valid MLAT verification for all received messages, providing high accuracy with minimum GDOP values. Whether the attacker is located on the ground or in space, and if they attempt to spoof the location within the ADS-B message, this placement strategy ensures the presence of a reliable verification method to detect spoofing attacks effectively.

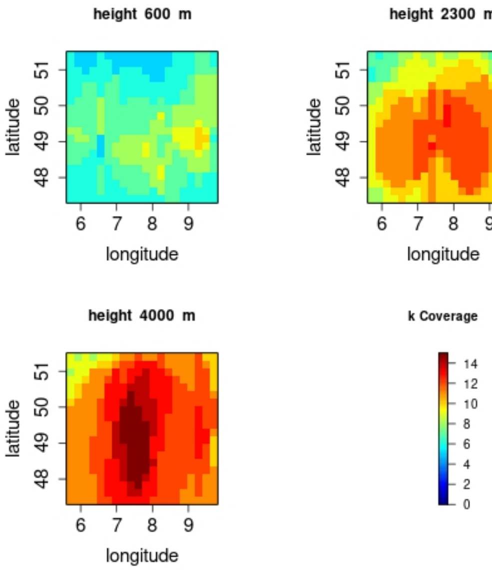


Fig. 13: K-Coverage Heatmap of Placing 10 Ground ADS-B Receivers Alongside Existing Space-Based Receivers

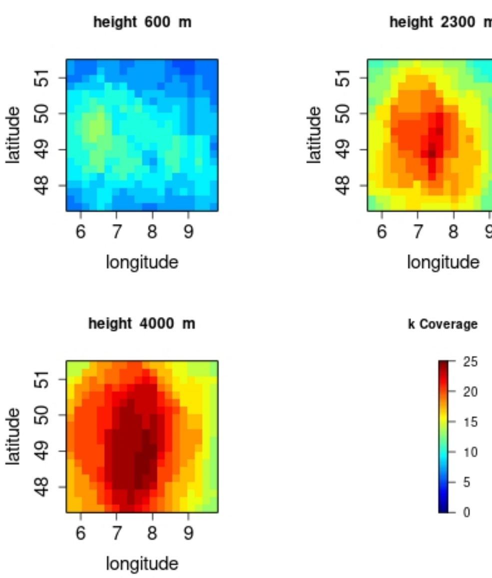


Fig. 14: K-Coverage Heatmap of Placing 20 Ground ADS-B Receivers Alongside Existing Space-Based Receivers

D. Scalability Analysis for Global Coverage

Given our observations, if a land area of size $197,136$ km^2 requires 10 sensors for adequate coverage, we can use this information to estimate the total number of sensors needed for the Earth's entire land area. The total land area of the Earth is approximately $148,940,000$ km^2. Using the ratio of the total land area to the area covered by 10 sensors, the sensors required are approximately $\frac{148{,}940{,}000}{197{,}136} \approx 755.52$. This ratio indicates that approximately 755 sets of sensors are needed if each set covers as much as the initial 10 sensors, totaling approximately 7,555 sensors to cover the whole landmass of the Earth. However, the current placement of ADS-B receivers by OpenSky, which totals around 7,000, is primarily concentrated in Europe and parts of the United States. This leaves large portions of the Earth's land and water regions uncovered. By strategically redistributing the same number of receivers using our optimized placement strategy, it is possible to achieve comprehensive coverage of the entire Earth's surface. This calculation provides a basis for planning the strategic deployment of ground receivers to ensure comprehensive global coverage over terrestrial regions.

Enhanced MLAT verification through the integration of space and ground receivers ensures robust defense against message spoofing, from terrestrial or space-based attackers. This setup guarantees a sufficient number of receivers with known locations, strategically placed to reduce GDOP and enable accurate MLAT predictions for message verification.

The proposed approach is applicable to any system requiring location verification to ensure the trustworthiness of messages using MLAT. Given that the OSP problem is common in wireless communication—where systems aim to either determine the sender/receiver's location or validate the accuracy of a reported location—our solution provides an effective method for determining the optimal placement and number of receivers needed to achieve optimal coverage. In this paper, we evaluate our approach specifically for ADS-B receivers as a use case, though it is equally applicable to other systems and scenarios.

V. Related Work

The widespread adoption of the ADS-B protocol has led to significant security concerns, as highlighted in various studies [15], [23], [31]. A major vulnerability is the exposure of ADS-B messages to spoofing attacks. Extensive research has been conducted to develop methods for safeguarding the messages or for detecting alterations by attackers.

The first category explores various approaches to protect messages, such as employing digital signatures [33] or Message Authentication Codes (MAC) [21] to encrypt them. However, these solutions necessitate a complete overhaul of the system, from the sensor to the receiver, which is impractical and contradicts the fundamental design principle of ADS-B, which is to transmit messages in plain text. Additionally, such methods are resource-intensive and time-consuming. Alternatively, the second category focuses on verifying the authenticity of claimed messages by assessing the trustworthiness of the received data and comparing it with expected values. Research presented in [32] proposed a lightweight solution that verifies the location of ADS-B messages using K-NN in 2D dimensions. Another approach, MAVPro [16], aims to verify the location of messages received by a single receiver, relying on trusted anchors.

MLAT [25] is a widely recognized method for location verification due to its accuracy. However, its application is limited by the requirement that messages be received by at least four sensors, a challenge given the random placement of sensors.

To address this, authors in [10], [17] have proposed optimizing sensor locations on the ground to improve MLAT coverage. Nevertheless, this approach primarily considers ground-based receivers and does not account for areas like oceans, which make up most of the Earth's surface. With the advent of space-based receivers, there is a growing need to integrate these with ground receivers, which is the focus of our paper.

VI. Conclusion

MLAT is used for verifying the accuracy of location claims in ADS-B messages. The effectiveness of MLAT is contingent on the placement of ground-based receivers, which can be a limiting factor due to their often random and uneven distribution. Such placement may result in densely covered areas while leaving others without sufficient coverage for MLAT, which necessitates at least four receivers to intercept a message. In this work, we introduce a strategy for placing the ground sensors that consider the positions of space-based receivers. By integrating both terrestrial and extraterrestrial sensors, our approach not only enhances the coverage where MLAT can be applied but also extends it to previously uncovered regions. Consequently, this enables the more widespread application of MLAT to the majority of ADS-B messages received, thereby optimizing the verification process.

Acknowledgment

This work was supported by the Center for Cyber Security at New York University Abu Dhabi (NYUAD).

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