GNSS Interference Detection and Localization using ADS-B Data: An Automated Pipeline for Global Coverage

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ION Alberta
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Denver GPS Interference Event Disrupts Critical Infrastructure

- On **January 21, 2022**, the **Denver area** experienced a significant GPS interference event.
- Impacted Sectors:
  - ❖ Aviation operations within ***50 NM*** of the airport
  - ❖ Emergency services and medical communications
  - ❖ Rail systems in Aurora, CO
- FCC locates and shuts down unauthorized emitter (1575.42 MHz). GPS services restored ~***33 hours*** after onset.

https://commdex.com/blog/land-mobile-radio-lmr-systems/

https://createdigital.org.au/new-video-based-analytics-software-set-to-improve-safety-at-level-crossings/

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What happened to GPS in Denver?

September 21, 2022 - By Dana Goward — Est. reading time: 3 minutes

Something big happened to GPS service in the Denver area on Jan. 21.

Notice To Airmen 21 January 2022

NAV GPS UNREL(INCLUDING WAAS, GBAS, AND ADS-B) MAY NOT BE AVBL WI A 50NM RADIUS CENTERED AT 394900N1044000W OR ALL QUADRANTS OF THE DEN VOR SFC-FL400. 22 JAN 05:00 2022 UNTIL 01 FEB 05:00 2022. CREATED: 22 JAN 05:33 2022

On that day, Air Traffic Control issued a notice advising pilots of problems with GPS reception spanning about 8,000 square miles in the Denver area.

Denver GPS Interference Event (Jan 21–23, 2022)

Jan 21
22:25 UTC

Initial Detection

- Commercial pilots report GPS loss and ADS-B issues when departing Denver.

+ 7 hours

Escalation

- More reports received with impacts confirmed in terminal and en-route airspace. FAA issues NOTAMs with undefined end time.

+ 11 hours

Ground Reports

- Reports from rail, emergency, and medical systems in Aurora, CO (~10 miles south of Denver Airport).

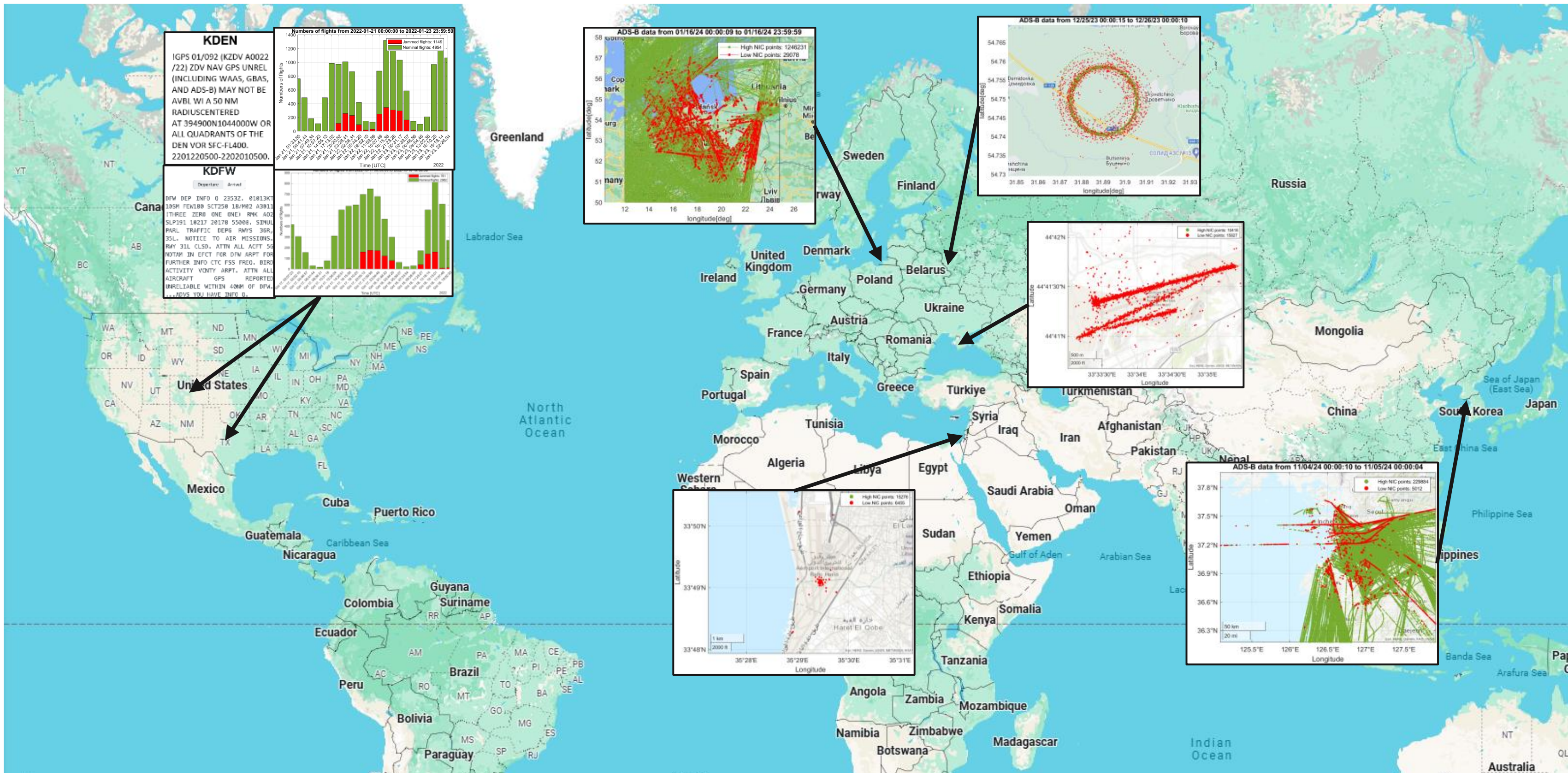
+ 13 hours

Source Identified & Resolved

- Area of Interest Estimation and Ground-Based Signal Detection.

Aviles, J. S., and Van Dyke, K. L. (2023). U.S. Department of Transportation (DOT) Global Positioning System (GPS) Interference Detection and Mitigation (IDM) Program. In Proceedings of the 36th International Technical Meeting of the Satellite Division of the Institute of Navigation (ION GNSS+ 2023) (pp. 1276–1298).

The Growing Threat of GNSS Interference Worldwide



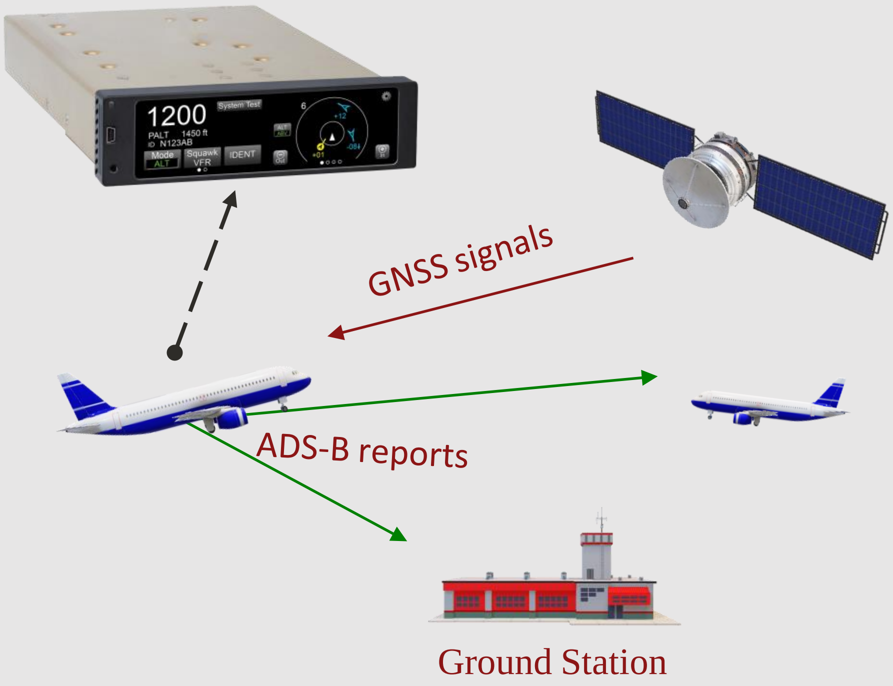
ADS-B (Automatic Dependent Surveillance – Broadcast)

Automatic -- periodically transmits information with no pilot input or external interrogation.

Dependent -- position and velocity vectors derived from aircraft's navigation system (GPS).

Surveillance -- provides surveillance data (aircraft position, altitude, velocity, identification).

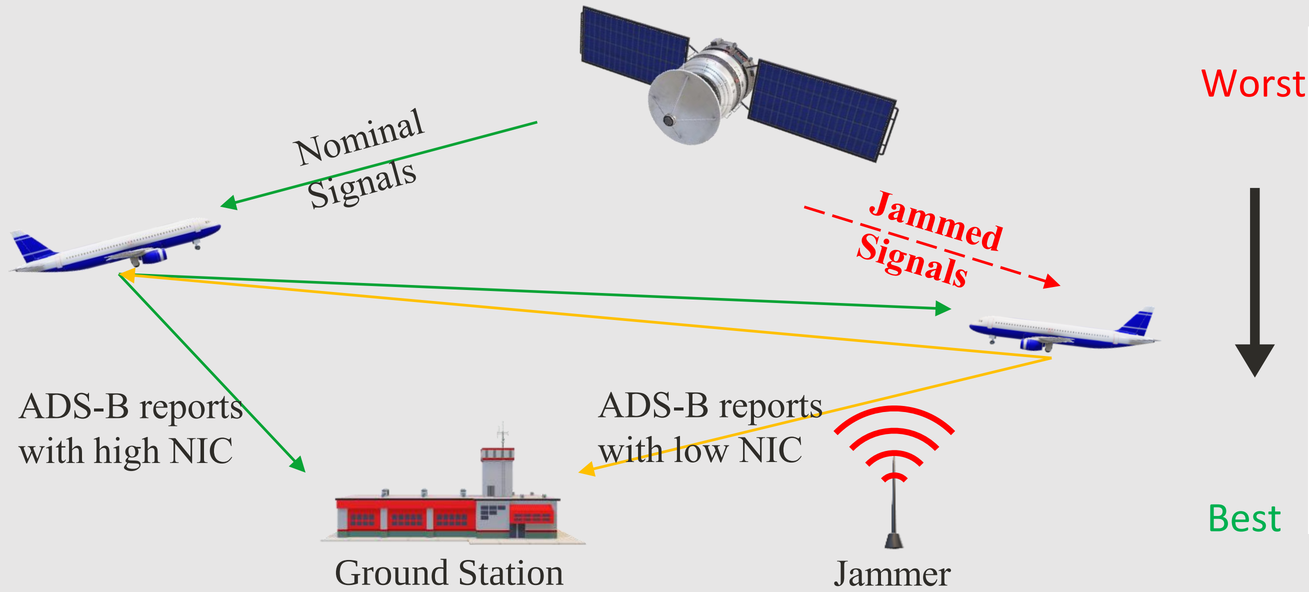
Broadcast -- broadcast every half-second on a 1090MHz, digital data link, available to aircraft and station with appropriate receiving equipment.



Lynx® ADS-B In / Out Transponder and Display System

Integrity/Accuracy Level Indicator

- NIC: Navigation Integrity Category (0~11)



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

Why Use ADS-B Data?

- Conventional ground-based detection and localization methods, constrained by line of sight, are inadequate for large-scale monitoring, thus necessitating a novel approach.

1. coverage of wider area from high altitudes
2. collection of crowdsourced data from multiple airplanes
3. publicly available sources for getting world-wide live/historical data

Challenges

Slow Detection & Response

- Relied heavily on pilot reports and manual escalation

Overly Large Search Area

- Initial Area of Interest was too broad for effective field deployment

No Automation at the Time

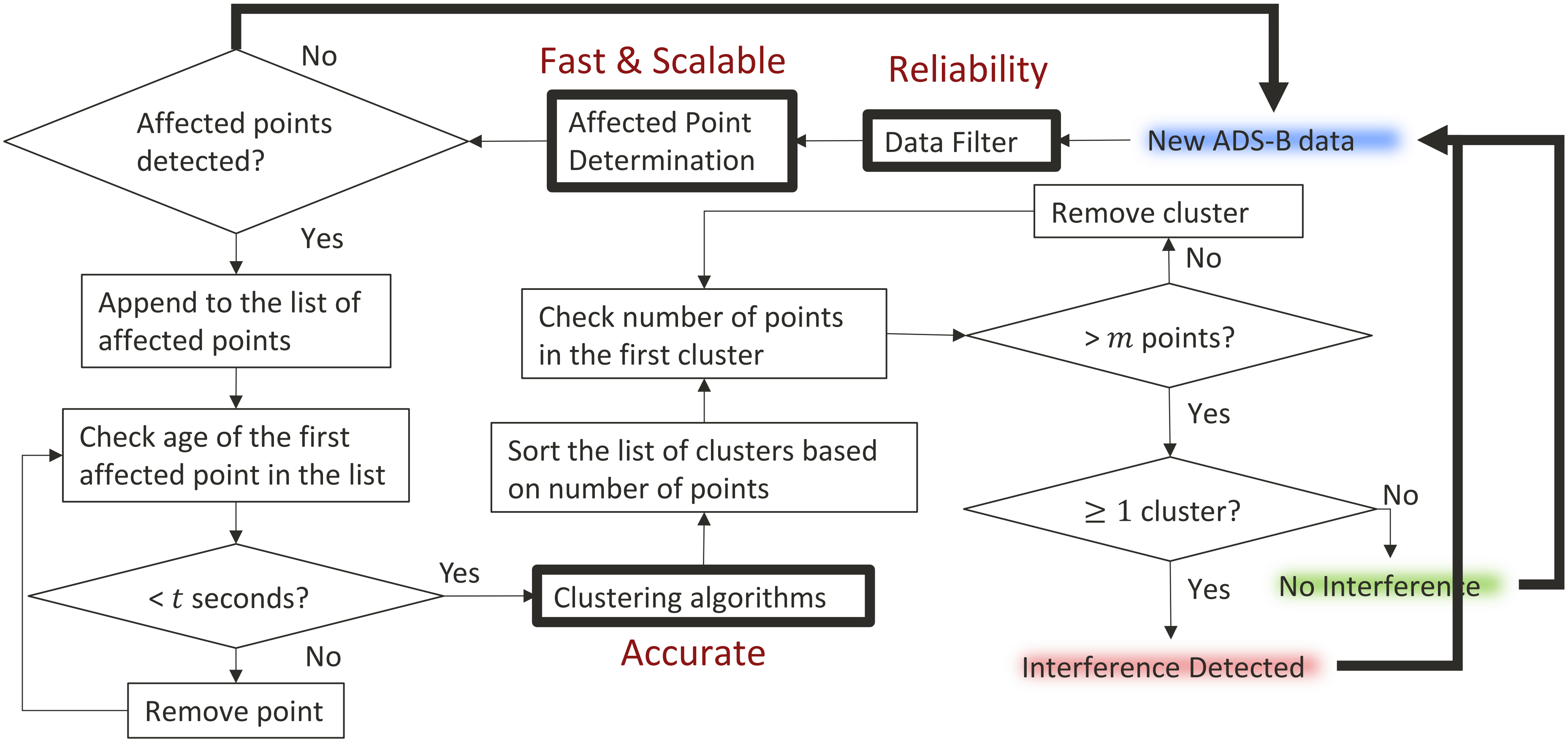
- No real-time system or automated tools to detect interference

Research Objectives

To mitigate the negative consequences of GPS interference on operational continuity and safety, a solution must be developed that achieves:

- ☐ Fast and Scalable Detection
- ☐ Accurate Event Determination
- ☐ Robust Geolocation of the Interference Source
- ☐ Global Situational Awareness

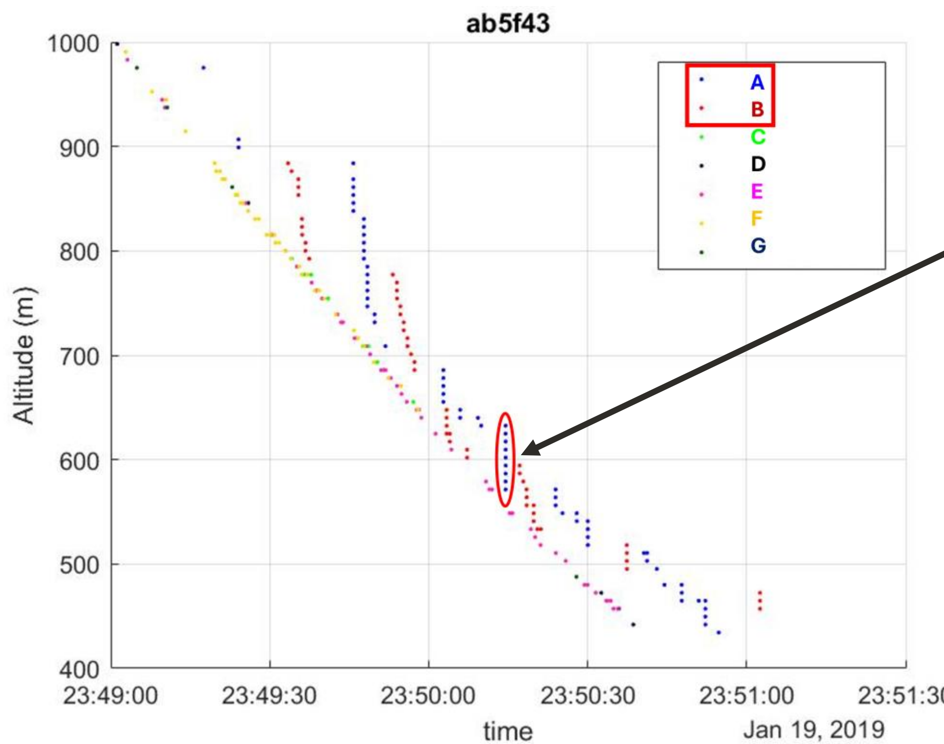
Overall structure of the detection algorithm



Data Filter

- Timestamp Inconsistencies Across Ground Receivers

Since ADS-B message doesn't include timestamp information, assigning an incorrect time can lead to an incorrect position.



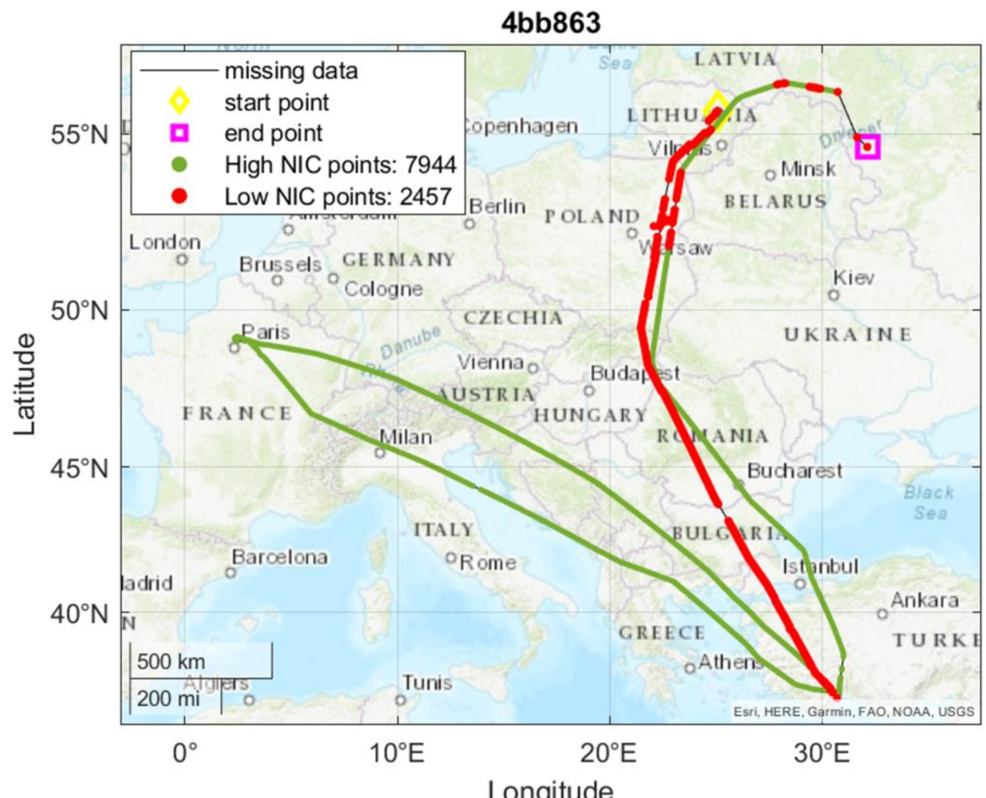
Receiver A: Tagged 15 messages with the same timestamp

Receivers A & B: Show incorrect time tagging, causing divergence from the expected flight path.

Data Filter

- Common Anomalies in the ADS-B System – **Persistent Low NIC**

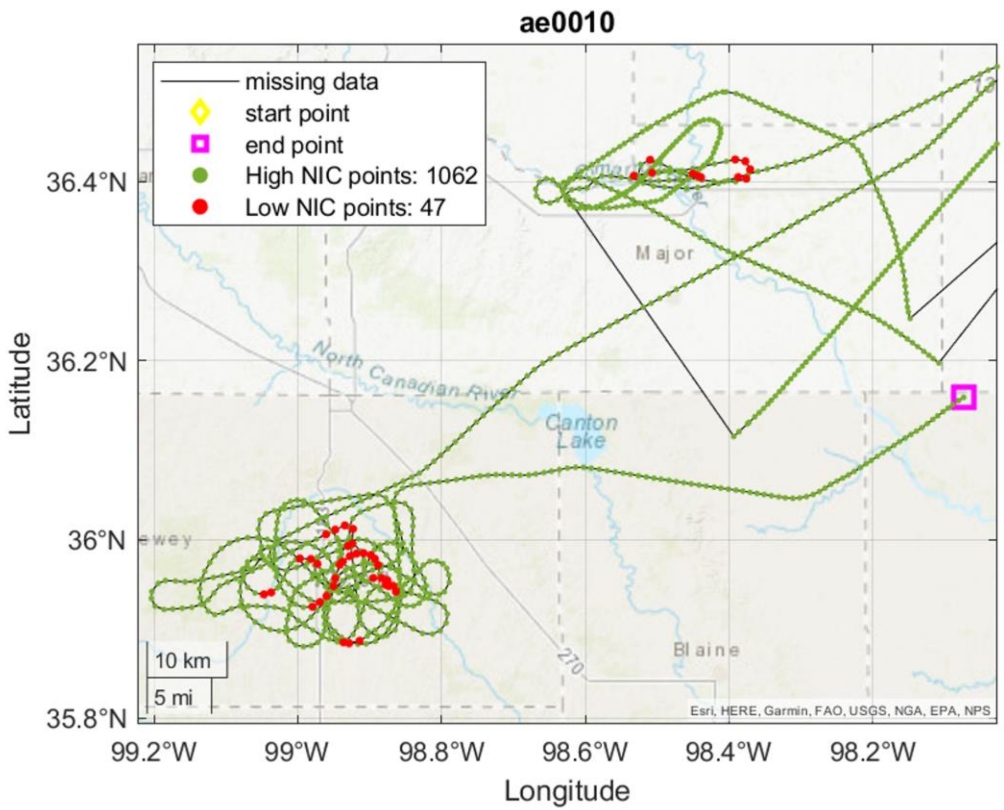
Aircraft reports NIC = 0 for entire flight caused by outdated equipment or faulty system behavior.



Data Filter

- Common Anomalies in the ADS-B System – **Military Maneuvers**

High-dynamic flight patterns cause temporary low NIC which appears as interference and leads to false positive.



Affected Point Determination (Jamming)

- Bayesian Online Changepoint Detection (BOCPD) is a method to detect changes in the behavior of time series data as new observations arrive in real time.

- BOCPD uses Bayesian inference to continuously estimate the probability that a changepoint has just occurred, using only the data seen up to that point.

Adams, R. P., & MacKay, D. J. (2007). Bayesian online changepoint detection. *arXiv preprint arXiv:0710.3742*.

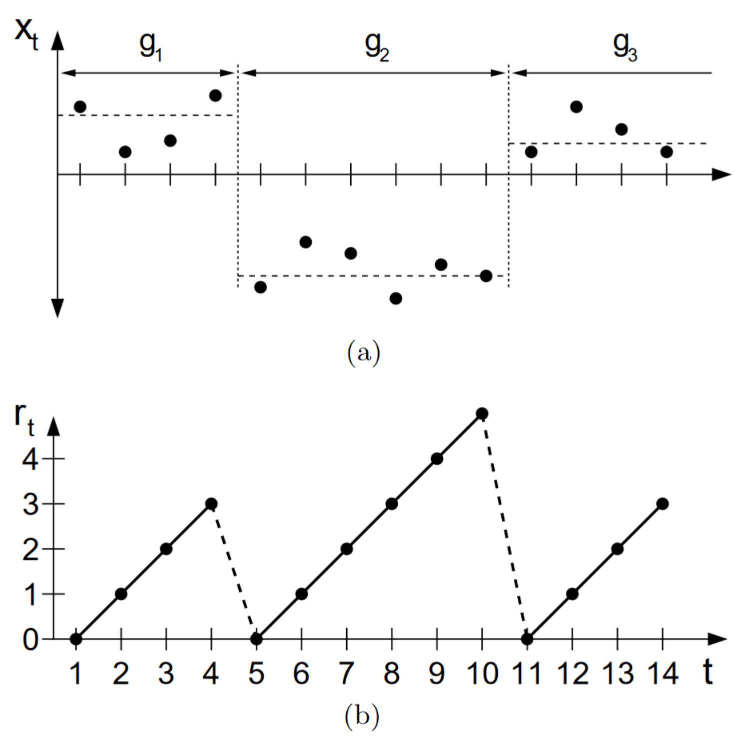
Bayesian Online Changepoint Detection (BOCPD)

- BOCPD tracks a quantity called the run length:

  Run length r_t is the number of data points since the last changepoint at time t.

- At every new time step t, BOCPD calculates the posterior distribution over run lengths: $P(r_t, \mathbf{x}_{1:t})$

  This tells you: how likely is it that the current run has lasted r_t steps, given the data up to time t.



Adams, R. P., & MacKay, D. J. (2007). Bayesian online changepoint detection. *arXiv preprint arXiv:0710.3742*.

Bayesian Online Changepoint Detection (BOCPD)

- Prediction

For each possible r_t, we predict the likelihood of the new data point x_t:

$$P(x_t \mid r_{t-1}, x_{t-r_{t-1}:t-1})$$

- Update Run Length Posterior

Apply Bayes' rule:

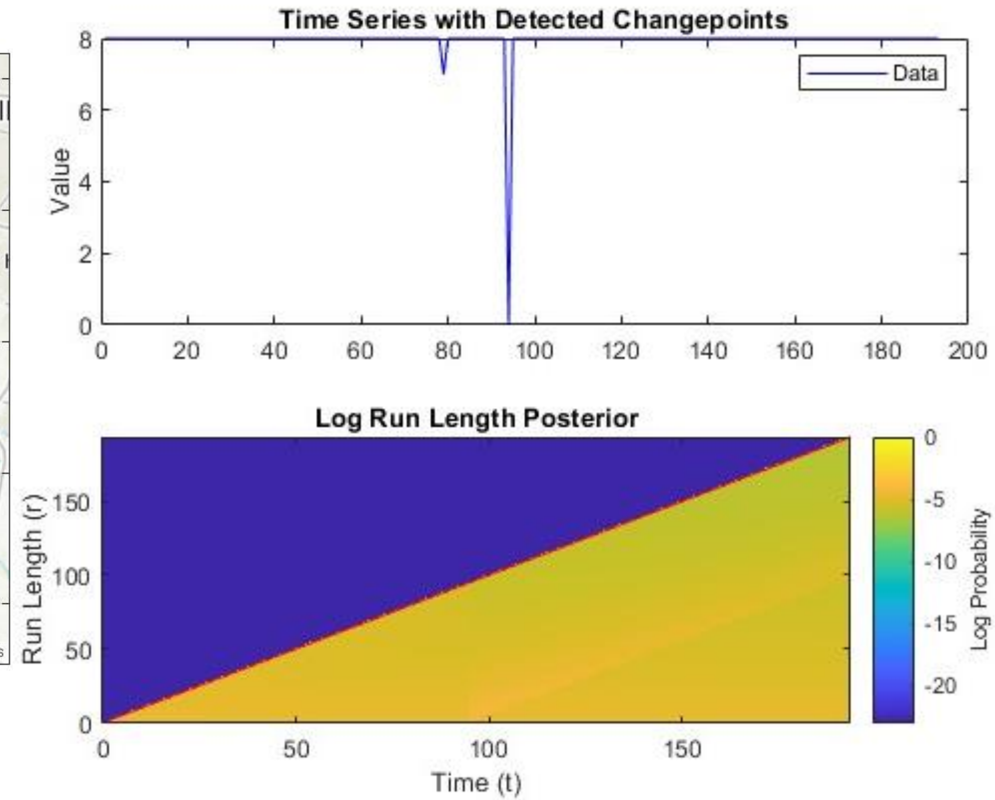
$$p(r_t, \mathbf{x}_{1:t}) \propto P(x_t | r_t, x_{1:t-1}) \sum_{r_{t-1}} P(r_t | r_{t-1}) \cdot P(r_{t-1} | x_{1:t-1})$$

- Detect Changepoints:

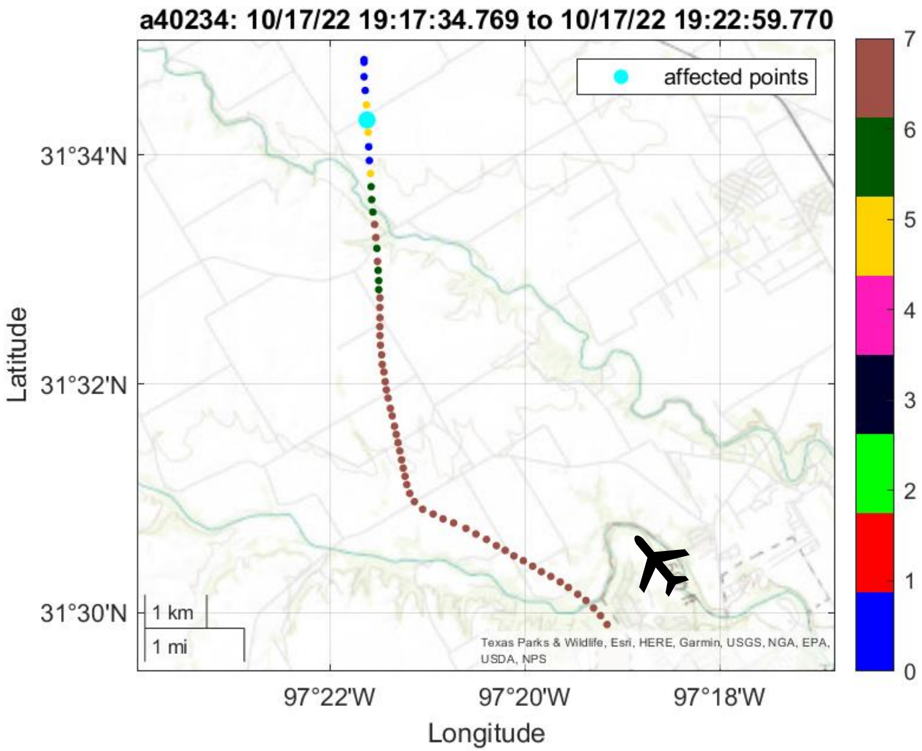
Whenever the posterior places high probability on $r_t = 0$, it suggests that a changepoint just occurred at time t.

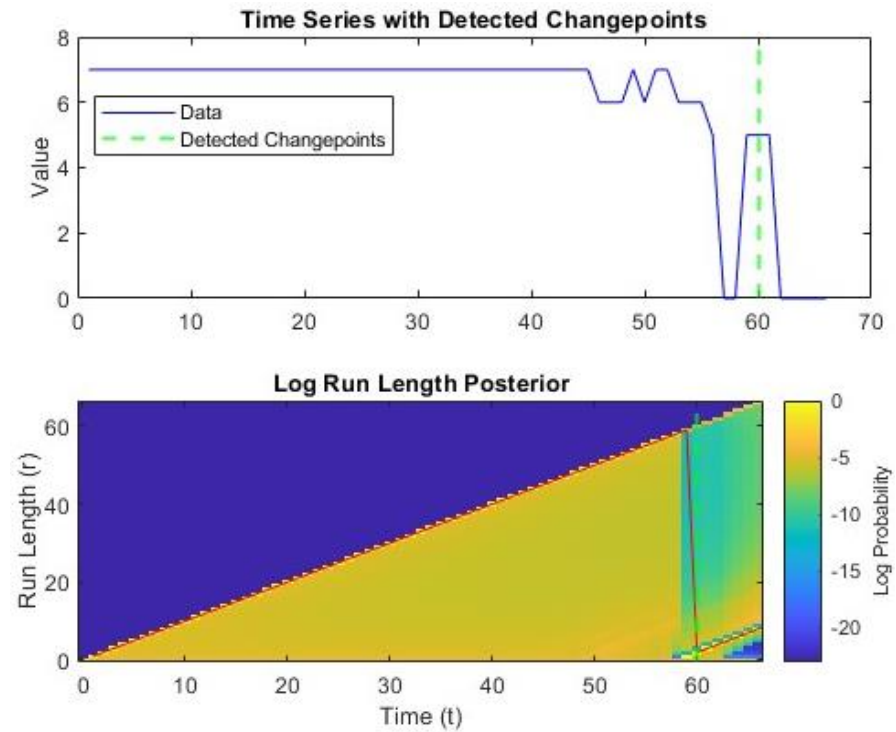
Adams, R. P., & MacKay, D. J. (2007). Bayesian online changepoint detection. *arXiv preprint arXiv:0710.3742*.

Using BOCPD compared with using NIC value directly



Example of Successful Detection using BOCPD





Affected Point Determination (Spoofing)

Estimating an aircraft's velocity using noisy GPS position reports.

The Kalman Filter combines:

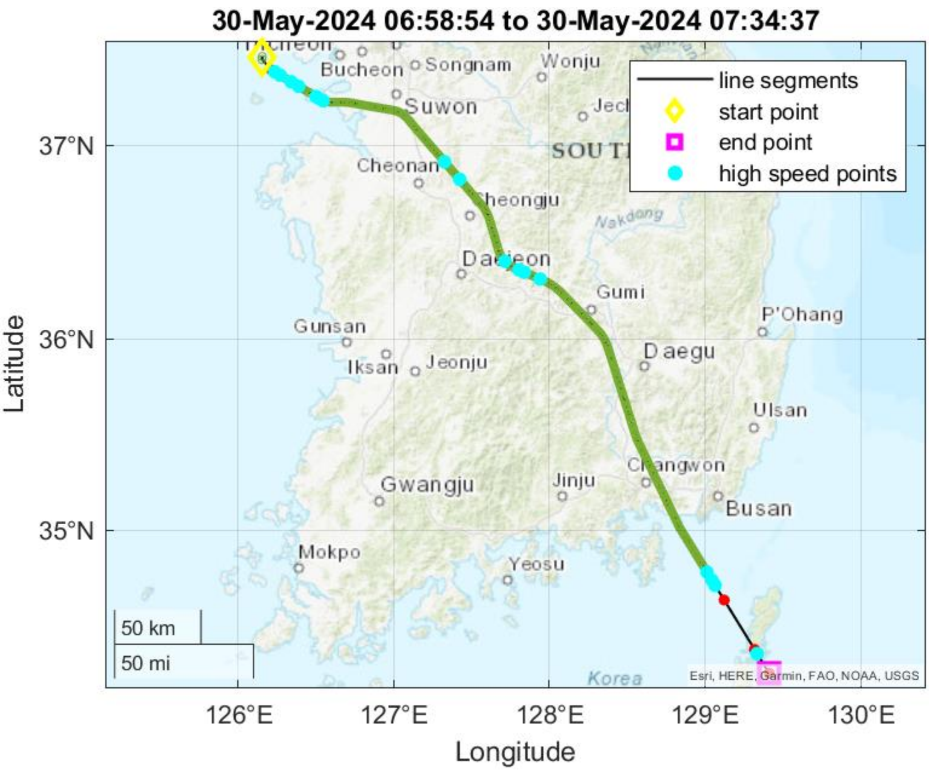
- knowledge of physics (how the aircraft moves)
- noisy measurements (from ADS-B)

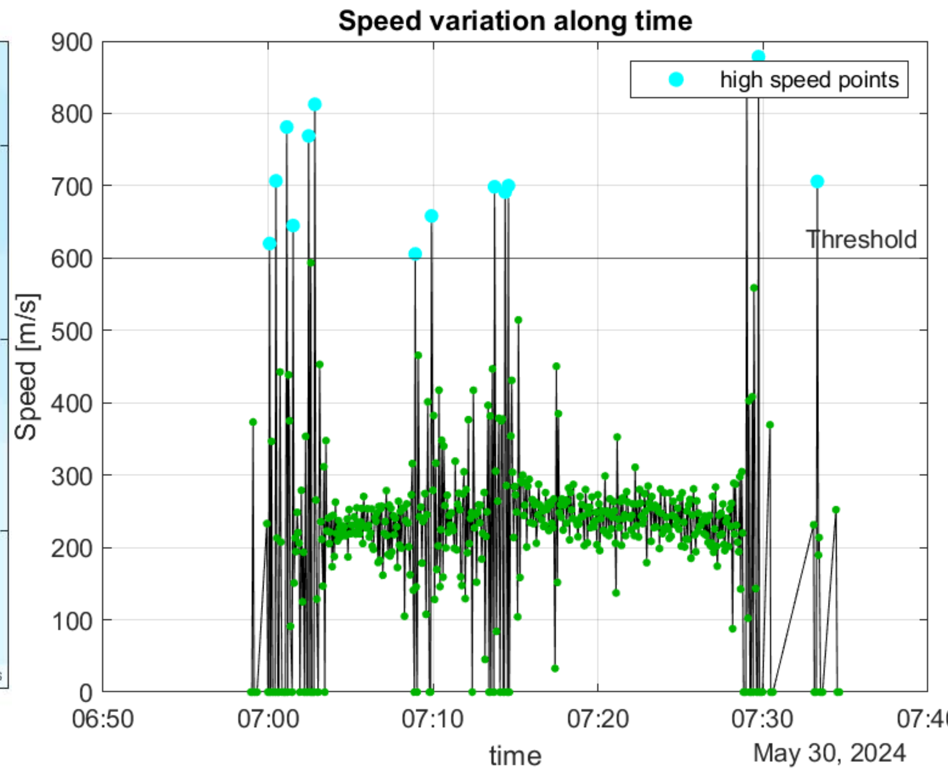
to give the best estimate of the aircraft’s current velocity.

Sudden spikes or drops in estimated velocity can signal potential spoofing effects.

Kálmán, R. E. (1960). *A new approach to linear filtering and prediction problems*. Transactions of the ASME. Series D. Journal of Basic Engineering, 82(1), 35-45. Springer

Comparing Kalman Filter Estimation with Direct Velocity Calculation





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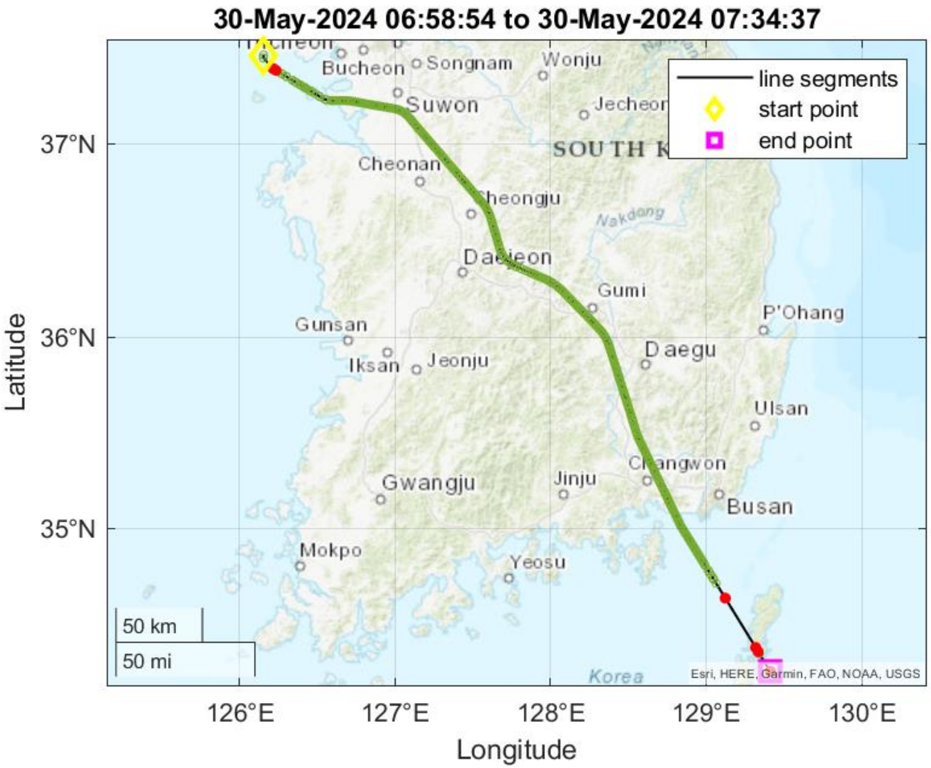
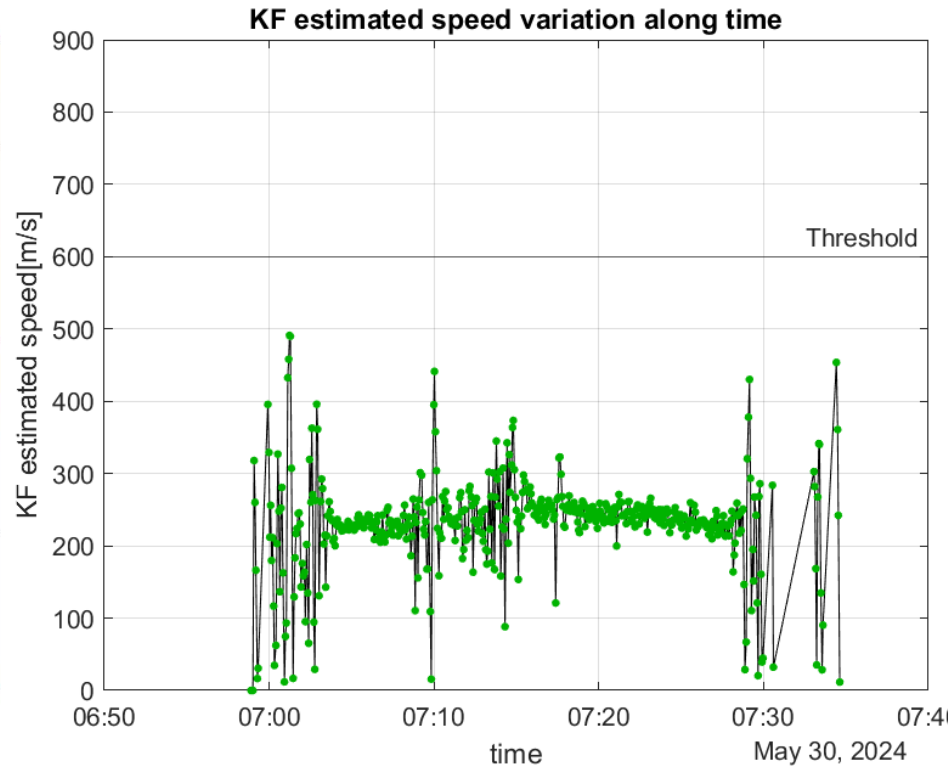
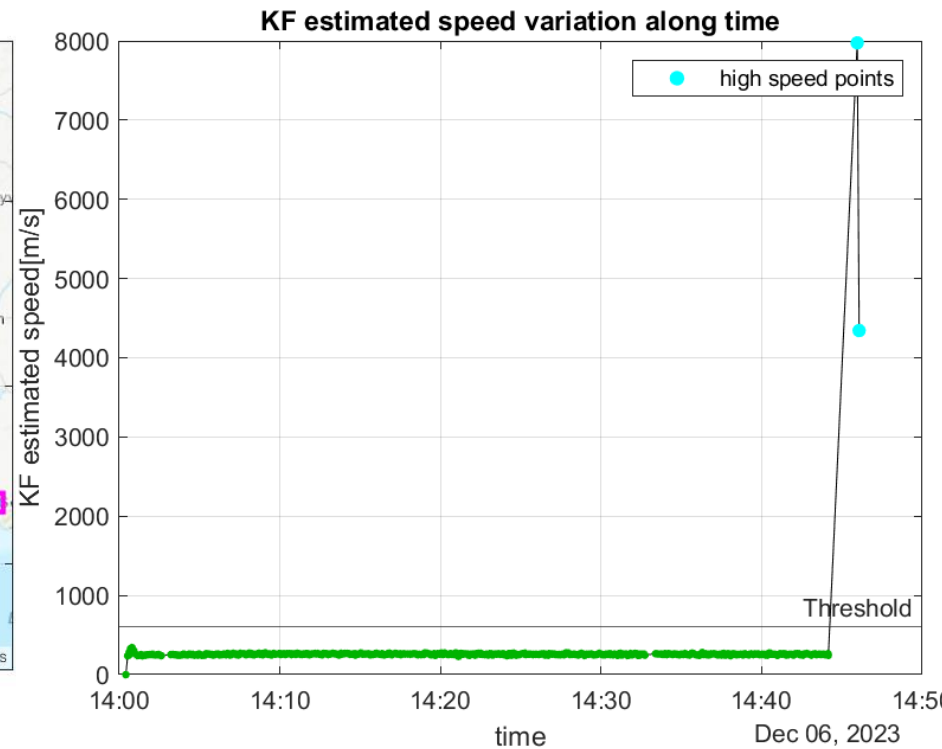


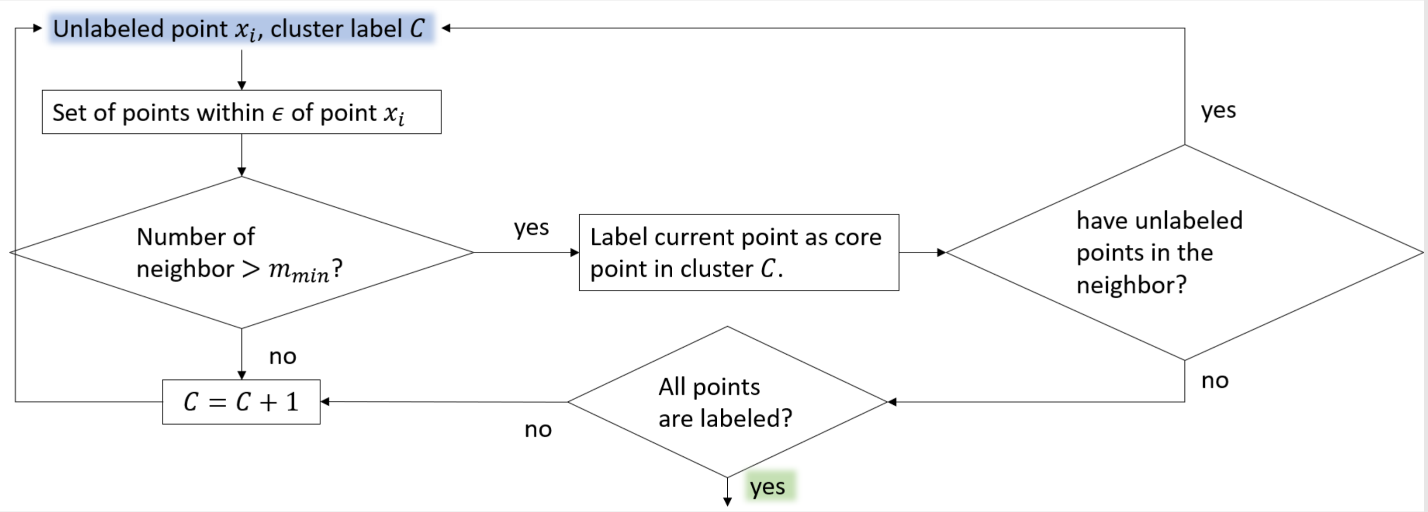


Example of Successful Detection using Kalman Filter Estimation



Event detection using clustering algorithm

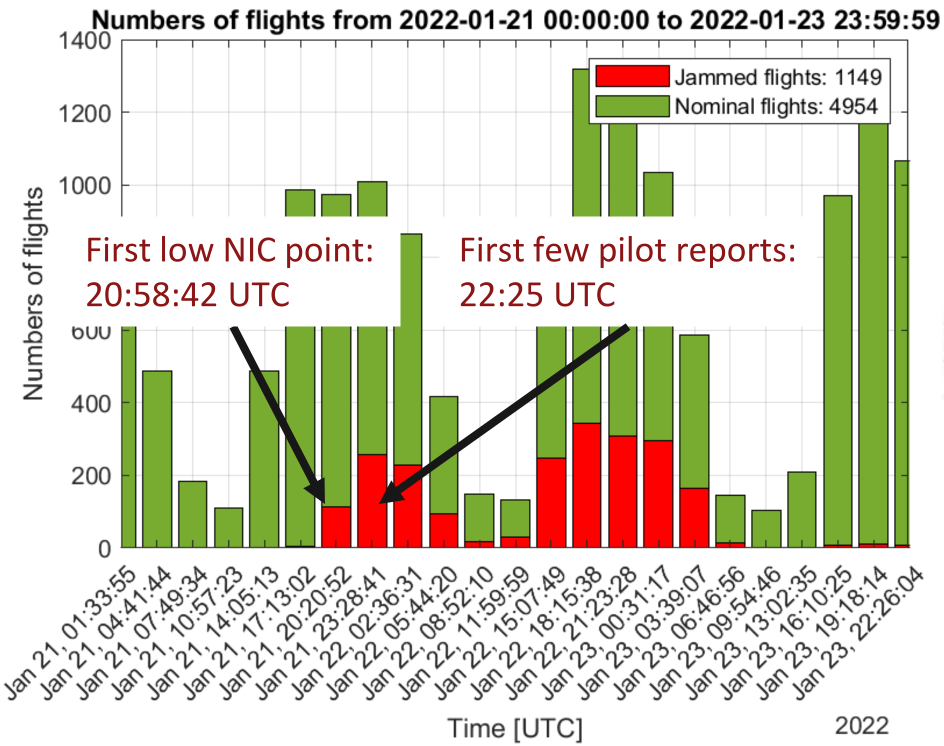
- Density-Based Spatial Clustering of Applications with Noise (DBSCAN).
  - no need for pre-specification, making it suitable for unpredictable interference events
  - can detect noise points, enhancing the accuracy of detection by filtering out irrelevant data

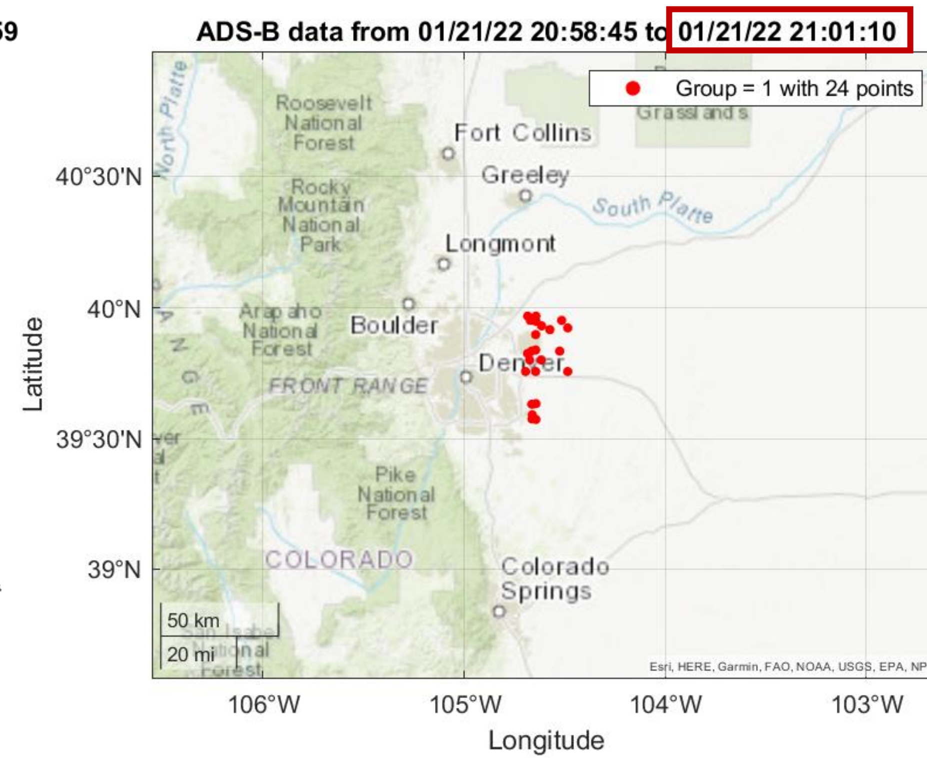


Ester, M., H.-P. Kriegel, J. Sander, and X. Xiaowei. "A density-based algorithm for discovering clusters in large spatial databases with noise." In Proceedings of the Second International Conference on Knowledge Discovery in Databases and Data Mining, 226-231. Portland, OR: AAAI Press, 1996.

Results and Analysis (Jamming)

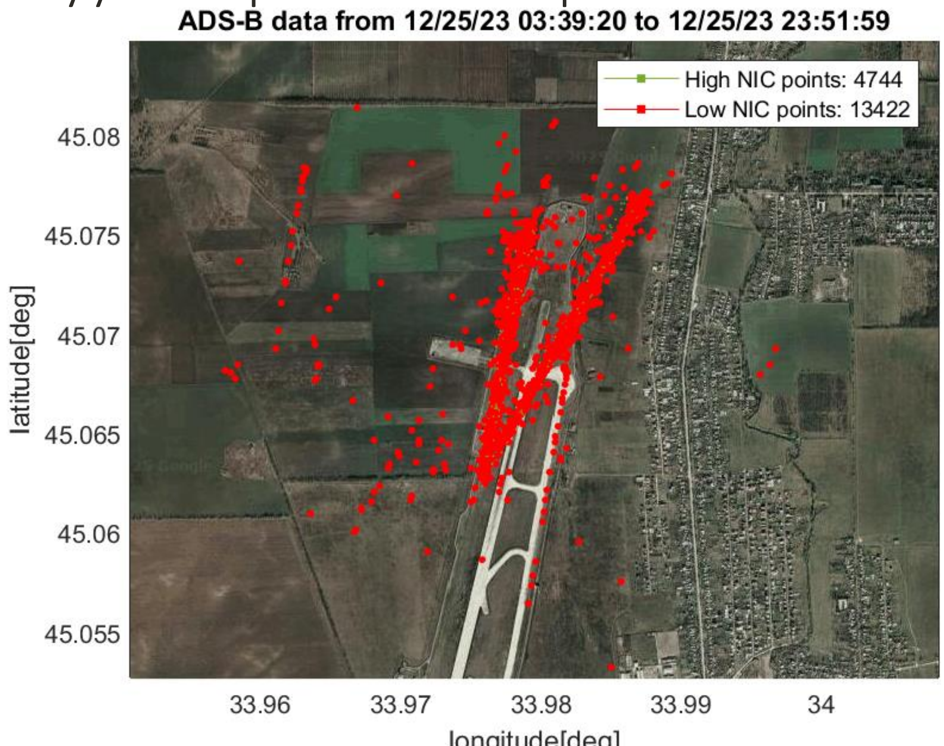
- Run one iteration of the algorithm and add new data every 1min.





Results and Analysis (Spoofing)

- 12/25/2023, 154 flights been spoofed into trajectories over runway19 at Mezhdunarodnyy Aeroport Simferopol'



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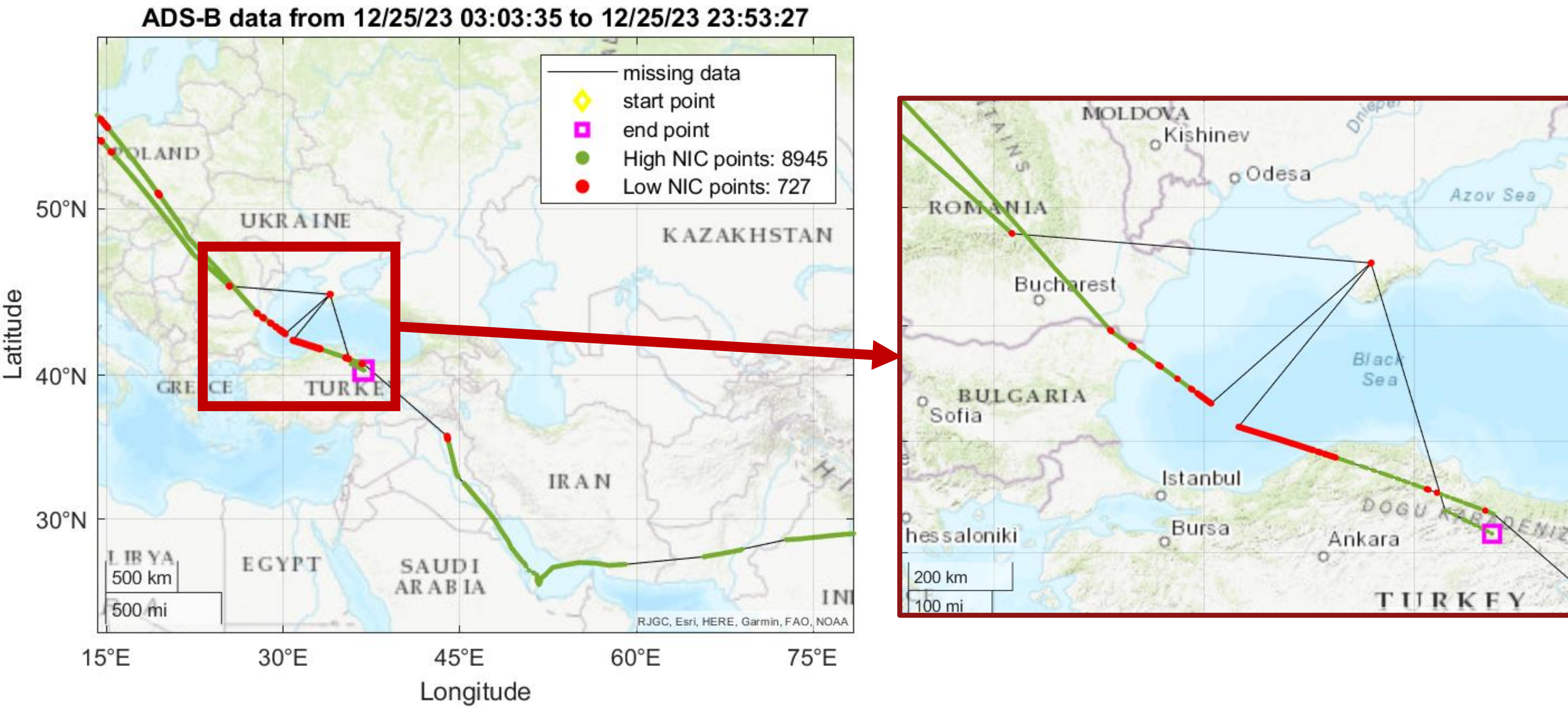

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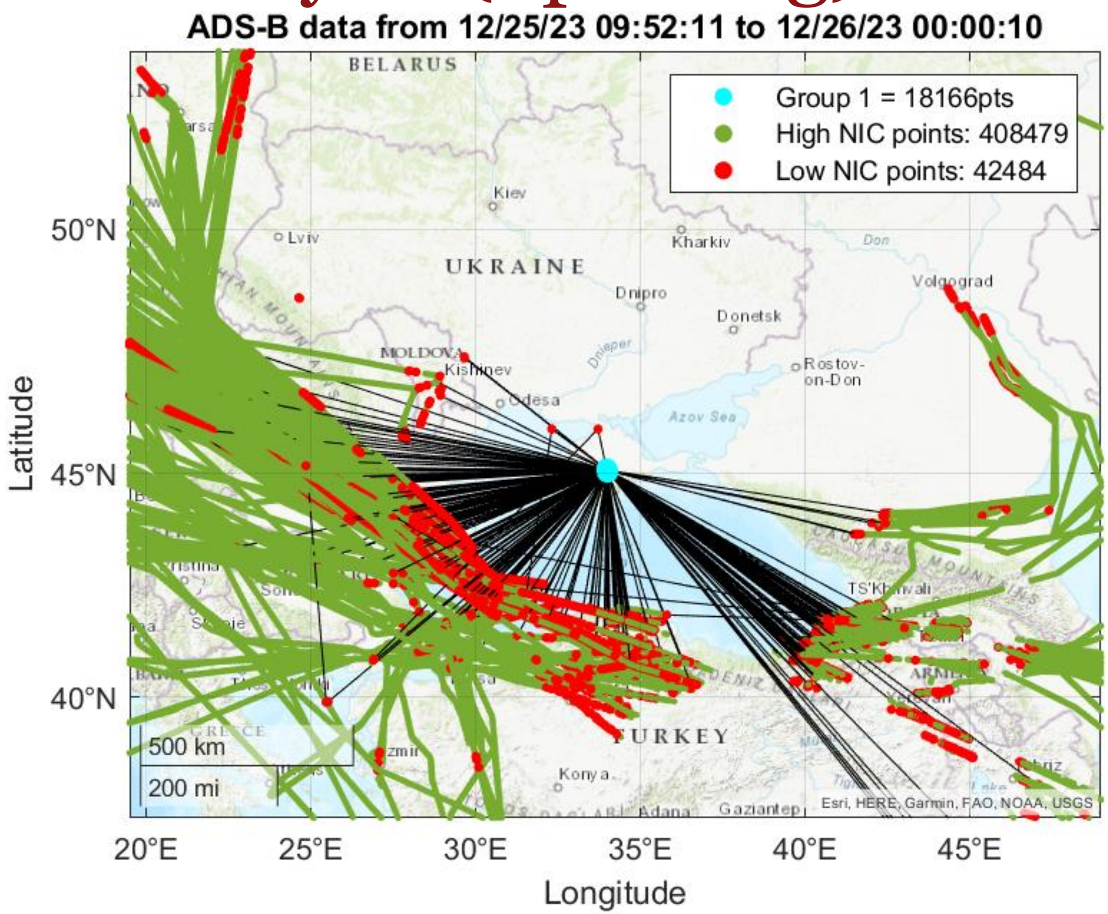

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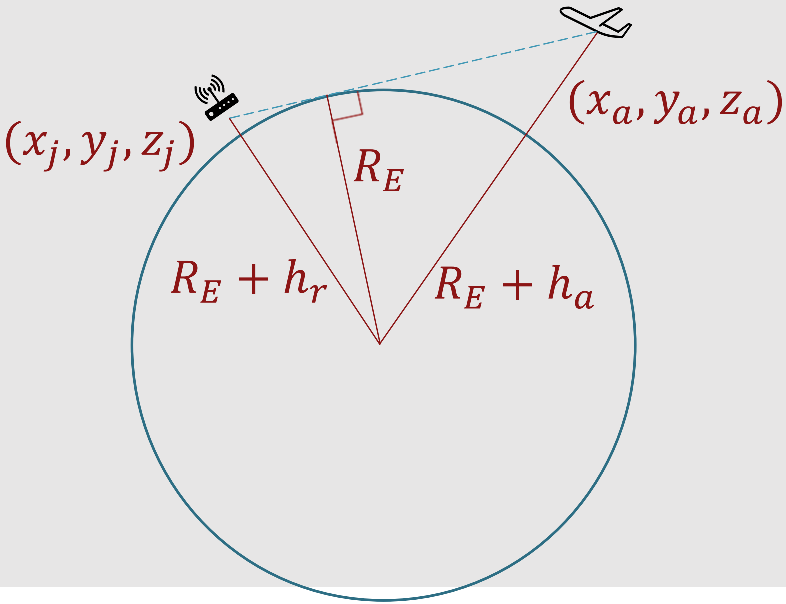
Line of Sight (LOS) Analysis

- Perform line-of-sight analysis by checking if most of the affected ADS-B points are in direct line of sight from a ground location, as interference signals can't pass through obstacles like mountains.



Radar horizon range against a target at a specific height:

$$RHR_{[km]} = 4.12 * (\sqrt{h_{r\,[m]}} + \sqrt{\mathrm{h}_{a\,[m]}})$$

In ECEF:

$$\sqrt{(x_a - x_j)^2 + (y_a - y_j)^2 + (z_a - z_j)^2}$$
$$\leq \sqrt{2 \cdot \frac{4}{3} R_E h_r} + \sqrt{2 \cdot \frac{4}{3} R_E h_a}$$

Selection of affected points

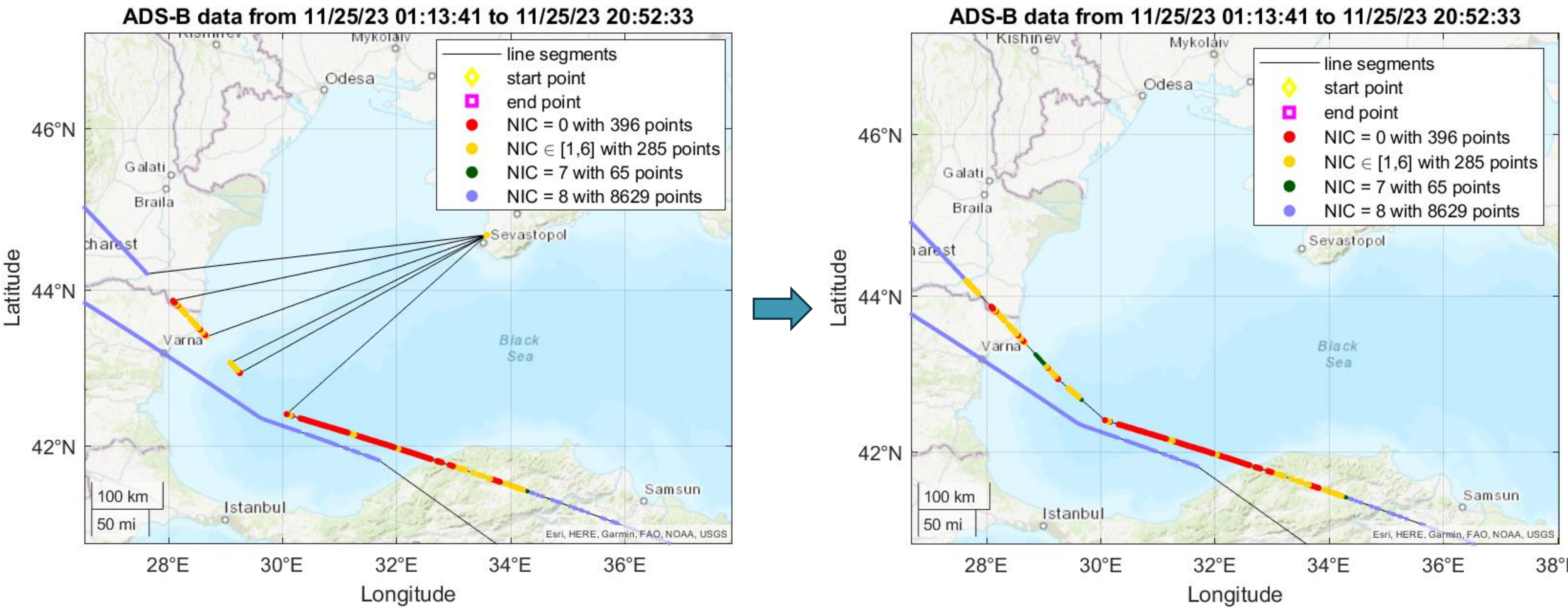
For Jamming:

- Everything between the changepoints. (BOCPD explained in previous section)

For Spoofing:

- Interpolate where the flight should be flying when being spoofed, indicating the ‘likely’ affected region.
- If the aircraft
  - follows a straight-line motion, linear interpolation might be sufficient.
  - follows a curve (e.g., turns), spline interpolation (e.g., cubic splines) is better.
  - follows a more complex trajectory such as a spiral, polynomial fitting or Kalman smoothing modeling may be required.

Example interpolation results



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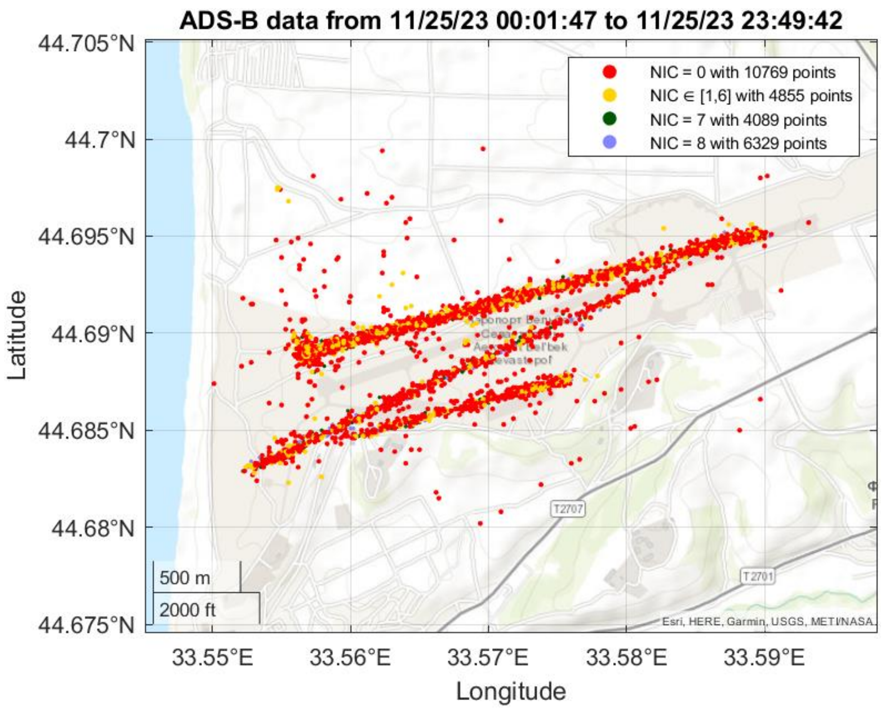
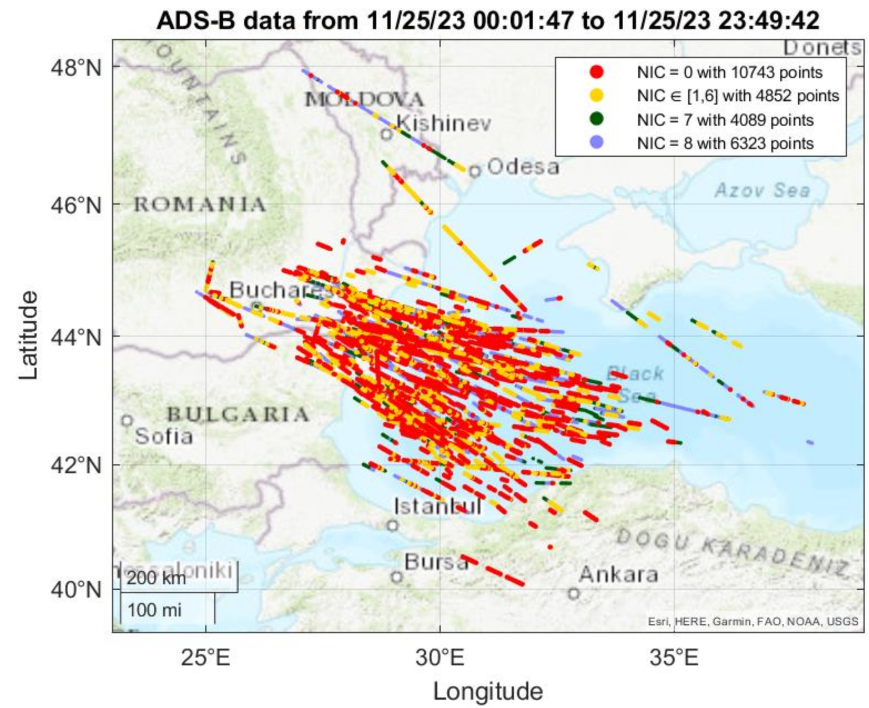
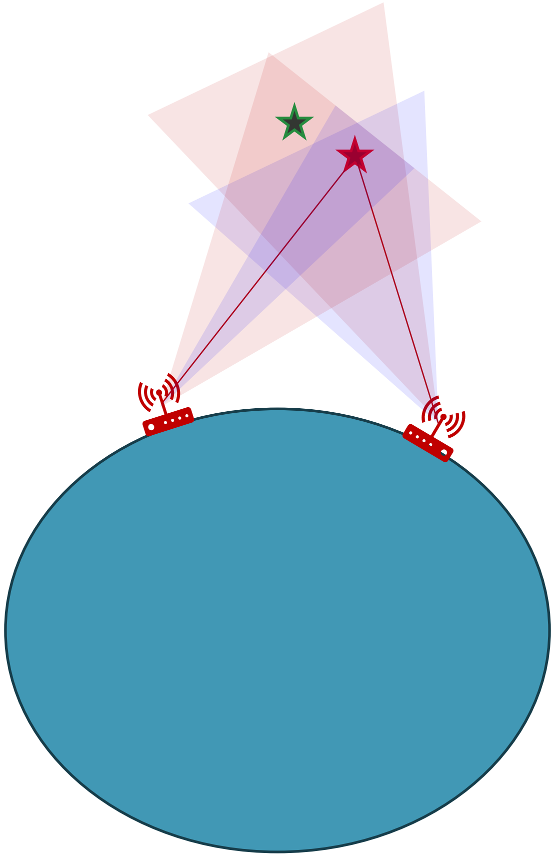




Use of non-affected points

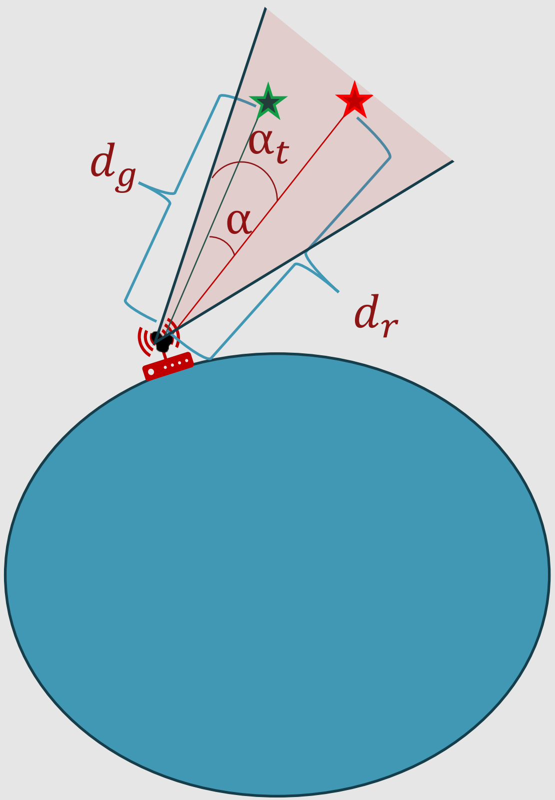


Use of non-affected points

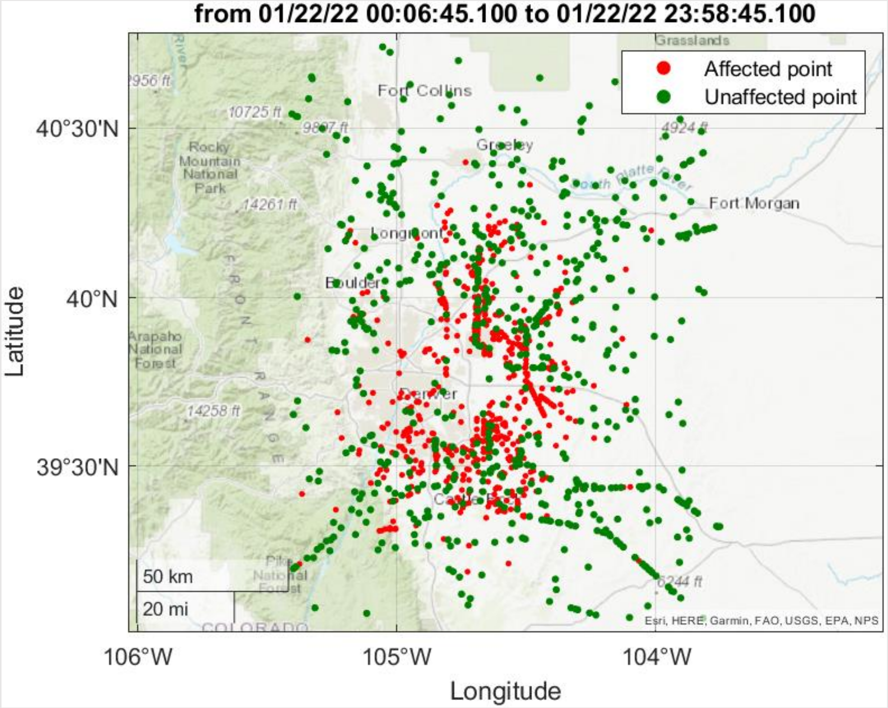
- Assuming the minimum impact region created by a transmitter is defined by a beam with a threshold angle α_t.

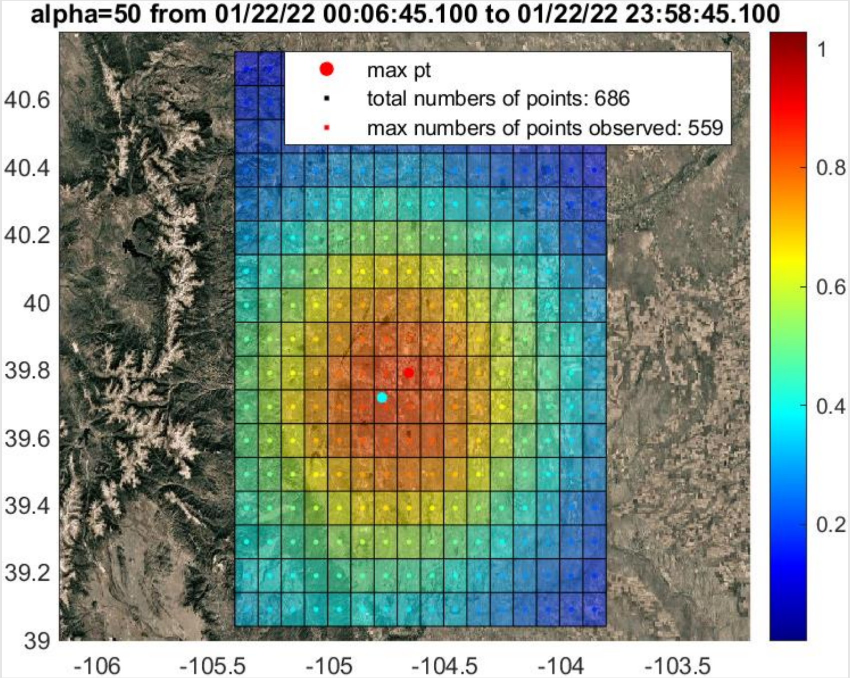
- If a non-affected point is within the beamwidth ($\alpha < \alpha_t$) and is closer to the transmitter than the affected point ($d_g < d_r$), there should not be a transmitter at that position.

- The non-affected points must be observed at the exact same moment to account non-static transmitter effect.

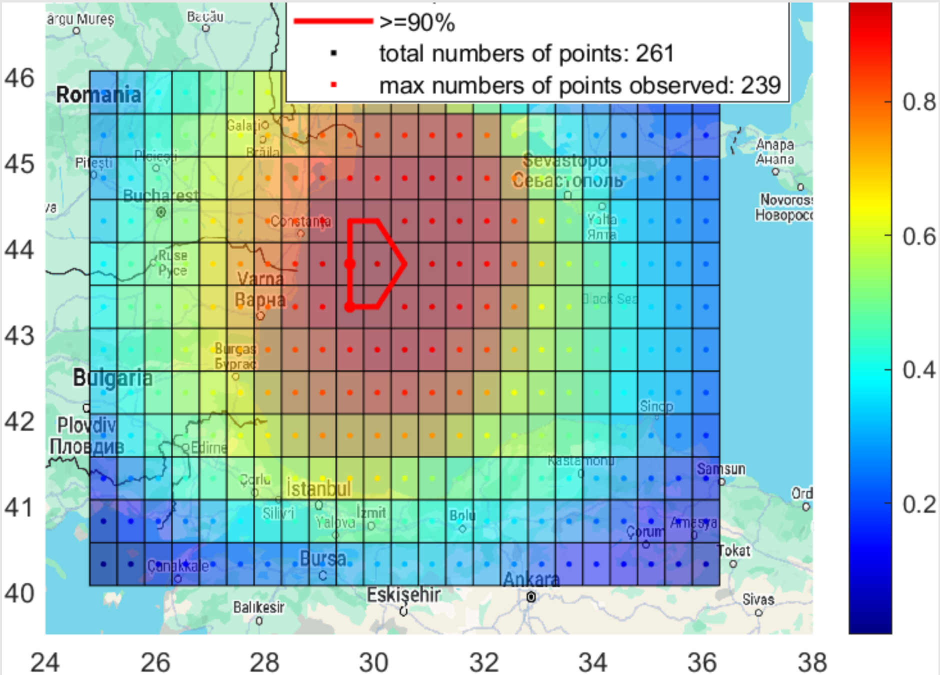


Localization result for KDEN jamming event





Localization result for example spoofing event



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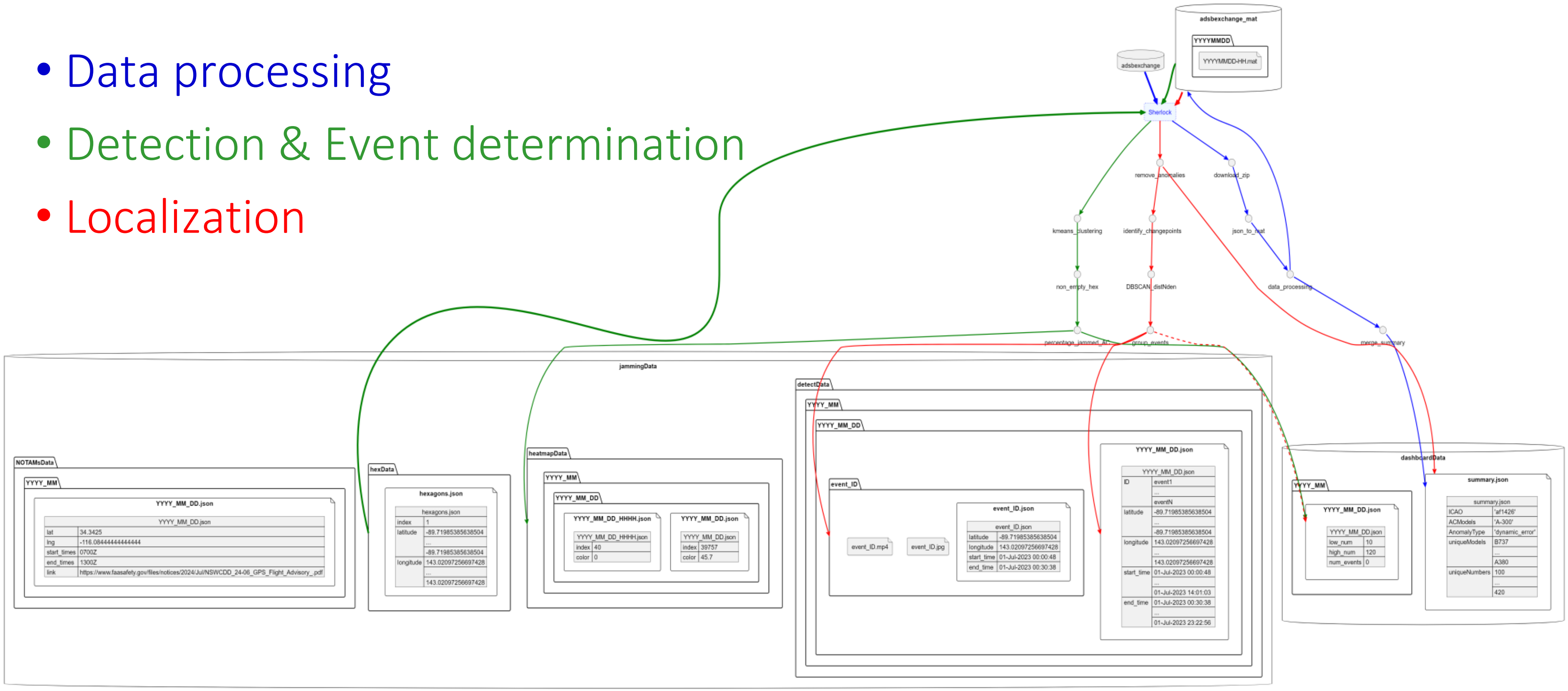
A Live and Automated Pipeline for Global GNSS Situational Awareness

- Data processing
- Detection & Event determination
- Localization



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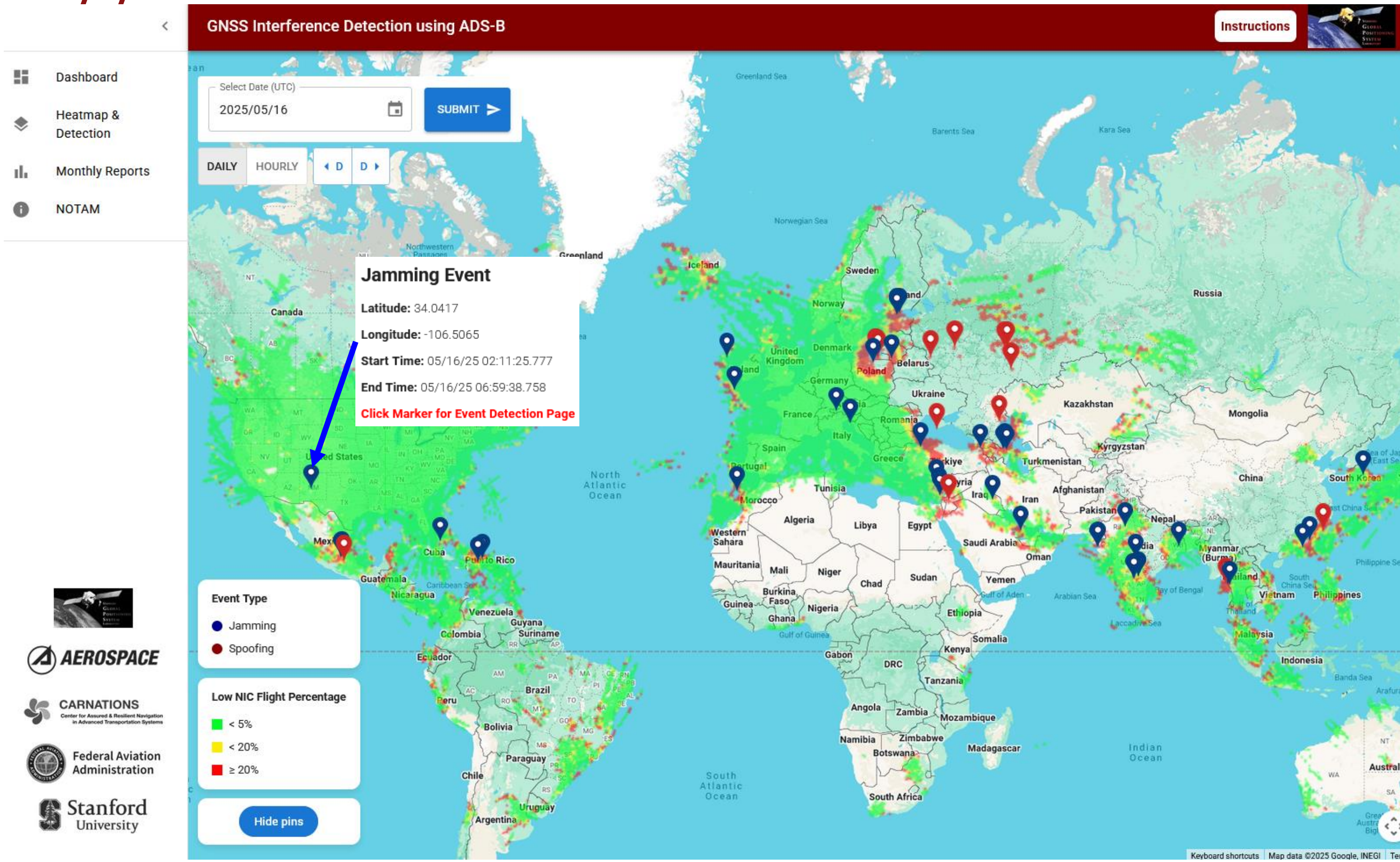

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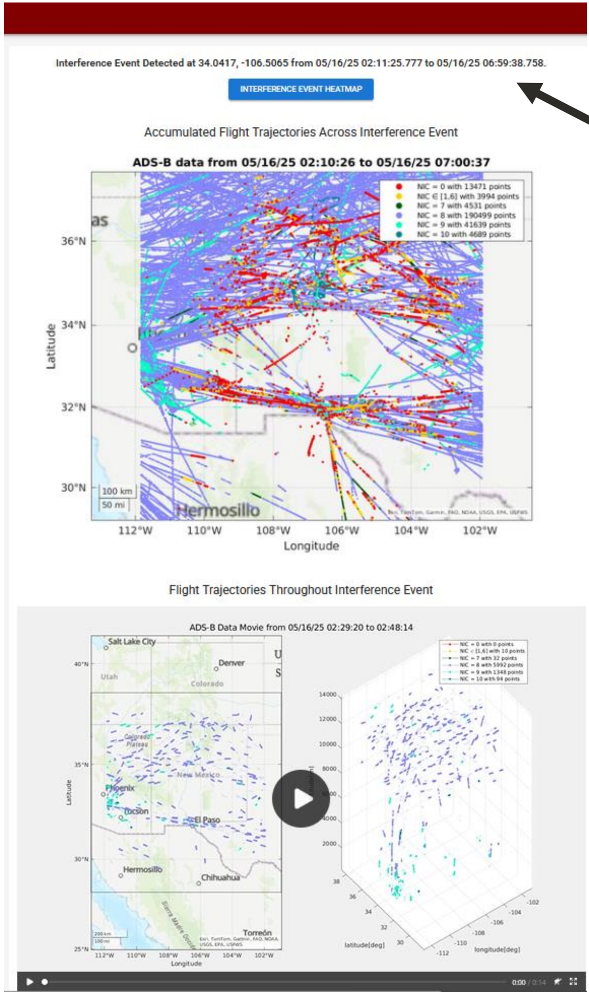
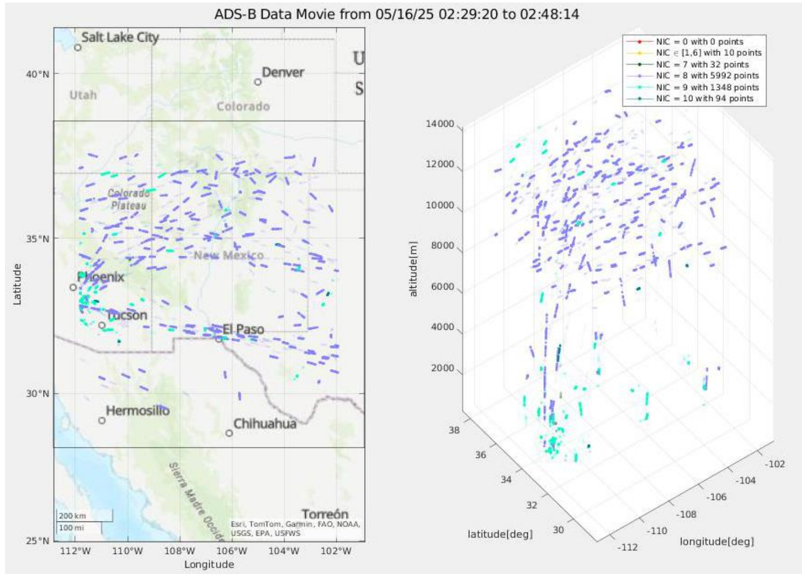
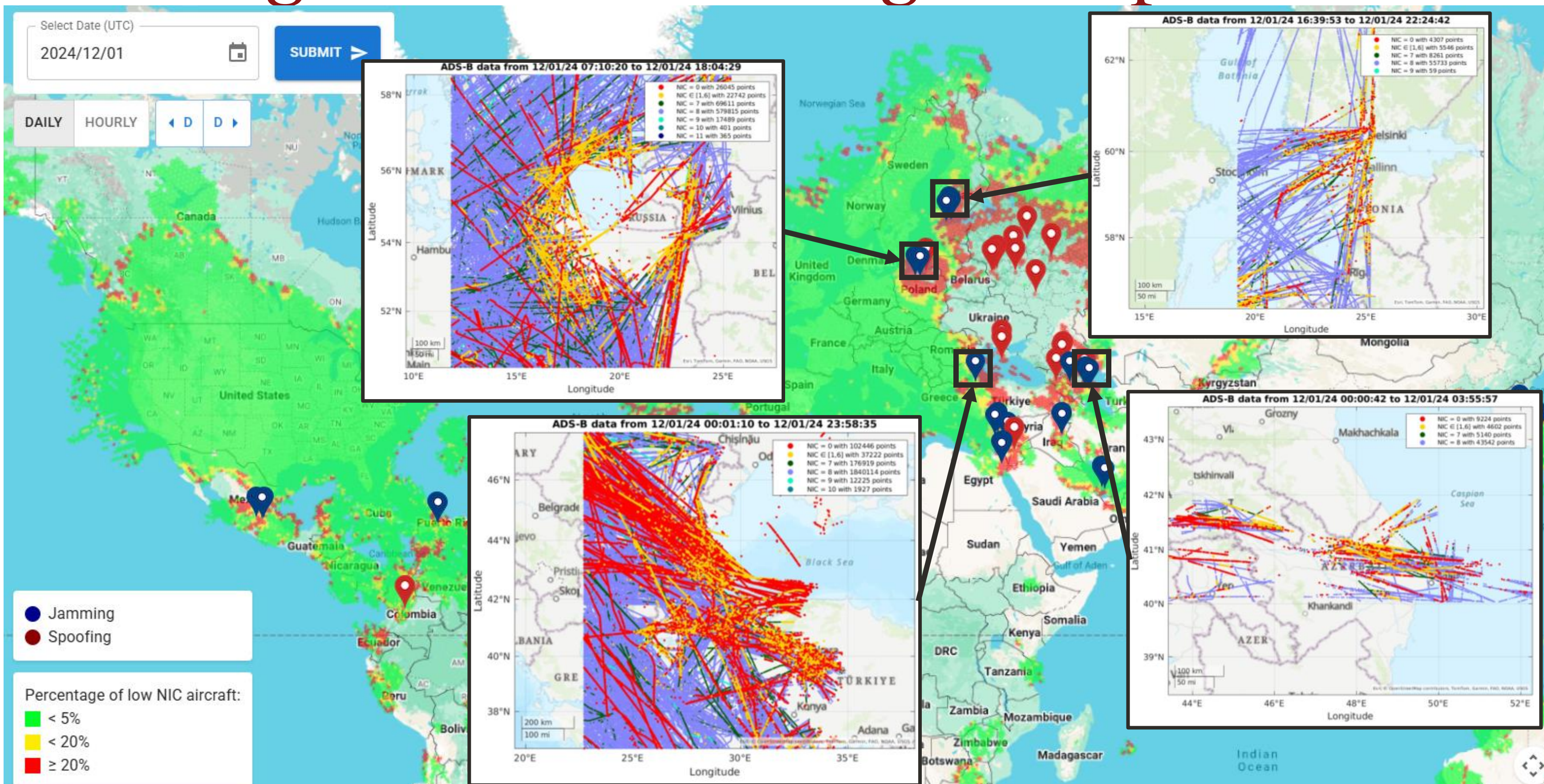


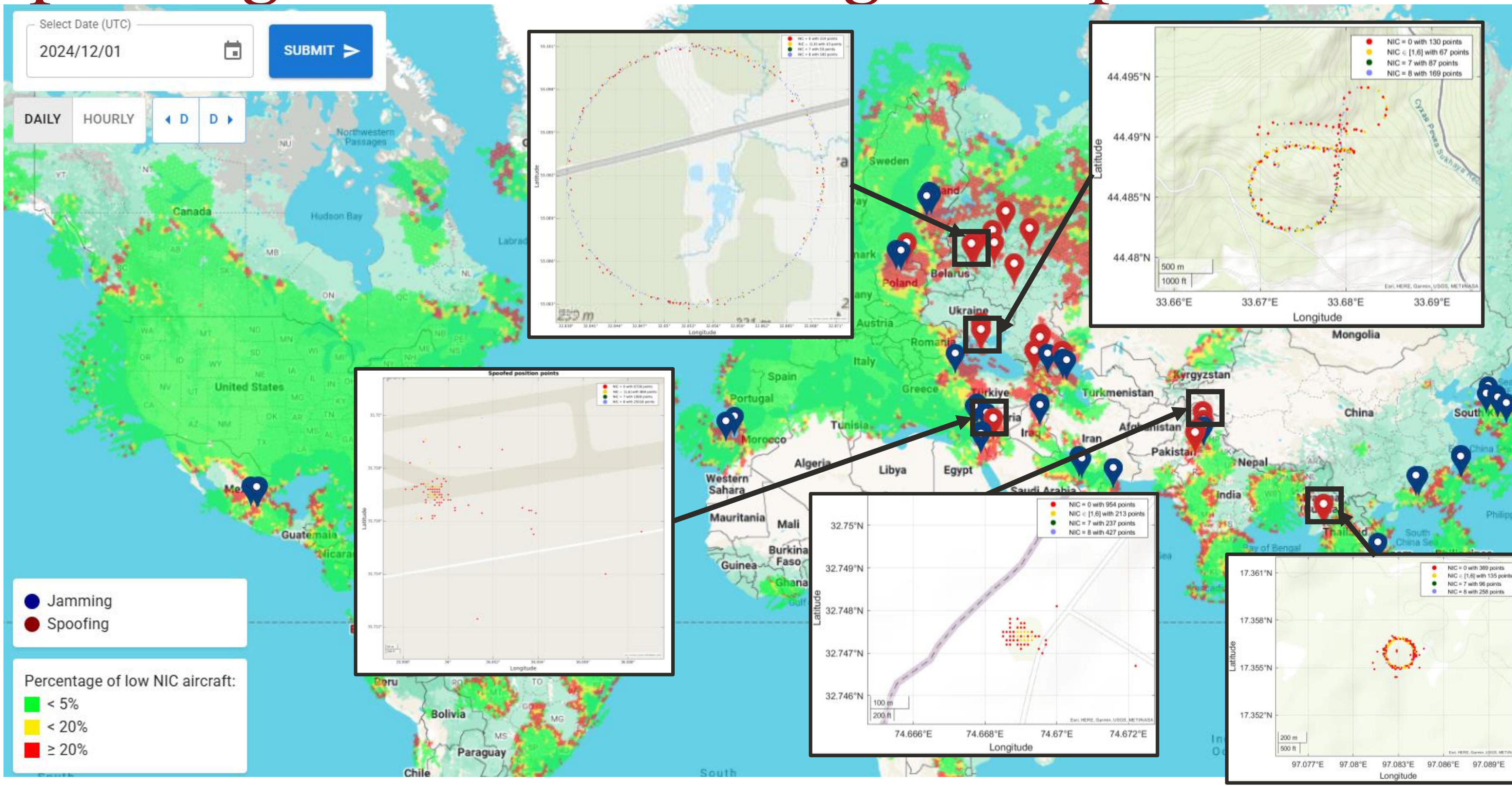
Interference Event Detected at 34.0417, -106.5065 from 05/16/25 02:11:25.777 to 05/16/25 06:59:38.758.



Jamming Event Monitoring Example



Spoofing Event Monitoring Example



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Automated Global GNSS Interference Monitoring

Developed an automated, near real-time, continuous system for rapid detection and robust localization of GNSS jamming and spoofing events.

Provides:

- Time and location of interference
- Estimated source location and power
- Improved situational awareness for rapid regulatory response
- Insight into global prevalence of interference

Acknowledgements

Federal Aviation Administration

AEROSPACE

CARNATIONS

Center for Assured & Resilient Navigation in Advanced Transportation Systems

Thank You!

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