Characterization of ADS-B Performance under GNSS Interference

Zixi Liu, *Stanford University*
Sherman Lo, *Stanford University*
Todd Walter, *Stanford University*

BIOGRAPHY (IES)

Zixi Liu is a PhD candidate at the GPS Laboratory at Stanford University. She received her B.Sc. degree from Purdue University in 2018 and her M. Sc. degree from Stanford University in 2020.

Sherman Lo is a senior research engineer at the GPS laboratory at Stanford University.

Todd Walter is a Professor of Research and director of the GPS laboratory at Stanford University.

ABSTRACT

Automatic Dependent Surveillance Broadcast (ADS-B) uses GNSS and other sensors to provide aircraft positions to air traffic controller (ATC) and other airspace users. This project seeks to use ADS-B messages to rapidly detect and localize interference events allowing for better protection and situational awareness for operations that rely on GNSS being available. This project first characterizes the effects of known GNSS interference events on ADS-B outputs. We then utilize these observed behaviors to identify suspected interference events at other locations. This paper performs this analysis using publicly available records of ADS-B transmissions. The events that we sought to identify were based on pilot reports of interrupted GNSS service to aircraft on approach to a San Francisco bay area airport. Approach procedures may be more likely to encounter interference due to the closer proximity to the ground and therefore to potential radiofrequency interference (RFI) sources. Further, these procedures have the most stringent safety requirements.

INTRODUCTION

Radio-frequency interference (RFI) sources can cause denial of GNSS-based landings for aircraft. Not only can RFI disrupt operations while the interference is ongoing, it can also result in the approach being made unavailable long afterwards. The aviation authority may wish to prevent use of GNSS while access is uncertain via a system such as notice to airmen (NOTAM), until the interference problem can be identified or resolved. The sudden loss of navigation is a safety issue since the landing phase is where the aircraft is closest to the ground and therefore, in the most vulnerable flight segment. Due to the growing dependence of critical and safety-of-life systems on GNSS in aviation, it is important to be able to localize the RFI source as well so that it can be removed as quickly as possible. Aircraft broadcast their GNSS-derived position information through the Automatic Dependent Surveillance–Broadcast (ADS-B) system to the ground station. Therefore, by monitoring the ADS-B outputs on the ground side, we can identify instances when interference impacts an aircraft's positioning and navigation capabilities. Similarly, the system can offer positive evidence when GPS is currently functioning well within an area providing air traffic controllers better situational awareness.

ADS-B is a surveillance system based on positions from certified GNSS based position estimates. Messages may be transmitted using several protocols with Mode-S Extended Squitter (Mode S ES) on the 1090 MHz frequency band which is the international standard. The 1090 MHz ADS-B transponder onboard the aircraft broadcasts its position and velocity messages every 0.4 – 0.6 sec for reception by any receiver in the area such as other aircraft and ground stations. ADS-B is already widely in use by commercial aircraft and was made mandatory for all aircraft in Europe and the U.S.A. by 2020. The ubiquity and openness of ADS-B provides an available widespread source of GNSS information from aircraft. Due to the threat of GNSS RFI, ADS-B may be used as a means to identify and localize instances of RFI.

Several groups have already investigated the use of ADS-B to localize GNSS interference. EUROCONTROL has looked at the use of ADS-B to determine GNSS affected regions in the eastern Mediterranean [1]. They used a grid probability calculation to generate heatmaps for identifying the RFI source position. Other researchers have proposed using existing ADS-B information such as Navigation Accuracy Category – Position (NACp) to characterize the presence of a GNSS jamming event for a given airspace [2].

This project uses ADS-B data from the OpenSky Network which is a community-based receiver network that collects ADS-B data and stores historical data [3]. Our goal is to analyze the capability and limitation of crowdsourced ADS-B for RFI detection and localization. This project was motivated by two unrelated events. The first event was that we had received reports of GNSS interference causing a local pilot to be unable to complete a GNSS approach procedure into a nearby airport. The pilot experienced this effect twice at very similar points in the approach path. He recorded video of the GNSS receiver display during the second event [4], confirming that the receiver signal power suddenly disappeared for all satellites in view. The receiver then went into acquisition mode and a few seconds later began to acquire some of the GPS satellites again. It took nearly another 90 seconds before the receiver began to output a position fix again. This outage duration matches exactly with position outputs seen from ADS-B reports. Detailed information will be discussed in the following sections. Based on his and other pilot reports, the GPS RNP approach to Hayward airport was NOTAMed out of service. The second event was that we were able to collect airborne GNSS data during an interference testing event during which we knew when jamming was present. We had our own receiver installed on the aircraft and the aircraft also had an ADS-B transponder. We realized that examining these two events for which we had external corroboration that RFI was present provided us with a unique opportunity to characterize the impact of RFI on the ADS-B output. Once such effects were properly characterized, we could then search through recorded ADS-B data to look for other suspected events where RFI affects aircraft in flight.

CHARACTERIZATION OF GNSS INTERFERENCE EFFECTS

Mode S ES ADS-B messages provide basic information about GNSS position and its status. Nominally, position and velocity reports are sent every 0.5 seconds [5]. These reports are basic and provide only position or velocity as well as a sense of the integrity bounds and estimated accuracy levels. No explicit receiver information, such as number of satellites used or carrier to noise ratio (C/No), is sent. However, we can infer some information about GNSS reception even with the existing ADS-B. The integrity and accuracy levels can provide a sense of the quality of the GNSS measurements. DO-260B [5] indicates that if GNSS is unavailable but barometric altitude is available, ADS-B should continue transmission and send a Type 0 position report. Furthermore, according to RTCA/DO-181D (EUROCAE ED-73C) [5], if no new GNSS position data is received within 2 seconds of the previous data update, the ADS-B transmitting subsystem will clear all but the altitude and status subfields of the airborne position message. The position message could continue to be broadcast based on other navigation systems, but the quality indicators describing the integrity and accuracy of position data should drop. Currently only GNSS has been accepted as an adequate source for providing relevant accuracy and integrity data for ADS-B. Therefore, we can expect to observe a loss of airborne position and/or an increase of the claimed integrity bounds as the aircraft enters the area impacted by interference.

However, due to the different standards for Mode S ES ADS-B that have been developed (DO-260, DO-260B) as well as manufacturer implementation, ADS-B transponder behavior may not behave the same across different installations or even match with expectations based on the standards. Indeed, there are fielded transponders that do not meet the 2020 FAA ADS-B mandate requirements. Furthermore, we and other researchers have seen ADS-B reports that do not seem to exactly match what is anticipated from the standards. This may be due to ADS-B version, manufacturer implementation, or issues with data capture. Since the beginning of ADS-B, there have been several updates on ADS-B from Version 0 to Version 1 and to Version 2. These version updates are intended to enable more information in ADS-B. Some important parameters were introduced during the update from Version 0 to Version 1. Those parameters show integrity levels of position information including navigation integrity category (NIC) and surveillance integrity level (SIL). Version 2 then refines more details on that information. However, these variances need to be characterized using analysis based on real data. To eliminate some of the larger variations, we limit ourselves to only using ADS-B data from ADS-B transponders that report using Version 2 equipment.

This section of the paper shows the method and results of characterizing the effects of GNSS interference events under planned interference tests that had known characteristics, such as aircraft location and jammer power. The next subsection shows two observed properties from ADS-B outputs under interference events, including loss of position messages and variation in NIC parameters.

Edwards Air Force Base Flight Test Data

To examine ADS-B performance under known interference, we gathered data around Edwards Air Force base (EAFB) airport (KEDW) in September 2019 around the time of an interference exercise. The data came as part of our participation with the EAFB test pilot school. These tests occurred under normal conditions as well as during the operations of up to six GNSS jammers operating on GPS L1 and L2. From the flight tests, we have GNSS L1, L2 and L5 measurements and positions from our onboard GNSS receiver. Additionally, the jammer locations and ON/OFF states are known. During each flight test, three different types of data were recorded. Figure 1 shows the data from one of the flight tests done at KEDW airport. The blue line shows the L5/E5A GNSS and GLONASS generated positions from our onboard receiver. Since the jammers did not generate interference on L5 nor on the L1 GLONASS band, we use these measurements to create our reference location of the aircraft during the entire flight test as they were always available. The upper left corner of the flight path shows some yellow dots which represent L1/L2 GNSS positions from our onboard receiver. The yellow dot gives a clear indication of whether the GNSS signal has been jammed at each time stamp. The green dots show the ADS-B data obtained from the OpenSky Network. The unavailability of the ADS-B received position information may either be due to the loss of L1 GNSS by the onboard ADS-B GPS receiver or the inability of the ADS-B receiver on the ground to receive the ADS-B transmission. The second situation occurred often as there were mountains with an average height of 2 kilometers between the location of the flight track and the ADS-B ground receiver providing data to OpenSky . These mountains often impeded the ADS-B line of sight particularly when the aircraft was flying at altitudes lower than 3500 meters. In addition, even at altitudes higher than 3500 meters, the loss of ADS-B messages could still happen. In addition to the ADS-B messages transmission, the interrogations and responses of Mode S and the related Mode A and C systems are also being transmitted over the 1090MHz channel. These 1090MHz transmissions could cause interference on the ADS-B transmission.

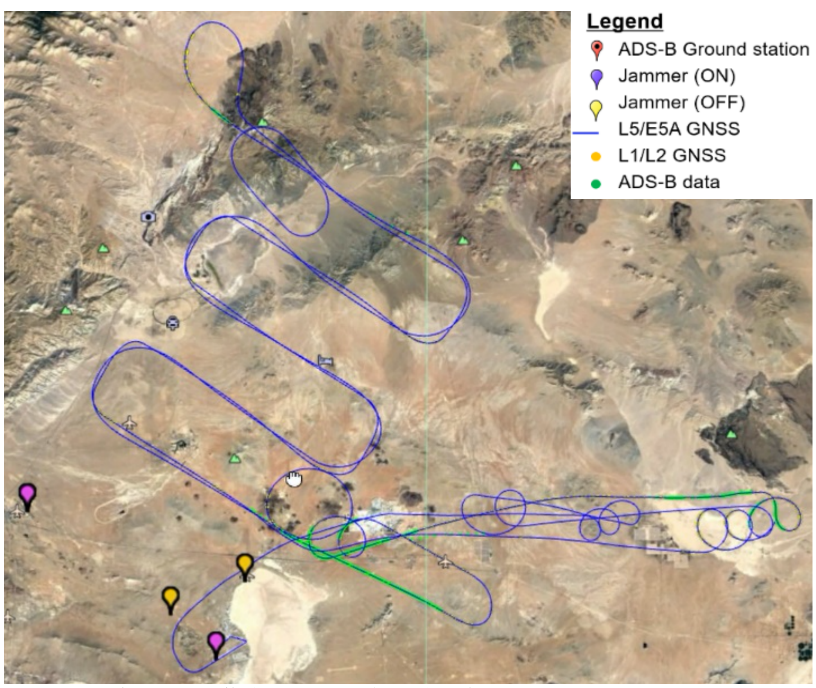

Figure 1. Flight test at Edwards Air Force Base (KEDW)

Results and Analysis

This section of the paper analyzes two main properties of the ADS-B behavior under interference which are loss of airborne position reports and variation of the reported integrity bounds in the position data. We examined different causes for the loss of position messages including loss of GNSS signals and inability of the ADS-B receiver on the ground to receive the ADS-B transmission. We noticed that the loss of position information is a relatively weak indication of interference event, especially given the poor placement of the ADS-B receivers compared to the test location. Therefore, we moved on to a further investigation on the integrity bounds of ADS-B position data. We also examined baseline performance from flight tests done on days with no interference events and where we could compare those results with flight tests done on days with interference. By doing this comparison, we were able to separate true GNSS loss from ADS-B reception loss.

a) Loss of Position Messages

By comparing the appearance of different types of position data, we try to determine the ADS-B position state at each point. Figure 2 shows a segment of the entire flight path. Some segments have only yellow dots but no green dots, meaning that the aircraft received GNSS signals and broadcast ADS-B reports that were not received by ground stations. In contrast, some parts have no yellow dots and no green dots, meaning that the aircraft entered the impact area of interference sources, therefore, likely meaning that the ADS-B GNSS receiver lost GNSS signals or it stopped broadcasting ADS-B position reports. For parts with both yellow dots and green dots, the ADS-B reports broadcast by the aircraft were successfully received by ground receivers.

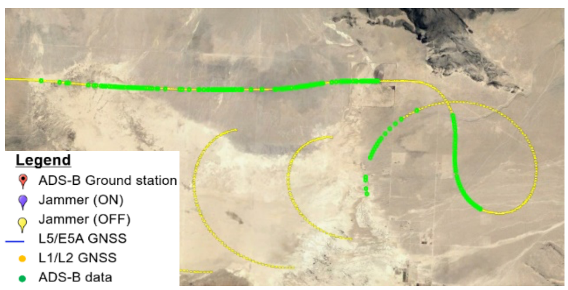

Figure 2. South-east segment of flight test at KEDW

Unavailability of ADS-B airborne position messages appears on both regular days and days with interference present. The reason for loss of ADS-B data on regular days is due to the mountains between the ground station and the airport that block the line of sight (LOS) between the ADS-B signals from aircraft and the ground ADS-B receivers. Figure 3 shows the highest point of the mountain with altitude around 2800 meters. This creates a screening of the signals which is shown by Figure 4 where the ADS-B outputs could only be received when the aircraft reached an altitude of 3500 meters and higher.

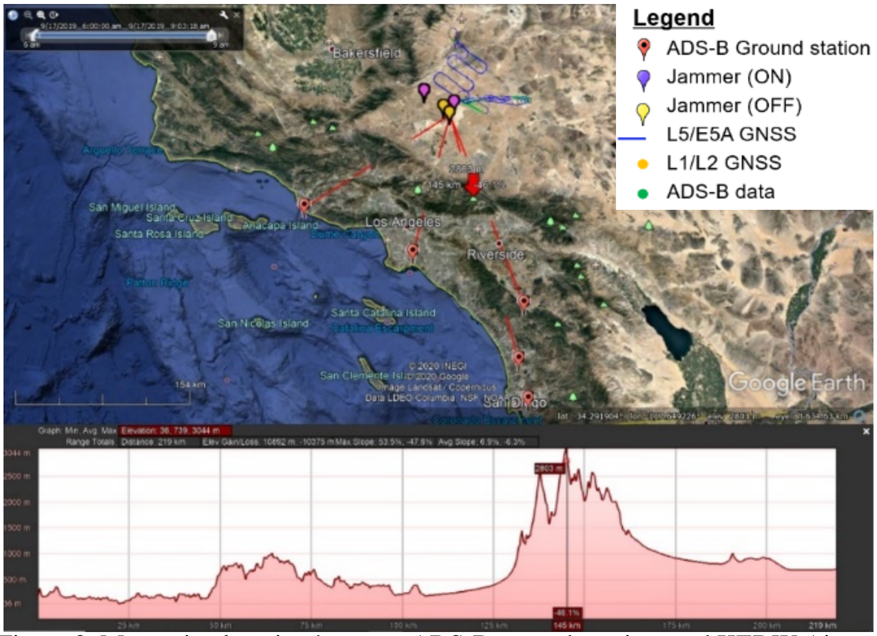

Figure 3. Mountain elevation between ADS-B ground receiver and KEDW Airport

Since the loss of ADS-B messages observed at ground stations is a common situation for both normal days and days with interference events, it is important to perform further analysis to distinguish the loss of ADS-B messages due to GNSS interference events from physical signal blockage. One way to distinguish this is to examine the reception of other ADS-B content that may not require GNSS reception.

b) Examination of Navigation Integration Category (NIC) Value from ADS-B

To further investigate the ADS-B airborne position message, we performed analysis on one of the ADS-B integrity parameters: Navigation Integrity Category (NIC). NIC is a number that represents the integrity bound of the error in the position estimate and it corresponds to a position error integrity containment radius (R_c) shown in Table 1. The NIC is included in the ADS-B position reports. Notice that a larger NIC value indicates better GNSS performance with a correspondingly smaller containment radius. When NIC equals zero, it may indicate a complete loss of GNSS signals.

NIC	Containment Radius
0	Unknown
1	$R_C < 37.04$ km (20nm)
2	$R_C < 14.816$ km (8nm)
3	$R_C < 7.408$ km (4nm)
4	$R_C < 3.704$ km (2nm)
5	$R_C < 1852$ m (1nm)
6	$R_C < 1111.2$ m (0.6nm)
	$R_C < 926$ m (0.5nm)
	$R_C < 555.6$ m (0.3nm)
7	$R_C < 370.4$ m (0.2nm)
8	$R_C < 185.2$ m (0.1nm)
9	$R_C < 75$ m
10	$R_C < 25$ m
11	$R_C < 7.5$ m

Table 1. NIC value and corresponding size of R_c[5]

We plot and compare various information from ADS-B position reports received on regular days and days with interference present. For instance, Figure 4 shows plots of time versus altitude for two different flight tests and the color of each point represents the value of the NIC parameter. The plot on the left-hand side shows a flight test done on a normal day where all jammers were turned off. Notice that the value of the NIC parameter remains steady at 8 for the entire time. The flight track gaps shown on this regular day are likely caused by signal blockage from the mountains. In contrast, the plot on the right-hand side shows a flight test conducted on a day with interference present. The asterisk on the plot marks the beginning or ending point of the flight track gap. This type of gap shows characteristics different than the gap that happened on non-interference days. This type of gap has a variation in NIC value before or after it. To have a clear indication of the gap, we use an imaginary line to connect the starting and ending asterisks. By comparing the time stamp at the starting point of each flight track gap with the times when the jammers were turned on, as well as observing the aircraft's location relative to the active jammers at that time, we believe the loss of position messages during those flight track gaps were caused by the interference event. Notice that at the starting point of each flight track gap, there is a variation in NIC value from reasonable values of 6~8 down to 0. Therefore, the appearance of both loss of airborne position and a variation of the NIC values in the ADS-B reports gives us a clearer indication of the presence of interference events. The beginning point of the gap also shows possible points when the aircraft is entering the area impacted by interference.

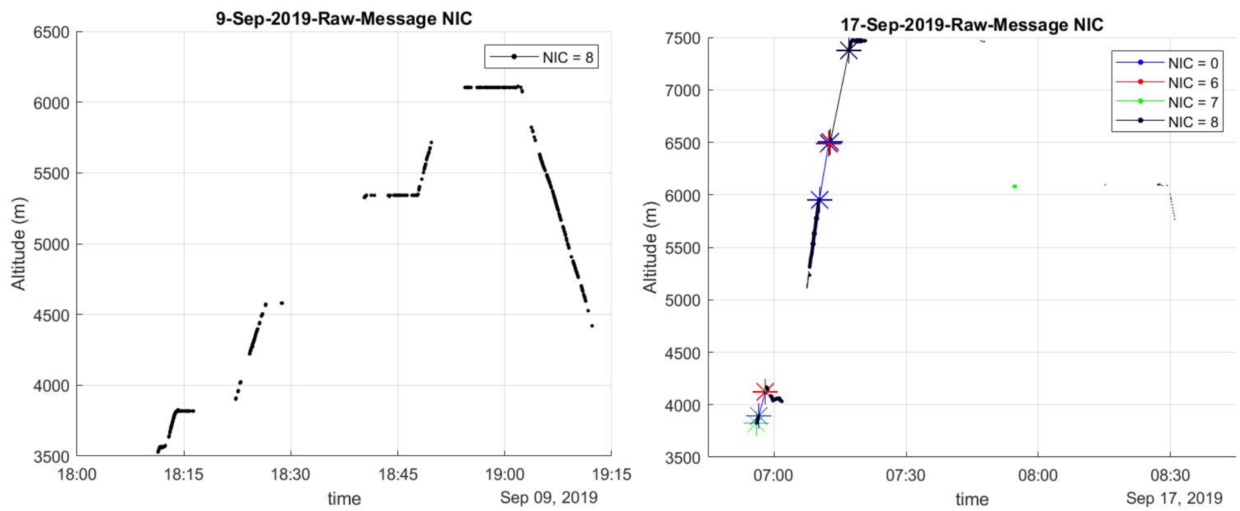

Figure 4. Flight on a day with no interference events (left) and a day with interference present (right)

We conclude that high-power interference events can be identified when there exists a position output gap that lasts for at least 10 seconds with a change in NIC value from reasonable values above 6 down to 0 in the data surrounding this flight track gap.

GNSS INTERFERENCE IMPACT REGION

From the prior analysis, where we had both ADS-B data as well as reference data from an affected aircraft, we identified some basic ADS-B characteristics indicative of interference. We now apply those properties to suspected events using only ADS-B data from OpenSky. We then use the data to estimate the possible position of the source of the interference as well as the corresponding impact area.

ADS-B Data from Hayward, CA

We examined an area around Hayward Executive Airport (KHWD) in Hayward, CA based on pilot and FAA reports of suspected GNSS interference in early 2019. We received three reports on flights being affected by GNSS interference events. Table 2 shows detailed information. Note that two of the reports were from the same flight which has a transponder hex code of A6FE05. Among those interference events, the event that happened on February 15th has a video recorded from the cockpit perspective which was mentioned in the introduction section. The primary area of interest is shown as a black square in Figure 5, which covers the area where the interference event was documented. We conducted our analysis first by focusing on this area in the black square to simplify the investigation. Later, we will perform analyses on larger airspaces encompassing much of the San Francisco bay area.

Date	Transponder Hex Code	Aircraft Model
01/06/2019	ACB876	IAI Astra SPX
01/20/2019	A6FE05	Cessna 525A
02/15/2019	A6FE05	Cessna 525A

Table 2. Three reported GNSS interference events

Figure 5 shows results from the ADS-B data queried from the OpenSky network with each green line representing a flight path of an aircraft entering and leaving the target airspace. The surface elevation of the ground between each ADS-B ground receiver and the airport is relatively low; the highest point of the elevation is round 130 meters. Therefore, the lines of sight are not expected to be obstructed and any loss of ADS-B airborne position message should mainly be due to the presence of interference events.

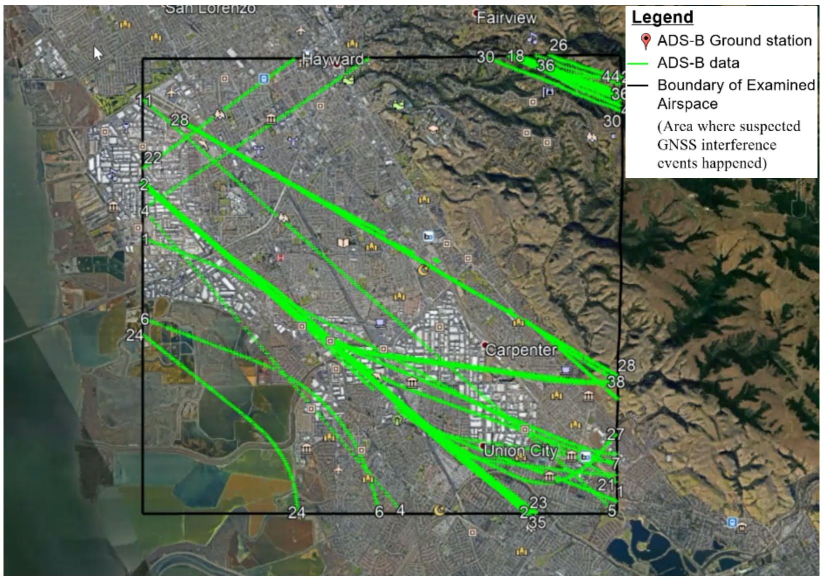

Figure 5. Crowdsourced ADS-B data at KHWD

Results and Analysis

This paper queried data for flights from January 2019 to March 2019, as well as flights from January 2020 to April 2020. Based on the characteristics we identified in the previous section, we found that only 17 days have potentially jammed flights. On those 17 days, there were 265 flights that had an approach to HWD. Among those flights, only 25 potentially jammed flights were identified, which means the interference events at HWD are intermittent. Among those 25 potentially jammed flights, we successfully detected all three reported jammed flights. The remaining 22 flights are suspected jammed flights that are newly discovered.

Figure 6 shows the altitude versus time for all flights passing through the target airspace on January 6th, 2019. Notice that there are only six flights on approach to land at KHWD and only two of them appear to be potentially jammed flights; that is, only those two flights contain position output gaps that last for at least 10 seconds and have a large drop in their NIC values.

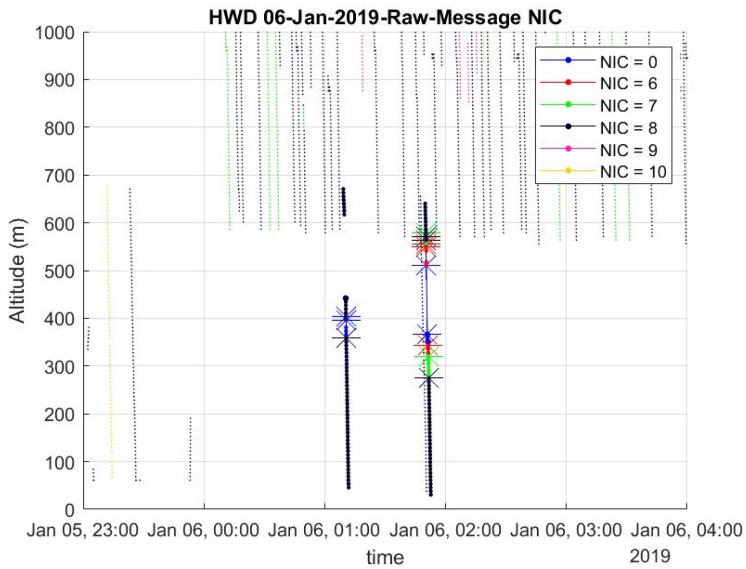

Figure 6. Altitude versus time plot for all flights passing target airspace on 01/06/2019

The left side of Figure 7 shows a 3D plot of latitude and longitude versus altitude for the two potentially jammed flights. The green star is the location of the airport and the cyan circle shows the location of an industrial area under the approach path. Note that the flight track gaps are located at places close to the industrial area which may be the area containing the interference source. This industrial area is highlighted on the right side of Figure 7 which shows the paths overlayed on a Google Earth satellite view. Similar outcomes were observed during all of January 2019.

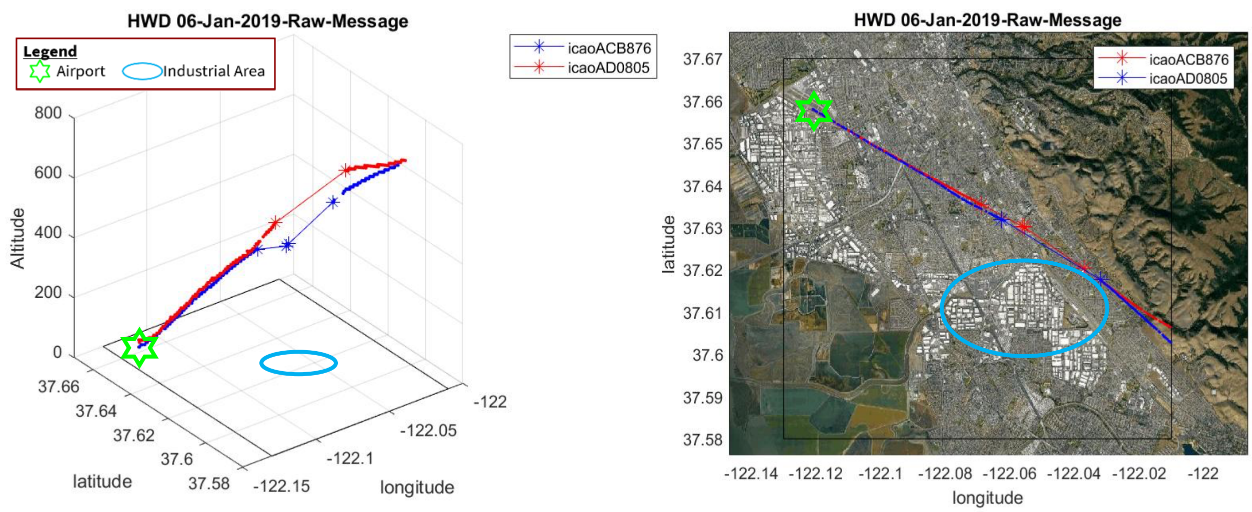

Figure 7. 3D plot (left) and top view (right) of two potentially jammed flights shown in Figure 6

Figure 8 shows the 3D plot of a reported jammed flight landing at KHWD on February 15th, 2019. As we mentioned before, this flight has a recorded video from the cockpit perspective during the time under the impact of interference. The screenshot of GPS status at the beginning and ending points of the flight track gap is labeled in Figure 8. The bar graph on the left-hand side of the screenshot shows the signal strength and the number of satellites in view. The graph on the right-hand side of the screenshot shows the location of the satellites relative to the aircraft. During that entire day, there were 22 flights on approach to land at KHWD and this reported flight is the only jammed flight that we detected. Note that when the aircraft lost connection to all satellites at the beginning point of the flight track, the aircraft stopped broadcasting ADS-B position messages immediately. Later on, when enough satellites were acquired and tracked by the aircraft GNSS receiver, the aircraft started to broadcast ADS-B reports with NIC values gradually recovering back to the initial value.

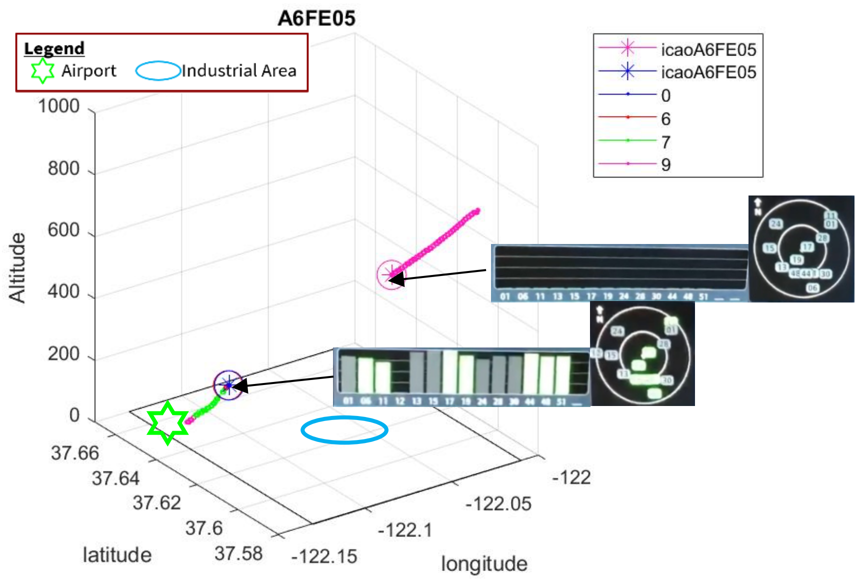

Figure 8. 3D plot of reported jammed flight on February 15th, 2019

Since the loss of position indicates that the aircraft is entering the area impacted by interference and the aircraft GNSS receiver should be able to reacquire the position shortly after the aircraft leaves the impact area, the gap in the flight track provides a basic sense of possible interference impact area. We plotted all flights from same month that we identified as potentially jammed based on the outage onto the same 3D plot. This is shown in Figure 9 to give a better overall picture of the GNSS interference impact area.

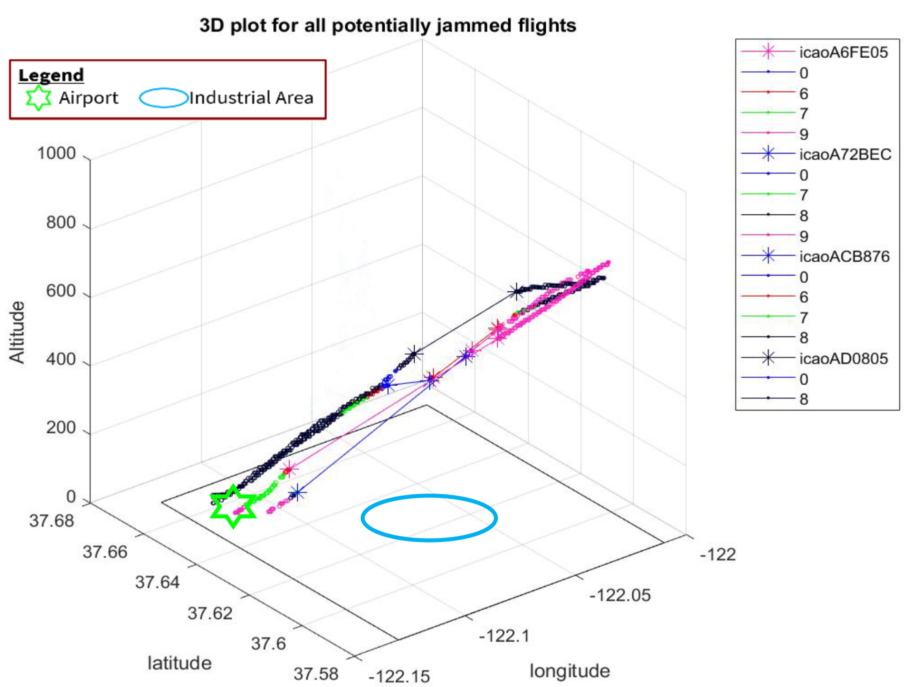

Figure 9. 3D plot for all flights passing target airspace on January 2019

Other than spatial impact area of interference events, placing all flights from the same month onto one plot also gives us an overall picture of the time range of the interference impact. Figure 10 shows the hours of the day versus altitude for all flights shown above in the 3D plot. Note that in the entire month, most of the potentially jammed flights happened at around midnight Greenwich time which corresponds to 4pm local time.

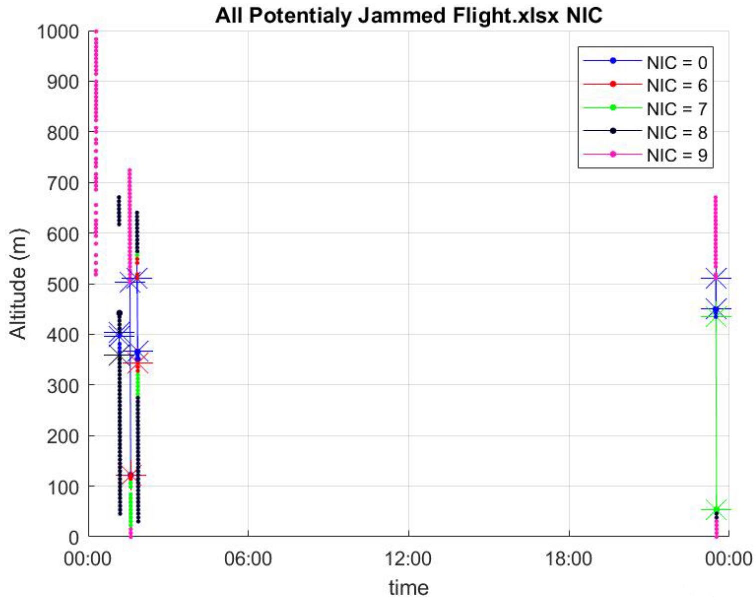

Figure 10. Hours of a day versus altitude for all flights on January 2019

Alternative Signatures

The flight in red in Figure 7, which corresponds to the second potentially jammed fight on the right-hand side in Figure 6, has characteristics similar to what we observed at KEDW airport. It has a gradual drop of NIC value from 8 down to 6 and then down to 0 which is treated as a standard interference case. However, the flight on the left-hand side in Figure 6 shows a sudden drop of NIC value from 9 to 0 which is different from what we are expecting, and therefore has been treated as a non-standard case. We found out that, among all of the data that we investigated from this region, there are two common types of non-standard potentially jammed ADS-B reports that are different from the characteristics we found from the Edwards flight tests. The first type of non-standard case is are reports that have a sudden drop in NIC parameter within a few seconds. What we commonly saw during flight tests at KEDW is a gradually variation of NIC with loss of position messages usually lasting longer than 10s. This makes the sudden drop and recovery of the NIC parameter somehow unexplainable based on outcomes caused by the known interference events. Another type of non-standard case shows a sideways jump of position on the flight track. During that time, the NIC value remains at 0. These two types of non-standard cases are shown in Figure 11. The flight on the left-hand side is the first type of non-standard potentially jammed flight and the flight on the right-hand side is the second type.

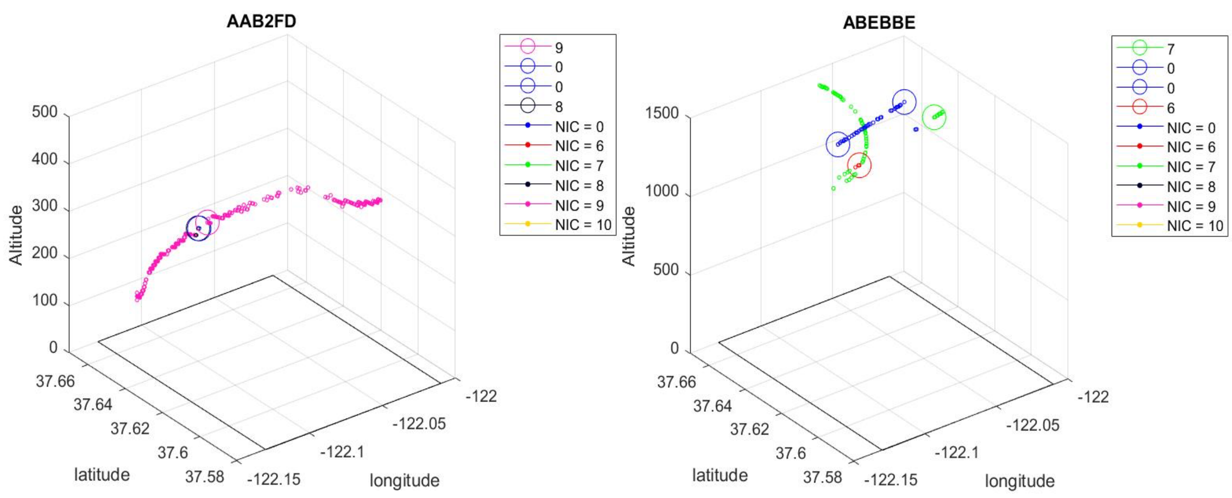

Figure 11. Two typical types of non-standard potentially jammed flights

CONCLUSIONS

This work describes some characteristics of ADS-B performance under the influence of GNSS interference events. We concluded that for high-power interference sources, the corresponding interference impact could be identified when there exists a position output gap that lasts for at least 10 seconds and is associated with a significant drop in the NIC value from 6 and above down to 0. By applying these criteria to recorded ADS-B data near KHWD airport, we discovered some flights that were potentially jammed, in line with pilot reports. We also discovered behaviors that were different from what we learned at KEDW airport. With further analysis, we hope to identify the causes of those alternative ADS-B signatures and determine whether or not they are associated with jamming. We identified a rough estimation on the interference impact area. Subsequent work will focus on narrowing down the possible locations of interference sources. Our longer-term goal is to develop a methodology that allows the use of ADS-B data to provide ATC situational awareness of the status of GNSS performance and whether or not interference is likely present.

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