Approximating Regional GNSS Interference Sources as a Convex Optimization Problem using ADS-B Data

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BIOGRAPHY

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ABSTRACT

While the Automatic Dependent Surveillance-Broadcast (ADS-B) has been widely used for air traffic operations and management, it has also been useful recently in identifying, detecting, and localizing (IDL) potential GNSS/RFI jamming sources in regional, high air traffic environments. With an increase in reported GNSS interference around the world, there is a necessity to find and remove jammers from the environment to prevent additional unsafe air travel operations. The major indicator that infers as whether an aircraft is likely being jammed (from ADS-B) is by monitoring the Navigational Integrity Category (NIC) value included in the ADS-B message. While not as effective as other metrics typically used in interference detection, it can still provide an indication if jamming is present, but presents an opportunity in localizing the potential source in real time.

This paper seeks to approximate the area of potential GNSS/RFI interference by fitting a Euclidean Cone to ADS-B data reporting low NIC values. This problem is formulated as a convex optimization problem, which is derived from an alternative version of maximum inscribed ellipsoid approach. By fitting the optimal cone to data potentially impacted by interference, the apex of the cone will reveal the estimated jamming location. Raw ADS-B data is processed, decoded, interpolated and filtered to improve localization results. The proposed convex formulation is then applied to two reported interference events, the first over a period of 36 hours near Denver International Airport in January 2022, and the second over roughly 8 hours near the Dallas-Fort Worth Area in October 2022. The Denver localization results show that the four estimated jamming locations - calculated from four six hour time windows - are grouped in between the downtown Denver area and the airport. With the Dallas interference jamming localization results, it can be seen that the three estimated jamming locations - determined from three, one hour windows - also show a tighter grouping on the southern side of the Dallas/Fort Worth area.

I. INTRODUCTION

The Automatic Dependent Surveillance-Broadcast (ADS-B) is a communication framework that sends aircraft positioning, velocity and operational data from individual aircraft to regional ground stations over an aviation broadcast channel. There are various versions of the ADS-B, but the most commonly used in the United States is the 1090 Mode S Extended Squitter (ES) format, which is transmitted with a carrier frequency of 1090 MHz and provides a 112-bit message that contains position, velocity and operational information pertaining to a given aircraft [1]. ADS-B has been developed and implemented over the past 20 years, and is now required by the Federal Aviation Administration (FAA) and other civilian aviation authorities around the world for commercial and private aircraft operations. ADS-B has played in important role in monitoring, developing, and improving air traffic management at major airport hubs across the United States, and has provided pilots, controllers, and other operators useful information in making decisions that affect airport and airspace operations.

With the rise of GNSS interference around the world, there is a greater need to detect and localize these jamming source effectively and quickly [2]. One benefit to using ADS-B is that as aircraft are sending out position information, the message also contains operational information about the onboard receiver, which can also infer the status and functionality of GNSS on the aircraft. As a result, this information - combined with its position reports - can be used to generate an approximate region (or regions of airspace) as to where possible jammers might exist. However, with massive amounts of flight data, there have only been few localization methods proposed to estimate possible jamming locations, which is the desirable outcome.

This paper seeks to both estimate the jammer location and model the area of interference created from a potential jamming source by fitting a Euclidean Cone to ADS-B data reporting low Navigational Integrity Category (NIC) values. This data fitting problem is achieved by formulating it as a convex optimization problem. By incorporating existing data processing methods from previous work along with this new localization approach, both can be applied to recent (2022) interference events: Denver and Dallas International Airports (DEN and DFW respectively). Section II discusses the current localization techniques that are used to find potential jammers using ADS-B data. Section III outlines the various data processing techniques that have been implemented from previous work, as well as additional filtering methods to accommodate the convex approach, and Section IV proposes the convex approach. Section V shows the results for both the Denver and Dallas interference events, and the localization solutions over various time windows during their respective, reported time periods.

1. Navigational Integrity Category (NIC)

While ADS-B is known for sending positioning and status information for a given aircraft, it however does not send much GNSS receiver metrics such as information regarding the signal strength of GPS-acquired signals, or the power in the channel. Therefore other reported values, such as the Navigational Integrity Category (NIC), which can be used to infer potential interference affecting the receiver. Within the ADS-B message, the NIC value reports an integer value scaling between 0-11, as shown in Table 1; A higher NIC is commensurate with a smaller containment radius (and therefore a more accurate solution that includes the true position), whereas a lower NIC value reflects a larger containment radius, thus increasing the uncertainty of the aircraft's true location.

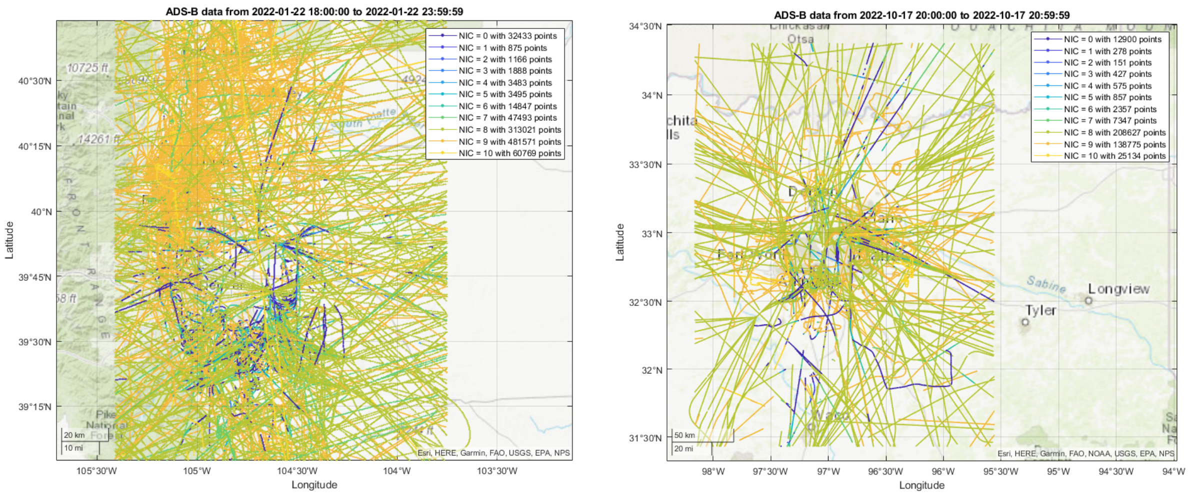
From general flight data observation, the majority of aircraft during nominal conditions report a NIC value of 8 or higher, and it has been noticed that drastic drops in NIC value have been indicative of moderate GPS interference caused by a jamming source. However, because ADS-B involves sending data to ground stations, other variables such as receiver coverage, potential multipath, and communication interference could be the cause behind ADS-B outages, besides the possibility of a potential jammer. Therefore the following processing and filtering techniques on the incoming ADS-B dataset are used to mitigate such issues, and improve the localization solver.

NIC	Containment Radius (R_c)
0	Unknown
1	37.04 [km]
2	14.816 [km]
3	7.408 [km]
4	3.704 [m]
5	1852 [m]
6	1111.2 [m] 926 [m] 555.6 [m]
7	370.4 [m]
8	185.2 [m]
10	25 [m]
11	7.5 [m]

Table 1: Navigational Integrity Category (NIC) values and their corresponding containment radii [1]

2. Denver and Dallas Interference Events

To apply the convex localization formulation to real-world data, two reported interference events will be used: ADS-B data surrounding Denver International Airport on January 22-23 2022, as well as a more recent interference event near the Dallas/Fort-Worth International airport on October 17, 2022. ADS-B Data reported a decrease in NIC among several aircraft arriving and departing Denver International over 36 hour period, spreading to an area over 50 nm wide. Based on initial data observation, aircraft impacted by interference (noticeable drop of NIC value) form a nearly circular search area around the airport. With the interference event that occurred in Dallas, a number of aircraft passing through the area - as well as landing at DFW - also experienced a decrease in NIC value. However, unlike the ADS-B positions associated with the Denver Interference event, the aircraft that experienced drop in NIC values can mostly be seen in various areas around DFW, where aircraft were intermittently reporting low NIC values in other parts of DFW airspace.



(a) **(b)**

Figure 1: Processed and Interpolated Results of sample OpenSky ADS-B data around Denver 1a and Dallas/Fort-Worth 1b International Airports

A sample of the impacted area of interference for both the Denver and Dallas interference events (and indicated by their reported NIC value) are shown in Figures 1a and 1b respectively.

II. RELATED WORK

While ADS-B data was originally designed - and is currently being used for - air traffic management and operations, it has only recently been used for IDL purposes. In conjunction with previous work more specifically focused on ADS-B data processing and interpolation [3], Liu et. al has also analyzed both the Denver and Cypriot interference events in a series of papers, using a variety of localization approaches. More specifically for the Denver interference event, she used a probabilistic Bayesian updating approach by monitoring potential interference in a two dimensional grid format, where the likelihood of jammer being in a given location is based on NIC value of nearby aircraft. She also has used a least-squares approach by minimizing the residual between the estimated received power, and the mean power inferred from the NIC value [4]. Finally, she has also implemented Neural Networks and other ML models to analyze the Cypriot interference event; all approaches have yielded promising results [5].

Because of increasing interest in localizing potential interference sources, combined with the more accessible open-source databases like OpenSky, FlightAware and ADSBExchange, there has been a push to create a live interference monitoring system using commercial air traffic. GPSJam.org combines basic mapping software with ADS-B messages from ADSBExchange to provide a near global coverage interference monitoring interface. Based on the website information, he calculates the percentage of ADS-B messages with low Navigational Accuracy values in each airspace (hexagon grid) in order determine signal degradation [6]. While a live interference monitoring system using ADS-B data such GPSjam.org may be beneficial in high traffic areas, the one disadvantage is that it is more difficult to detect interference in less populated or traveled areas. Stanford is also developing a real-time monitoring system similar to GPSJam, but implements different filtering methods and algorithms to remove low NIC values and other erroneous data not caused by interference, which could improve localization results [7].

III. DATA PROCESSING

1. OpenSky Decoding and Processing

ADS-B data from both interference events are collected from the OpenSky network, an open-source receiver network that collects raw ADS-B messages from aircraft and stores the data on their API. OpenSky gathers all three types of messages (position, velocity, and operational), but the convex approach used in this paper only requires position message [8]. Once the position message is obtained from OpenSky, the raw message is then decoded per the 1090 Mode S ES ADS-B Minimum Operational Performance Standards (MOPS) [1]. Furthermore, duplicate messages (same message recorded by different receivers) were also removed, as well messages that contain inconsistent timestamps. Messages may report inconcistent timestamps because

OpenSky ground stations are crowd sourced and not regularly maintained and monitored like federally contracted air navigation service providers.

After the raw position messages are decoded, further preprocessing is needed to fill in missing flight data potentially impacted by possible interference as a means of improving the jamming localization approach. To fill in missing flight data within a given path, a simple cubic spline interpolation is drawn based on the last reported ADS-B messages (before losing signal), and when the ADS-B signal is reestablished. To determine whether missing flight data can be interpolated, additional criteria, such as the duration of ADS-B message and directionality of the flight path (straight-and-level, ascending/descending, or turning) are also considered, and were the major focus of previous work [3].

Lastly, in order to the reduce the size of the dataset, each flight path is downsampled from the nominal approximate reporting frequency for ADS-B of 2 Hz to 1 Hz by using every other ADS-B positioning message. Not every ADS-B message is needed because the high resolution/update of ADS-B provides close interval spacing between reported adjacent positions, which is not needed for this localization approach or the convex solver. The datasets were also split into equal time windows to reduce computational time of the convex solver, and improve data management use.

2. Airspace Altitude Filtering

In addition to basic processing of the ADS-B dataset from the OpenSky network, filtering the dataset by its geographic location relative to the altitude above the terrain elevation, as well as the nearest regional airspace was needed. Both Dallas Fort-Worth International Airports are both classified as Class Bravo Airspace, which both generally have an airspace height at 10000' above mean sea level (MSL). For these specific airports, since the airport elevation for Denver International (DEN) is 5433', the ceiling of its airspace is 12000' MSL; the height for Dallas Fort-Worth (DFW) is 11000' MSL. In both cases, processed ADS-B messages are removed from the dataset if they are above their respective ceiling height. This filtering criteria was chosen from data observation, where the vast majority of aircraft passing through the airspace above each Class Bravo were reporting high NIC values; the majority of aircraft reporting low NIC values were found within the the controlled airspace, both for Denver and Dallas International Airports.

In order for the convex solver to localize an estimate jamming location on airborne ADS-B data, ADS-B positioning data was removed if it was below 1000' above ground level (AGL). In order to determine AGL height, Shuttle Radar Topography Mission (SRTM1) elevation data was used from the USGS Earth Explorer API database, which provides near global coverage at 1 arc-second resolution (30 meters). Elevation data tiles were gathered for both Denver and Dallas areas, then meshed together to form a complete topographic model [9]. To find the AGL height of a specific ADS-B position, the `geointerp` MATLAB command was used, which accepts latitude/longitude coordinates, a georeferenced raster grid, and a geographic raster.

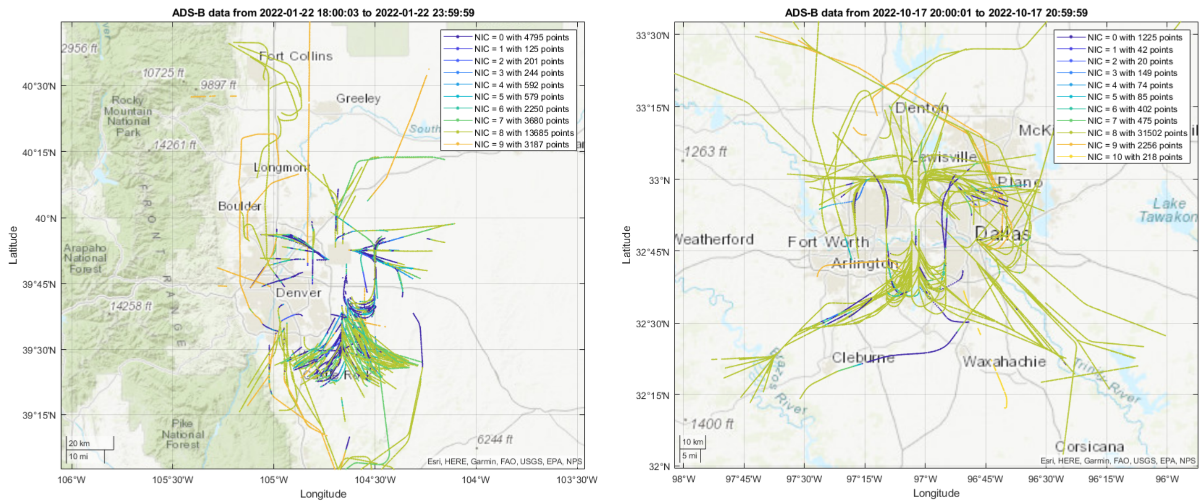
3. Filtering by ICAO Address

Finally, in order to further reduce the size of the dataset and improve computational time of the convex solver, only ADS-B messages transmitted from major airliners (Part 125) and charter aircraft (Part 135) were used. To determine which aircraft were from major airliners or charter aircraft, the ICAO code included in the ADS-B message was cross-referenced with external databases provided by the MITRE Corporation. As a part of this database, it links the ICAO address (assigned to a particular aircraft) to which flight operations it belongs; thus aircraft that fell under other flight operations (such as Part 91 General Aviation) were removed. This filtering criteria was not only chosen to reduce the dataset size, but also to provide a dataset that would be uniform and consistent in aircraft type, regulation status, and receiver equipage standards.

Figures 2a and 2b shows as a sampled time window of the final filtered results for both Denver and Dallas interference events respectively.

IV. MAXIMUM VOLUME INSCRIBED CONE APPROACH

The Maximum Volume Inscribed Cone problem is based on an alternative approach of the Löwner-John ellipsoid formulation, where the objective function is to maximize the volume of the cone that will contain all reported ADS-B flight data indicating potential interference (as indicated with a NIC of 0) [10]. It is also important to note that - given this problem formulation - it can be assumed that there is only one jammer in the region, and thus one cone and estimated jamming location to be solved. To set up this problem, we define a convex set $\mathcal{C} \in \mathbb{R}^3$ as a polyhedron that contains all affected ADS-B position, and thus fit a cone within the convex set. Similar to the maximum volume ellipsoid formulation, the problem is modified to where the main constraint is the boundary of a non-empty interior cone, not an ellipsoid. The main formulation for this problem is found below:



(a) **(b)**

Figure 2: Final Filtered Results of sampled ADS-B data around Denver (DEN) 2a and Dallas/Fort-Worth 2b International Airport

$$\begin{aligned} \underset{A,r}{\text{maximize}} \; & \log det(A) \\ \text{subject to} \; & \|Ax_i + r_{1:2}\|_2 + r_3 \le t_i \\ & r_3 \ge b_{min} \\ & r_3 \le b_{max} \end{aligned} \tag{1}$$

where $A \in \mathbb{R}^2$ is a positive semidefinite (PSD) parameter matrix, and $r \in \mathbb{R}^3$ is the vertex of the cone, or the location of jammer in East, North and MSL altitude relative to the airport location. Additionally, $x_i \in \mathbb{R}^2$ is the horizontal (East, North) position of the reported ADS-B message, whereas t_i is the corresponding reported altitude. To constrain how the cone is positioned above the Earth's surface, elevation at the apex (r_3) is bounded by b_{max} and b_{min}, which represents the maximum and minimum surface elevation determined by the USGS terrain data. Since the jammer is assumed to be located within the vicinity of the ADS-B reported flight paths, the elevation of the jammer must also be within the bounds of the highest and lowest elevation points on map.

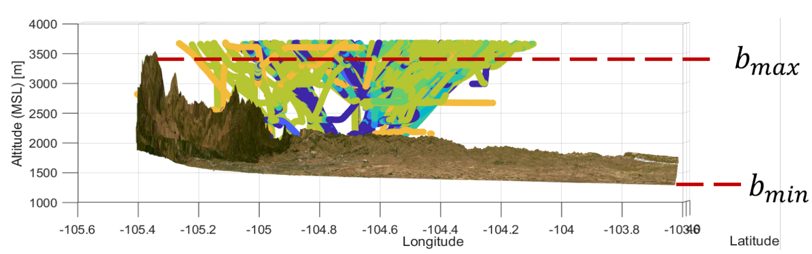


Figure 3: The maximum (b_{max}) and minimum (b_{min}) surface elevation constraint from USGS terrain data, Denver Interference Event

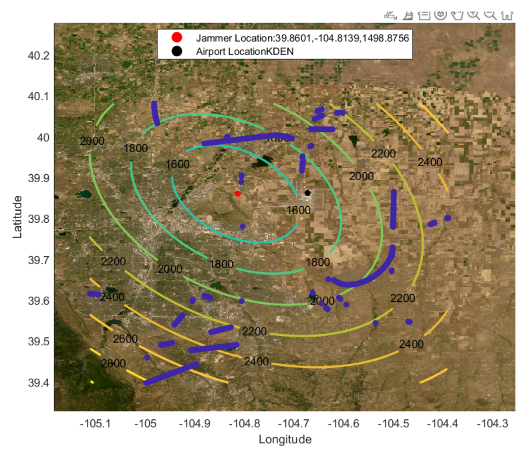
From the formulation, the objective function seeks to maximize the volume of the cone (proportional to log determinant of parameter matrix), but is constrained by the condition that reported ADS-B positions (or the convex set) affected by interference must serve as the outer boundary of the cone fitting problem. This type of approach was chosen because it is undesirable for the cone to completely contain all points within its conic hull; instead, it serves as an upper bound as a means of showing where interference is almost guaranteed to occur. Also, this approach was chosen over the Löwner-John approach because the CVX MATLAB package cannot solve a minimization over the inverse log determinant [11].

V. RESULTS AND DISCUSSION

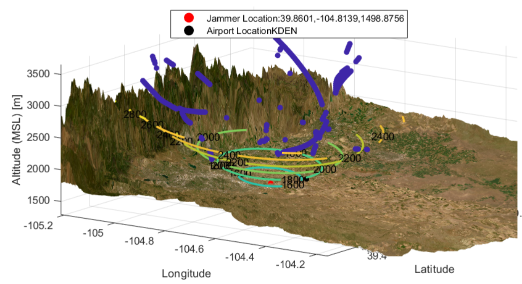
The following results show the localization solution using the Maximum Volume Inscribed Ellipsoid Formulation approach for both the Denver and Dallas Interference events.

1. Denver Interference Event

Figures 4a and 4b show the estimated jammer location using the first 6 hour time window of reported ADS-B data near Denver International Airport. From these results, it can be seen that it solves for the optimal cone, and contains all ADS-B data with reported NIC value of 0. While the shape of cone visually captures the area of interference, the estimated jammer location is found to be approximately 7 miles west of the airport, in between I-76 and Pena Blvd, the main expressway to Denver International.



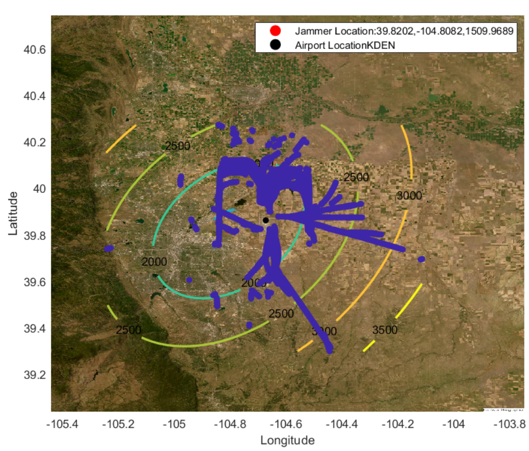
(a)



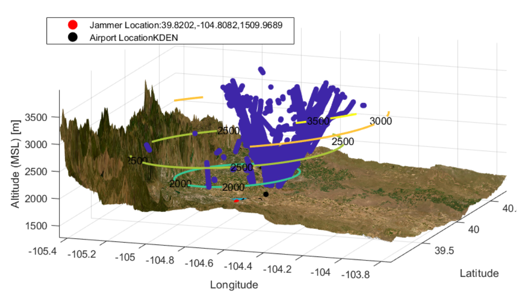
(b)

Figure 4: Convex Localization Results near Denver International Airport, January 22, 2022 0600-1159 UTC

The next six hours (1200-1759UTC) as shown in Figures 5a and 5b also confirm that the optimal cone fits the impacted reported ADS-B data correctly, reflecting the approximate area of interference. As it can been seen between the datasets, this six hour time window has much more ADS-B data impacted by interference, yet it is still forms a similar sized cone - and more importantly - calculates similar estimated jamming locations. In this six hour tour time, the estimated jamming location is also 7 miles southwest of the airport, and approximately 3 miles south from the first estimated jammer location.



(a)



(b)

Figure 5: Convex Localization Results near Denver International Airport, January 22, 2022 1200-1759 UTC

By solving for the following time windows (1800-2359UTC, and January 23 0000-0559 UTC), the center locations estimated by the convex solver are plotted on Figure 6, and show similar locations covering an area spanning 8 miles. The estimated jamming location reported between 1800-2359UTC is fairly close to the first estimated solution, and roughly 8 miles south-southwest of the airport. While more aircraft are arriving and departing into DEN at this point during the day, it does not drastically affect the localization solution. The main reason as to why the estimated jamming location changes slightly is not the quantity or density of the data, but rather where aircraft reporting low NIC values are located; the cone size is optimized to contain all aircraft reporting NIC values, so aircraft reporting in less populated airspace (or the edges of the cone) will have have a greater impact in the cone shape and apex location (this can be seen in Figure 5b).

The final six hour window (January 23 0000U-0559UTC) forms an estimated solution roughly 4-5 miles from DEN, and 2 miles from the first estimated jamming solution. All four locations indicate that the jamming is approximately 4-5 miles west of the airport and are close in proximity, despite having data of aircraft reporting in various parts of the Denver airspace.

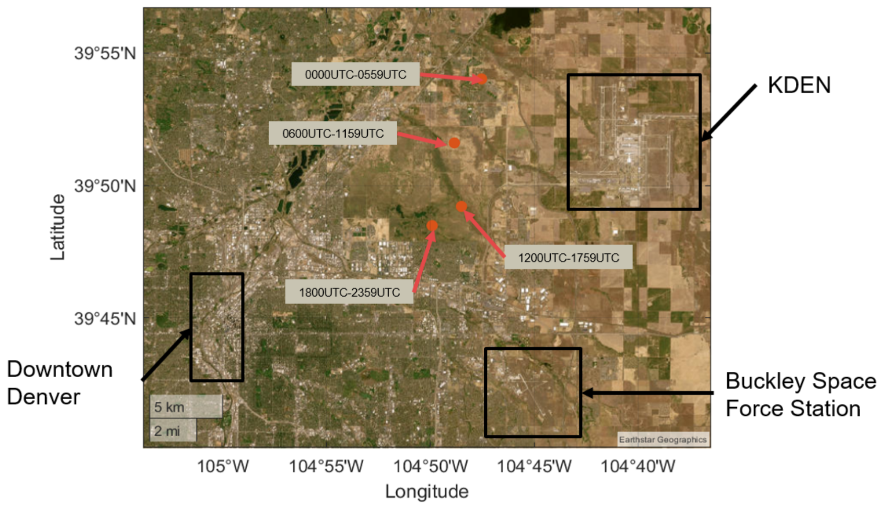


Figure 6: Convex Localization results using of four, six hour time windows of reported ADS-B data near Denver International Airport, January 22-23 2022

2. Dallas/Fort-Worth Interference Event

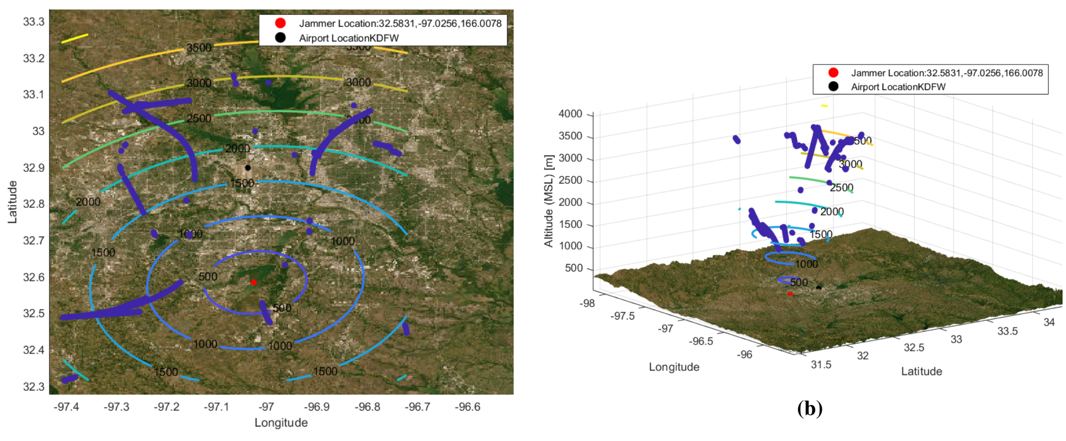
Similar to the Denver Interference event, Figures 7a and 7b show the estimated jamming location and area of interference near the Dallas/Fort-Worth area during its respective interference event on October 17, 2022. Since this event is solved into one hour time windows, there is less reported ADS-B flight data than the Denver Interference event, yet it is still able to solve for a cone that can fit the impacted data. From this one hour window, the estimated jammer location is almost 20 miles south of the Dallas/Forth-Worth International airport. One interesting point about this location is that it is aligned with the final approach path for the Runway 36 at DFW.

Figures 8a and 8b also show similar results, this time during the following one hour window. Unlike the previous hour, this time window has more data affected by potential interference, which is beneficial for the solving for the optimal impact cone. The cone reflecting the approximate area of interference also has a similar size and shape as the previous area, and also estimates the jammer location in the same relative area: James Pool Lake.

By solving the estimated jamming location and area of interference for following hour (2100UTC), the estimated jamming locations for the Dallas Interference event are once again are plotted on Figure 9. By solving for the additional time windows, the three estimated jamming locations are relatively close to each other, spaced out approximately 1-2 miles apart. While this area is mostly a residential/park area, it is interesting to note that the locations are directly south of the airport. More importantly, based on VFR and TAC sectional charts, the nearby town of Cedar Hill has multiple radio station towers within the area. These are areas of interest, but additional investigation is needed before confirming the true jamming location.

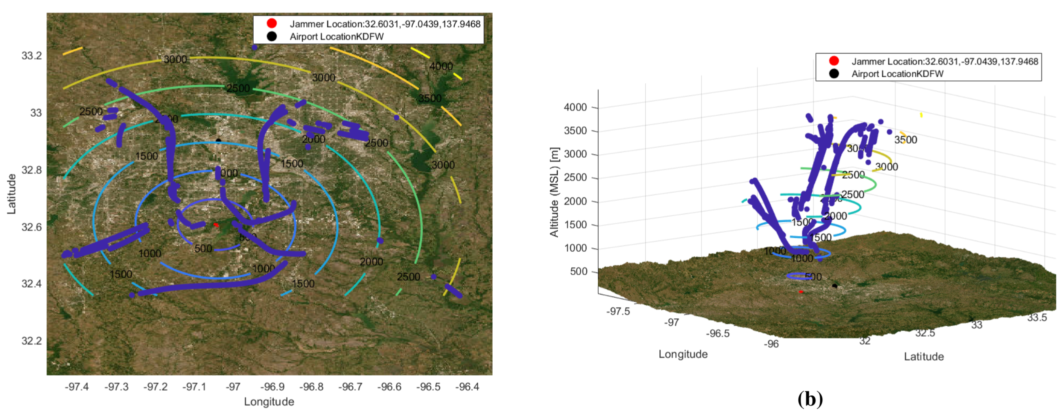
VI. CONCLUSION

This paper seeks to provide a unique convex optimization formulation that aims to model the area of interference as a Euclidean Cone caused by potential GPS/RFI jamming, with the ultimate goal of providing an estimated jammer location. Using an alternative formulation of the maximum inscribed ellipsoid formulation to represent this area of interference, this cone encompasses ADS-B flight data reporting a NIC value of 0, which indicates mild to moderate signal degradation. This



(a) **(b)**

Figure 7: Convex Localization Results near Dallas/Fort-Worth International Airport, October 17, 2022 1900-1959 UTC



(a) **(b)**

Figure 8: Convex Localization Results near Dallas/Fort-Worth International Airport, October 17, 2022 2000-2059 UTC

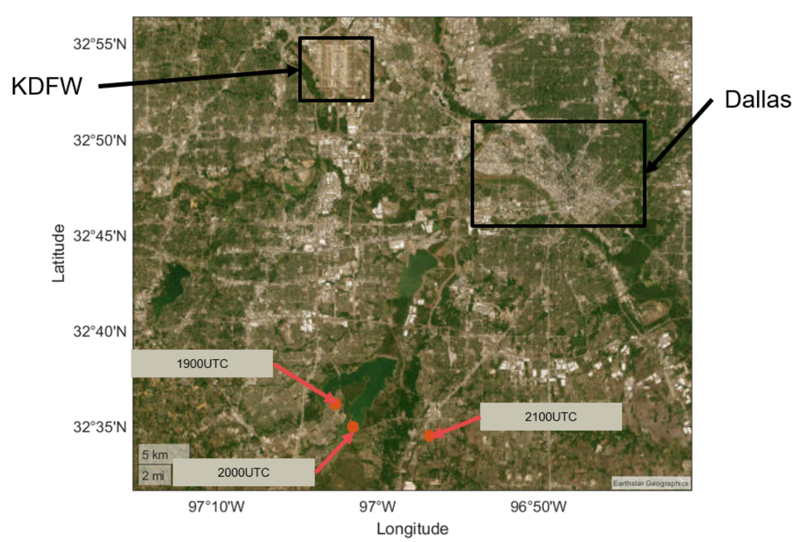


Figure 9: Convex Localization results using of three, one hour time windows of reported ADS-B data near Dallas/Fort-Worth International Airport, October 17 2022

formulation was implemented on two real-world interference events (Dallas and Denver International Airports), and both events solved for estimated jamming locations in roughly the same areas, regardless of the amount of provided ADS-B data, and the departure/arrival patterns of the major airport hubs.

While this convex formulation provides a novel approach to finding terrestrial jamming sources, the additional data filtering methods also play an important factor in the localization solution. Filtering by airspace reduces the size of the data, while filtering aircraft down to ICAO address provides a more consistent and balanced dataset.

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