WHITE PAPER

APRIL 2025

Dr. Michael A. Garcia, Systems Engineering, Aireon LLC
Dr. Giuseppe Sirigu, Systems Engineering, Aireon LLC
John Dolan, Systems Engineering, Aireon LLC

Observations of trends in GPS anomalies affecting aviation

The Global Positioning System (GPS) serves a central role in most aircraft systems: supporting communications, navigation, and surveillance. Recently, over the last few years, the scale and severity of jamming and spoofing of aircraft GPS systems has increased and diversified significantly. Aireon can observe such impacts via its comprehensive space-based Automatic Dependent Surveillance Broadcast (ADS-B) receiver system, which collects billions of aircraft-transmitted ADS-B messages per day in real-time. Patterns and trends of GPS anomalies can be analyzed in this extensive geo-temporal dataset, which can be used in applications such as airspace monitoring and flight planning. In this paper, the scope of GPS anomaly incursion from state and/or non-state actors is viewed at the global as well as the local level.

Introduction

GPS is a critical resource for modern aviation, not unlike fuel or weather data. Naturally, GPS is the primary system used for aircraft navigation although there are backup means through inertial reference systems and distance measurement equipment (DME). Additionally, accurate time is needed from GPS to exchange digital communication messages such as Controller-Pilot Data Link Communications (CPDLC) or internet services provided to the cockpit and passengers. Furthermore, GPS acts as the backbone of surveillance systems, supporting Automatic Dependent Surveillance Broadcast (ADS-B), the successor to radar for tracking aircraft in a more scalable, efficient, and economical fashion.

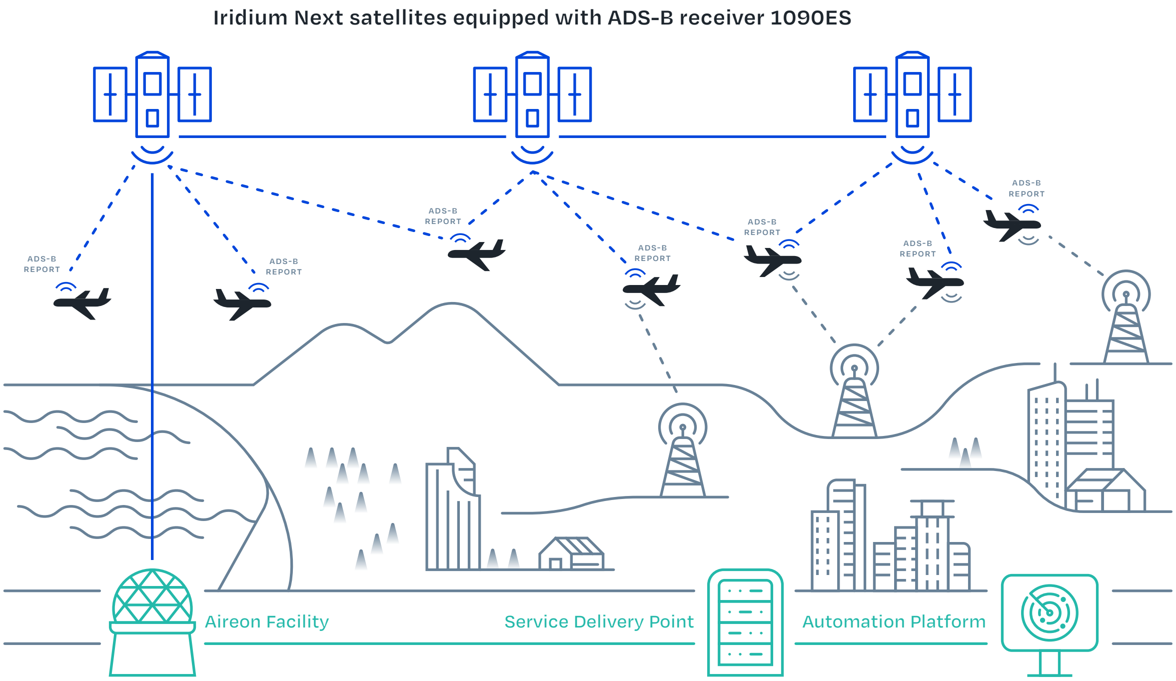
Recently, over the last few years, the scale and severity of jamming and spoofing of aircraft GPS systems has increased and diversified significantly [1]. Estimates by OPSGROUP put the increase as high as 500% over the course of 2024 alone [2]. Their report includes interviews from pilots, controllers, and other aviation community members on this topic. Other models estimate an 80% increase in GPS outage events between 2021 and 2024 [3]. The situation for aviation has become so significant that the European Aviation Safety Agency (EASA) issued a safety bulletin in July of 2024 warning of the increase in frequency and multitude of impacts from GPS interference [4].

The EASA report includes potential impacts such as:

- Inconsistent navigation position and/or time
- Loss of or misleading surveillance (e.g., ADS-B)
- Loss of Airborne Collision Avoidance System
- Loss or misleading Terrain Awareness and Warning System (TAWS)

Aireon, a global space-based ADS-B service provider (Fig. 1) to over 20 Air Navigation Service Providers (ANSPs) and many commercial customers, has examined GPS jamming and spoofing issues in the aviation community and published several reports on the subject [5, 6, 7]. Given the recent increases in GPS interference and Aireon's intrinsic involvement in contributions to the increased operational safety of international aviation, Aireon was motivated to leverage its extensive ADS-B data set to build methods and applications that allow for the identification and even mitigation of intentional GPS interference worldwide.

FIGURE 1
High level Aireon system architecture



In this paper, the scope of GPS anomaly incursion from state and/or non-state actors is viewed at the global as well as the local level. Various regions of military conflict have accelerated the use of wide-spread GPS jamming and spoofing devices that (although likely intended for military aircraft and ground systems) have encroached on civil aircraft's use of GPS for navigation and timing. The anomaly types are categorized based on observations to begin to standardize the classification from the emerging methods and applications that are seeking to monitor airspaces. Once the categories are set, a combination of metrics in the form of heatmaps, trendlines, and other analytics are used to correlate changes in the GPS anomaly metrics to regional interference events. In this paper, recommendations will be given for using such metrics for airspace monitoring, flight planning, avionics monitoring, and traceability of interference pattern migration.

GPS anomaly types

A. Background

When an aircraft encounters a GPS interference source there are several different ways that its avionics may respond. If the navigation system is robust enough (e.g., multi-constellation or algorithmic defenses) then they may not exhibit any negative symptoms as they traverse a GPS interference source's coverage area. However, most operational avionics were not required or designed to defend against the level of jamming and spoofing currently being experienced. The vast majority only use GPS L1 since that was the only navigation constellation system certified for aviation use until the Galileo constellation achieved aviation certification in 2023.

Aireon can get a sense of what an aircraft's navigation system is experiencing via the ADS-B messages that are transmitted by the aircraft and received by its 66 satellites. However, this view is indirect and complicated by the fact that the navigation system is connected the transponder and the flight management system. Therefore, even if an aircraft is flying with an inertial reference unit or using distance measurement equipment (DME) to navigate, these data sources are typically not used by the ADS-B transponder. Additionally, there is often more than one GPS receiver operating in an aircraft and there are no means to determine which GPS an ADS-B message is getting its data from (although they tend to have similar position and time solutions).

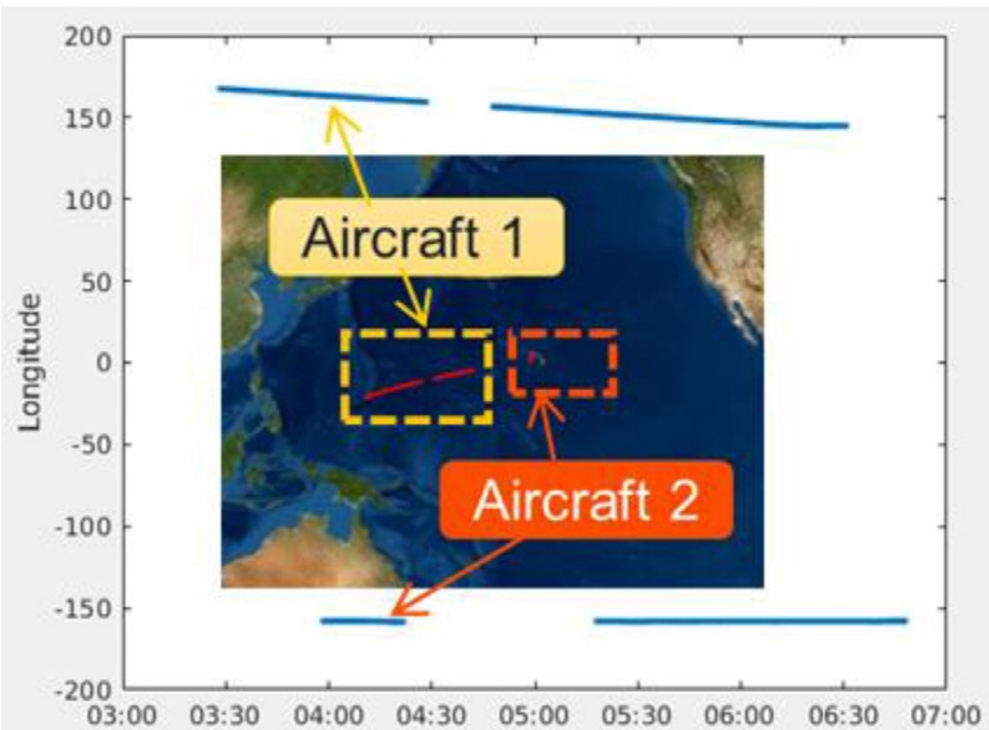
B. Position/navigation integrity category (PIC / NIC)

FIGURE 2
Depiction of the ADA-B reported PIC

The most common way to detect GPS anomalies from ADS-B messages is to utilize the aircraft's reported Navigation Integrity Category (NIC) or the EUROCONTROL report equivalent known as the Position Integrity Category (PIC) [8, 9]. This value is a horizontal position integrity bound (Fig. 2) that is calculated from the horizontal protection limit and quantized to fit into a limited number of bits in an ADS-B message. Generally, if the PIC is greater than or equal to some threshold (e.g., 7, representing a radius of containment < 0.6 NM) then it is assumed the aircraft navigation system has a high-quality GPS solution. However, if it is below this threshold, then either there is an avionics issue, a GPS constellation issue, or it is experiencing GPS jamming or spoofing. The first two cases can generally be ruled out if the symptoms are experienced by more than one aircraft in an area over several hours or longer.

C. Duplicate addresses

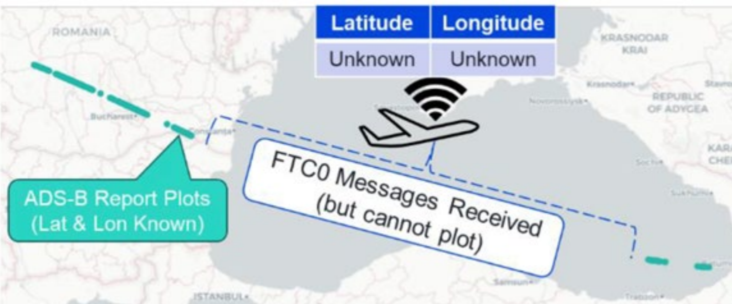
FIGURE 3
Examples of ADS-B duplicate address condition



One of the tenets of the ADS-B protocol is that each aircraft/airframe should have a unique 24-bit address that is set in the Mode S/ADS-B avionics upon installation (and almost never changed). These 24-bit addresses are registered with the International Civil Aviation Organization (ICAO) and blocks of these addresses are given to different countries for local distribution. Occasionally, one of these addresses is mistakenly configured in more than one aircraft at the same time. This leads to a "Duplicate Address Condition" (Fig. 3) and can make it more challenging for ADS-B receiving systems to associate the appropriate message sets to each aircraft. This duplicate condition can also be triggered where GPS interference causes the aircraft's navigation system to experience position errors. If these position errors are greater than 6 NM and occur within a relatively small time window (30s) of otherwise accurately transmitted positions (i.e., noisy position data), this can result in the aircraft creating a duplicate "with itself" as viewed by another ADS-B receiver [10]. This condition can consequently be considered another indication of significant GPS interference.

D. Field type code = 0

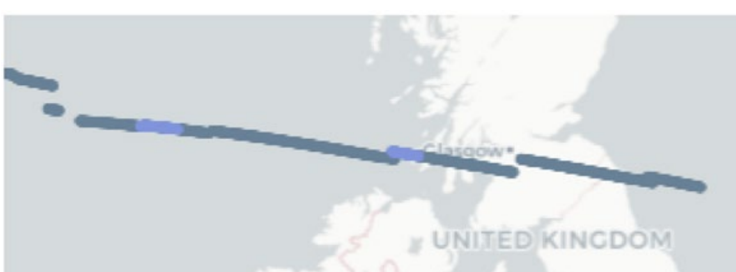
FIGURE 4
ADS-B messages transmitted with unknown lat and lon (FTC0)



If the aircraft navigation system experiences severe interference, the GPS solution may cease to operate, resulting in unreliable or unknown position data. When the latitude and longitude are unknown, the ADS-B position message is set to a special value known as Field Type Code 0 (FTC0) [10]. With a 5-bit encoding, there are 32 possible ADS-B message Field Type Codes and the FTC0 case was included primarily for when avionics are first powered on and the GPS is acquiring a signal lock on satellites, forming its initial solution. However, these symptoms are now being observed while the aircraft is airborne where GPS interference is prevalent. When ADS-B reports are plotted (Fig. 4), this can be observed as gaps in the track (although a system would need to capture and retain the raw FTC0 messages to separate these gaps from other causes such as unintentional 1090 MHz interference).

E. Track discontinuities

FIGURE 5
Flight track "jumps" and shows discontinuity

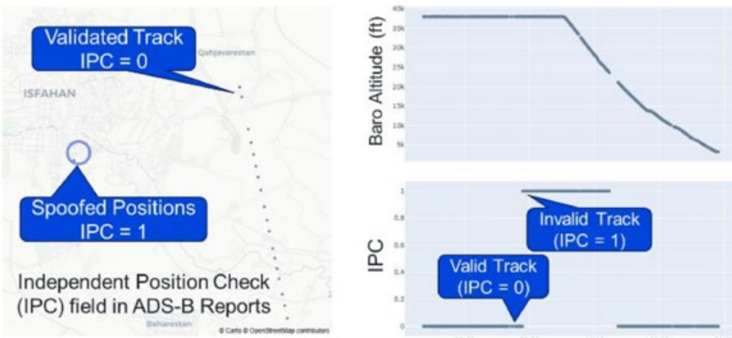


If the position reported by the aircraft begins to "jump" or shows large offsets in short periods of time relative to expected trajectories, then these anomalies can be flagged as having position errors. Typically in these cases, ADS-B reports low PIC values and sometimes duplicate as well as FTC0 flags.

F. Improbable or invalid flight track

FIGURE 6

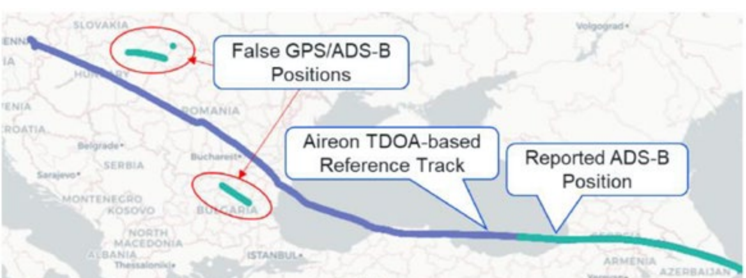
"Circle pattern" caused by GPS spoofing with IPC field flagged



Detecting spoofing of an aircraft's navigation system (GPS) can be difficult depending on the nature of the device creating the spoofing signals. When false GPS signals are created and transmitted from the ground with a signal strength higher than true GPS signals from space, they can cause aircraft avionics to lock onto the false signals resulting in incorrect position broadcasted in ADS-B messages. For example, circular patterns have been observed (Fig. 6) while an aircraft is airborne [7]. Not only is the aircraft's position spoofed, but also the velocity (which is typically calculated from the doppler measurements of GPS signals). Fixed-wing aircraft flying above 18,000' are not expected to have velocities lower than 100 kts but aircraft spoofed into circular patterns are observed reporting velocities at around 60 kts.

FIGURE 7

Spoofed GPS/ADS-B compared to Aireon's reference track



Note that part of the track shown in Fig. 6 was flagged by Aireon's Independent Position Validation (IPV) algorithm [5,6], which uses Time Difference of Arrival (TDOA) measurements from overlapping satellites and kinematics to calculate a 'reference track' that is independent of GPS-based positions reported from aircraft ADS-B messages. When the ADS-B-reported positions are measured to be greater than a configurable distance (e.g., 3 NM) from Aireon's calculated reference track, Aireon will set the Independent Position Check (IPC) flag to 1 (i.e., position check failed validity test) in its ADS-B reports to ANSP and commercial customers.

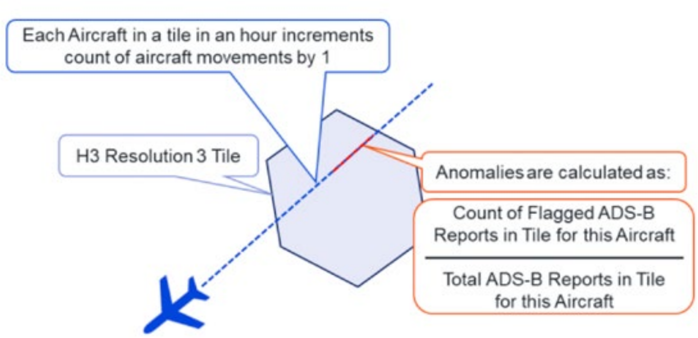
Fig. 7 shows both the ADS-B-reported position (green) and Aireon's reference track (blue) where the aircraft travelling from Bangkok to Vienna was subject to GPS interference near the Black Sea. This resulted in a FTC0 condition, and the aircraft subsequently having its position spoofed into Bulgaria, Hungary, and the Ukraine. These anomalies were detected by comparing the reported positions to Aireon's reference track and alerting on the track when the IPC flag was set. By having a more accurate estimate of the aircraft's state vector during the anomalies, the association of where and when GPS anomalies actually occurred (vs. where their "symptoms" were projected to occur) can be substantially more reliable.

Data analysis aggregation methods

With several different anomaly types identified and billions of ADS-B messages collected globally every day, the aviation industry is in clear need of a suitable method for aggregating and normalizing counts of GPS Interference to more effectively compare patterns and trends from multiple regions of interest. A growing trend for geospatial data is to use H3 hexagonal tiles (developed by Uber [11]) and bin the data to a chosen resolution to suit the need of the application. Since the H3 indexing system, aggregation applications, and many visualization tools are open source and fairly efficient to operate, it is a suitable solution through which to render counts from multiple time and space resolutions.

A balance is needed for the right duration of time and area to use to bin the data. Too short of a time will reduce the meaningful number of samples to make an inference, and too long will make it more difficult to determine when a transient event may have occurred. Similar issues are akin to the selected area of a tile. In this work, data was binned by hour over H3 resolution 3 (edge length of 69 km) tiles. For a given tile and individual aircraft, the counts of reports with anomalies are normalized by dividing the number of anomalous reports (e.g., IPC = 1) by the total number of reports in that hour (see Fig. 8). This gives an effective weighted aircraft movement count such that momentary "glitches" in the data flags have less weight than persistent data problems.

FIGURE 8
Method for normalizing anomalies detected from ADS-B into H3

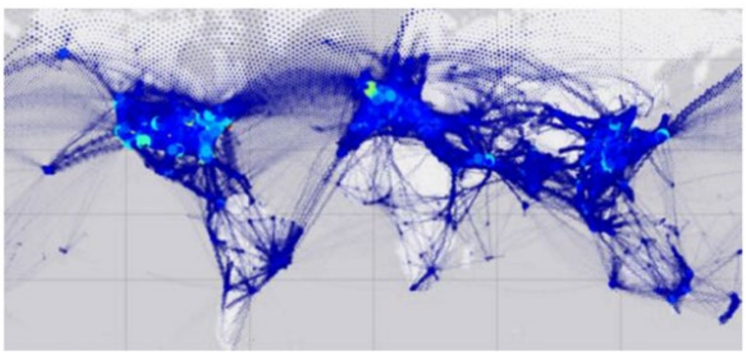


Results and analysis

Once the aggregation method and parameters are established, the event data detection triggers can be set algorithmically and counts of data can be appropriately added to their respective bins. However, the time horizon for the results will analyzed only over the most recent six months of data (even though Aireon has operational data dating back to 2019). This is primarily driven by the fact that several event detection features, such as the IPV/IPC flagging of events, had only reached algorithmic maturity and been deployed operationally within that timeframe.

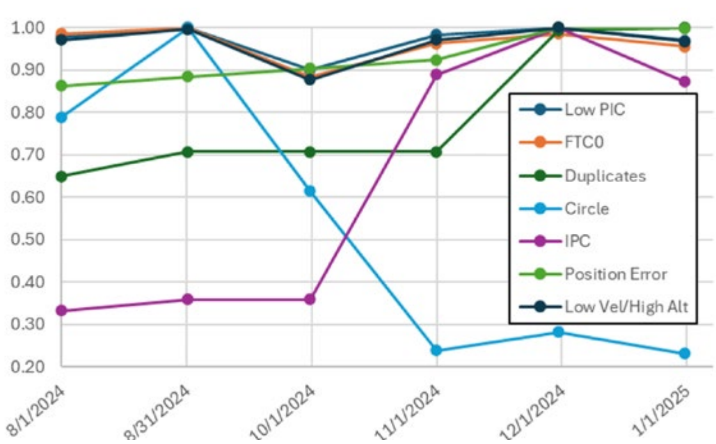
A. Global perspective

FIGURE 9
Global ADS-B aircraft movement density on Sept 1, 2024



To give a sense of the scale of the data being analyzed each day, the top-level zoom for the Sept 1, 2024 global aircraft movement density is shown in Fig. 9. This density is shown with plot points (rather than hexagons) at H3 resolution 3 tile centers with a size and color that scales based on counts to highlight higher traffic areas and oceanic routes.

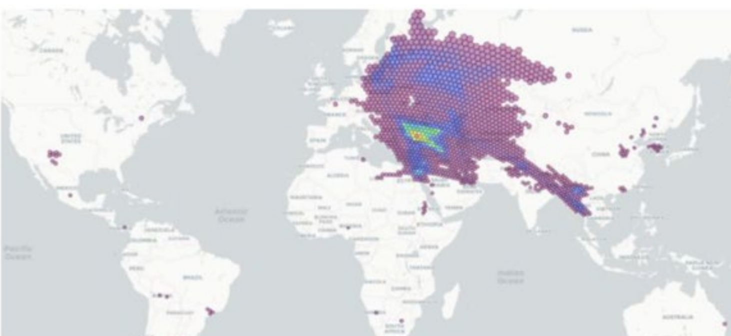
FIGURE 10
Normalized GPS anomaly rates at global scale



Applying the metric calculations for the GPS Anomaly types described in Section II (and further dividing by aircraft movements to factor out changes in flight counts from month to month), Fig. 10 shows the trends for these metrics between August 2024 and the end of January 2025. To compare the metrics on the same Y axis (and emphasize relative rather than absolute change), the metrics were each divided by their respective maximum value within the evaluation time window to normalize them.

Some initial observations from this data are that the Low PIC, FTC0, and Low Velocity/High Altitude trends appear to be nearly perfectly in sync over this 6-month period. The first two are generally indicators of GPS jamming (although they are also precursors for spoofing) and appear to be relatively steady with the exception of the 10% drop in October. Most of the indicators relating to GPS spoofing are showing increases: Duplicates, Position Errors (> 20 NM), and the IPC flag. However, the significant increase in the IPC rate in November comes with a caveat. This is when Aireon deployed an update to its IPV/IPC algorithm to increase its ability to detect false positions (although the increase from November to December is legitimate). One notable exception to the increasing trend in spoofing activity is the significant drop in circle patterns detected beginning in October. A significant shift in this baseline appears to have occurred recently, although this may mean that other spoofing patterns have been put into use that need to be added to the event detection application.

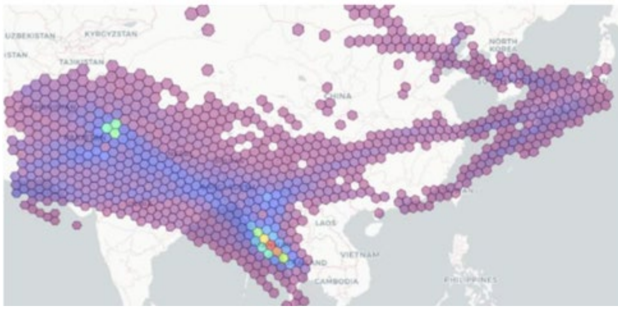
FIGURE 11
Global GPS anomaly density map (all types)



Viewing the six months of anomaly data as a heatmap in Fig. 11 shows hotspots near conflict zones in the middle east and Russia with significant coverage of eastern Europe as well. Note that H3 tiles with fewer than 1% counts relative to the peak tile are not displayed to reduce clutter. The following sections will evaluate more specific areas and smaller time windows with a focus on environments that show more dynamic GPS anomaly behavior.

B. Asia Pacific – duplicates

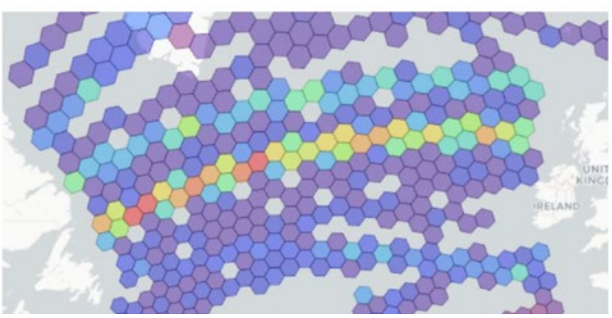
FIGURE 12
Asia Pacific heatmap of duplicate anomalies in Dec 2024



Regional, anomaly type, and date/time filters can be set to adjust the contrast of the heatmaps to further explore those that may have a more visible impact in a local environment. Fig. 12 shows the density of duplicate address anomalies during the month of December 2024 over the Asia Pacific region. As noted in Section III, the counts of anomalies were higher in general, and some of the areas shown in Fig. 12 can also be seen highlighted in Fig. 11. The two areas with the highest concentration of duplicates in Asia are near Lahore, Pakistan and Yangon, Myanmar. This certainly seems to align with news reports and other anecdotes related to GPS jamming and spoofing from pilots [1].

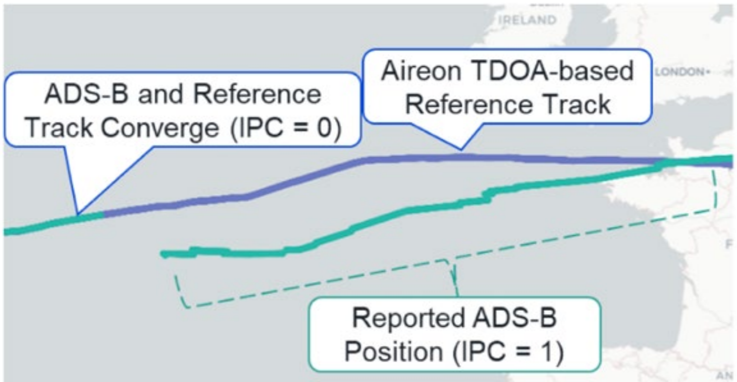
C. North Atlantic tracks (NAT)

FIGURE 13
North Atlantic tracks heatmap of IPC anomalies in Dec 2024



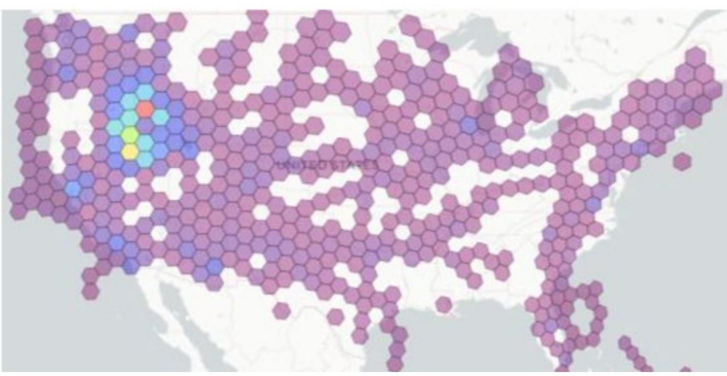
The North Atlantic Track (NAT) system between North America and Europe is the busiest oceanic airspace in the world. Although it is unlikely for aircraft to begin experiencing GPS jamming or spoofing when entering this airspace, some aircraft operating within the NAT system display persistent jamming and/or spoofing symptoms that originate from prior operations within other regions (e.g., the Black Sea). This has an impact on the aircraft's navigation as well as the surveillance of these aircraft, because Aireon's space-based ADS-B data is the primary source of surveillance for the ANSPs that manage this airspace (NAV Canada and NATS). Fig. 13 shows the IPC anomaly type singled out over the month of December 2024 in the NAT, which are probably indicating residual large position errors from previously jammed aircraft navigation systems. Filtering the time further to the peak day in December for IPC counts (Dec 12), Fig. 14 shows one of the aircraft with IPC flagged while crossing the NAT. This example shows how when examining GPS Interference one can start from a high level perspective, focus down into specific airspaces, and then continue on to the individual aircraft level.

FIGURE 14
Flight crossing NAT on Dec 12, 2024 with IPC flagged



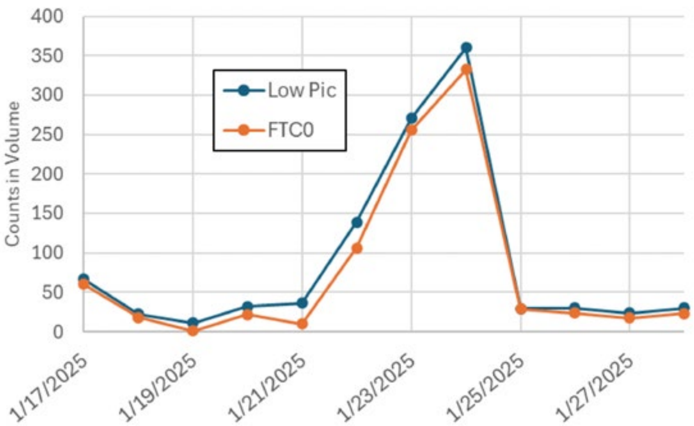
D. US Airspace

FIGURE 15
US heatmap of low PIC anomalies Jan 22-25, 2025



The US is an airspace that tends to clearly show changes in GPS interference activity. This is partly because large-scale GPS interference over CONUS is relatively rare compared to Europe and Asia, but also because the US occasionally conducts testing on its interference capabilities. Fig. 15 shows significant interference near Boise, Idaho on Jan 22–25, 2025, which is likely due to military exercises as advertised by a notice from the USCG Navigation Center [12]. Fig. 16 shows the degree of change for the Salt Lake City (KZLC) Flight Information Region (FIR), where the counts of aircraft movements with Low PIC and FTC0 increased 13 times its baseline and then rapidly declined.

FIGURE 16
KZLC FIR low PIC and FTC0 counts



Conclusions and future work

The methods and examples presented in this paper provide insights into an emerging application of ADS-B data to assess various types of GPS anomalies and determine how they evolve at small and large scales. Furthermore, Aireon proposes that GPS event monitoring/alerting applications could leverage this data for flight planning, incident investigation, and pattern of life analysis. Although using ADS-B is not a direct measurement of GPS interference since not all areas will be covered at all times (given that aircraft need to be present to "sample" the area) it nevertheless generates signals that could tip and queue more resource-intensive sensor networks. Additionally, if and when aircraft navigation systems are built more robustly to withstand interference these detection methods will lose some of their potency, however the application can be superseded by using new fields in ADS-B messages that report spoofing and/or jamming activity. Future work will certainly include investigating and trending more anomaly patterns, assessing trends by aircraft type, as well as refining and expanding the aggregation approaches introduced here.

Acknowledgment

The authors of this paper would like to thank Valerie Cox, Vinny Capezzuto, and Don Thoma for their technical review and contributions to this paper.

References

[1] M. Thurber, "GNSS Jamming and Spoofing Events Present a Growing Danger," March 2024. [Online]. Available: https://www.ainonline.com/aviation-news/air-transport/2024-03-04/gnss-jamming-and-spoofing-events-present-growing-danger.

[2] OpsGroup, "GPS Spoofing: Final Report," 2024.

[3] IATA, "Global Navigation Satellite System GNSS Radio Frequency Interference," 2024.

[4] EASA, "GNSS Outage and Alterations Leading the Communication, Navigation, Surveillance Degradation," 2024.

[5] J. Dolan and M. A. Garcia, "Aireon independent validation of aircraft position via space-based ADS-B," in ESAVS, Berlin, 2018.

[6] J. Dolan, M. A. Garcia and G. Sirigu, "Aireon Space Based Aircraft Position Validation and Multilateration," in DASC, Barcelona, 2023.

[7] M. A. Garcia, J. Dolan and G. Sirigu, "GPS interference and spoofing in the Baltics," 2024. [Online]. Available: https://aireon.com/white-paper-gps-interference-spoofing-in-the-baltics/.

[8] M. A. Garcia, "Global surveillance and tracking of aircraft via satellite," in SCPNT Symposium, 2020.

[9] S. Ali, W. Schuster, W. Ochieng and A. Majumdar, "Analysis of anomalies in ADS-B and its GPS data," GPS Solutions, 2015.

[10] RTCA, "DO-260C MOPS for 1090 MHz Extended Squitter ADS-B and TIS-B," RTCA, Washington, DC, 2020.

[11] I. Brodsky, "H3: Uber's Hexagonal Hierarchical Spatial Index," 27 June 2018. [Online]. Available: https://www.uber.com/blog/h3/.

[12] US Coast Guard Nav Center, "GPS Service Interruptions," 1 Feb 2025. [Online]. Available: https://www.navcen.uscg.gov/gps-service-interruptions.