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Detecting GNSS spoofing of ADS-B equipped aircraft using INS

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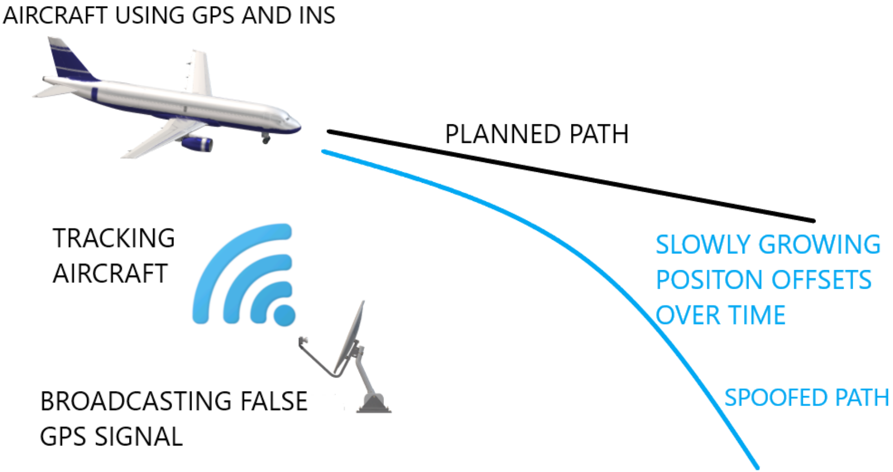
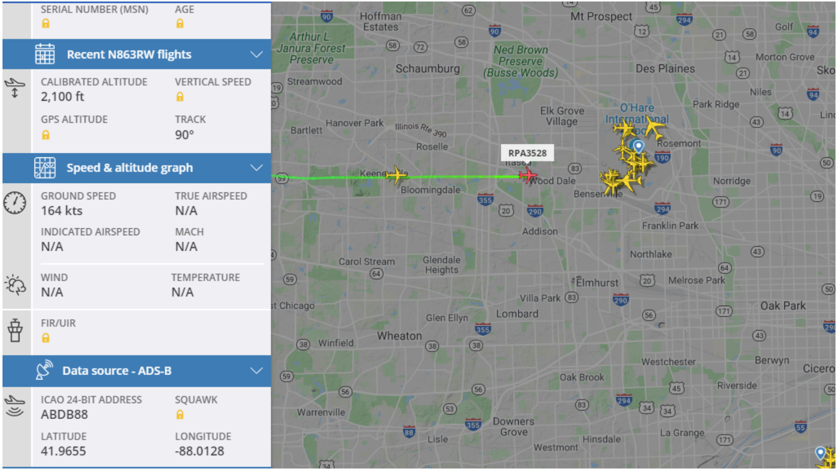
What is spoofing?



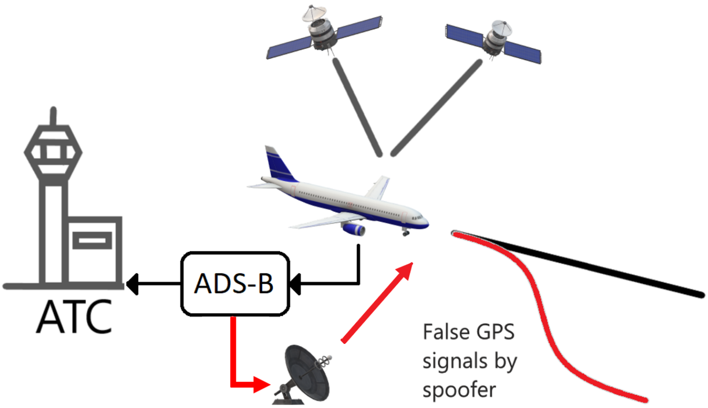
Background

Aircraft tracking using Automatic Dependent Surveillance-Broadcast (ADS-B)[1]



[1] Live Air Traffic. Retrieved from https://www.flightradar24.com/

How ADS-B can aid a spoofer?



Availability of low-cost ADS-B tracker[2]

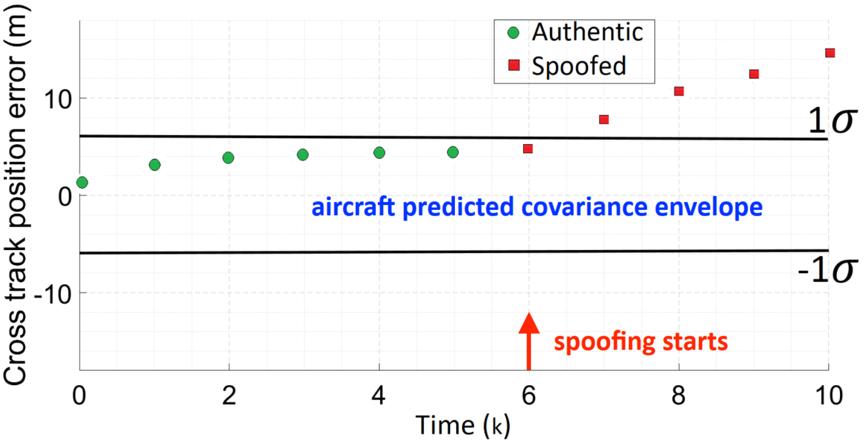
2 Share your ADS-B data. Retrieved from https://www.flightradar24.com/

Example: En route aircraft

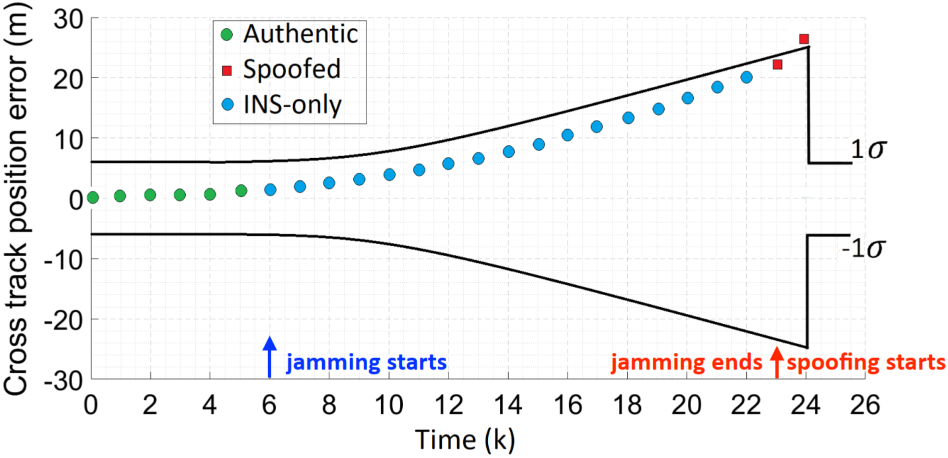
- Aircraft on level flight with constant cruising speed
- Inertial-aided GNSS in Kalman Filter (KF) for navigation and ADS-B Out
- Receives single frequency code and carrier measurements
- Idea also applicable to dual frequency multi-constellation GNSS, terminal and precision approach scenarios

Example: En route aircraft

How can spoofer deviate an aircraft?



GNSS outage (jamming) and re-acquisition



Spoofing scenario

- Position and velocity states from KF are used for ADS-B as $\hat{\mathbf{r}}_{k_{ADS-B}}$ and $\hat{\mathbf{v}}_{k_{ADS-B}}$.
- Spoofer receives ADS-B and predicts the future aircraft position

$$\bar{\mathbf{r}}_{k+1_s} = \hat{\mathbf{r}}_{k_{ADS-B}} + (\hat{\mathbf{v}}_{k_{ADS-B}} \times \Delta t)$$

- Compensating reasonably for other GNSS error states, spoofer creates signal corresponding to range measurements

$$\mathbf{z}_{k+1_s} = \mathbf{H}_{k+1}\bar{\mathbf{x}}_{k+1_s}$$

- Finally, the aircraft observes the measurements as

$$\mathbf{z}_{k+1_{s(A/C)}} = \mathbf{z}_{k+1_s} + \mathbf{m}' + \boldsymbol{\nu}_{th}$$

where, $\mathbf{H}$ is the observation matrix, $\mathbf{m}'$ is the multipath error and $\boldsymbol{\nu}_{th}$ is the receiver thermal noise.

ADS-B modulation

- Spoofer can predict the aircraft's position using accurate ADS-B information.
- No need to implement an active tracking device (e.g., Lidar).
- To deny potential spoofers such easy access, aircraft can "modulate" ADS-B Out positions (within FAA AC 20-165 standards)

$$\hat{\mathbf{r}}_{k_{ADS-B}} = \hat{\mathbf{r}}_k + \mathbf{b}_k$$

- This will cause subsequent spoofed measurement to have an inherent offset which can be detected using a monitor.

Position domain-innovation monitor

- Spoofing is detected by comparing position obtained from GNSS measurement and INS propagation.

- At any time k, the KF measurement update is

$$\hat{\mathbf{x}}_k = \bar{\mathbf{x}}_k + \mathbf{L}_k(\mathbf{z}_k - \mathbf{H}_k\bar{\mathbf{x}}_k)$$

  where, $\mathbf{L}$ is the Kalman gain, and $\bar{\mathbf{x}}_k$ is state obtained after INS propagation.

- Before using the measurement, we check the test statistic in one position direction

$$q_k = \mathbf{u}^T\mathbf{L}_k(\mathbf{z}_k - \mathbf{H}_k\bar{\mathbf{x}}_k)$$

  where, $\mathbf{u}$ is a single column vector that extracts the desired position state.

Position domain-innovation monitor

- If the measurement is authentic, this test statistic will have distribution with zero mean and variance,

$$\mathrm{var}(q_k) = \mathbf{u}^T \mathbf{L}_k \mathbf{S}_k \mathbf{L}_k^T \mathbf{u}$$

where, $\mathbf{S}$ is the innovation covariance matrix.

- The threshold for false alarm allocation can be chosen using the appropriate multiple of the standard deviation

$$T_k = k_{FA} \times \sqrt{\mathbf{u}^T \mathbf{L}_k \mathbf{S}_k \mathbf{L}_k^T \mathbf{u}}$$

- When the spoofer utilizes the modulated ADS-B and returns a spoofed signal, the bias sent out at previous time epoch appears in the current measurement.

$$\hat{\mathbf{r}}_{k_{ADS-B}} = \hat{\mathbf{r}}_k + \mathbf{b}_k \qquad \rightarrow \qquad \text{sent by aircraft}$$

$$\bar{\mathbf{r}}_{k+1_s} = \hat{\mathbf{r}}_{k_{ADS-B}} + (\hat{\mathbf{v}}_{k_{ADS-B}} \times \Delta t) \qquad \rightarrow \qquad \text{prediction by spoofer}$$

Position domain-innovation monitor

- If the spoofed measurement is received at time $k+1$ the test statistic is

$$q_{k+1} = \mathbf{u}^T \mathbf{L}_{k+1}(\mathbf{H}_{k+1}\bar{\mathbf{b}}_k + \mathbf{m}^{'} + \boldsymbol{\nu}_{th})$$

where, $\bar{\mathbf{b}}_k$ is $[\ \mathbf{b}_k \quad \mathbf{0}\ ]^T$.

- The test statistic has now a shifted mean of

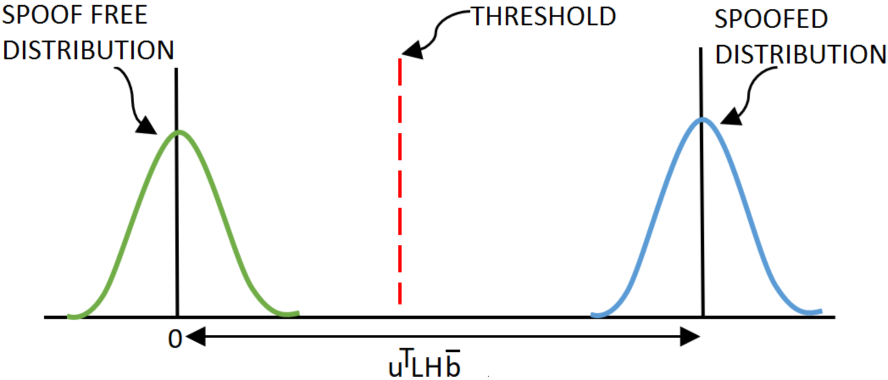
$$\mathbf{u}^T \mathbf{L}_{k+1}\mathbf{H}_{k+1}\bar{\mathbf{b}}_k$$

- The distribution of the test statistic due to spoofed measurement has variance,

$$\mathrm{var}(q_{k+1}) = \mathbf{u}^T \mathbf{L}_{\mathbf{k+1}}\mathbf{M}^{'}\mathbf{L}_{k+1}^T\mathbf{u}$$

where, $\mathbf{M}^{'}$ is the diagonal matrix with the multipath and thermal noise variances for the spoofed signal.

Test statistic distribution change



The ADS-B offset $\bar{\mathbf{b}}$ at any instant k can be chosen as

$$\mathbf{u}^T \mathbf{L}_{k+1} \mathbf{H}_{k+1} \bar{\mathbf{b}}_k = k_{FA} \times \boxed{\sigma_{\bar{x}_{k+1}}} + k_{MD} \times \boxed{\sigma_{m'_{k+1}}}$$

Position domain-innovation monitor

- where,

$$\sigma_{\bar{x}_{k+1}} = \sqrt{\mathbf{u}^T \mathbf{L}_{k+1} \mathbf{S}_{k+1} \mathbf{L}_{k+1}^T \mathbf{u}}$$

$$\sigma_{m'_{k+1}} = \sqrt{\mathbf{u}^T \mathbf{L}_{k+1} \mathbf{M}' \mathbf{L}_{\mathbf{k+1}}^{\mathbf{T}} \mathbf{u}}$$

  k_{MD} is chosen such that the desired missed detection probability is met using the threshold.

- The current ADS-B offset is chosen using predicted position covariances, since the offset will be appearing in the subsequent spoofed measurement set.

ADS-B accuracy and integrity

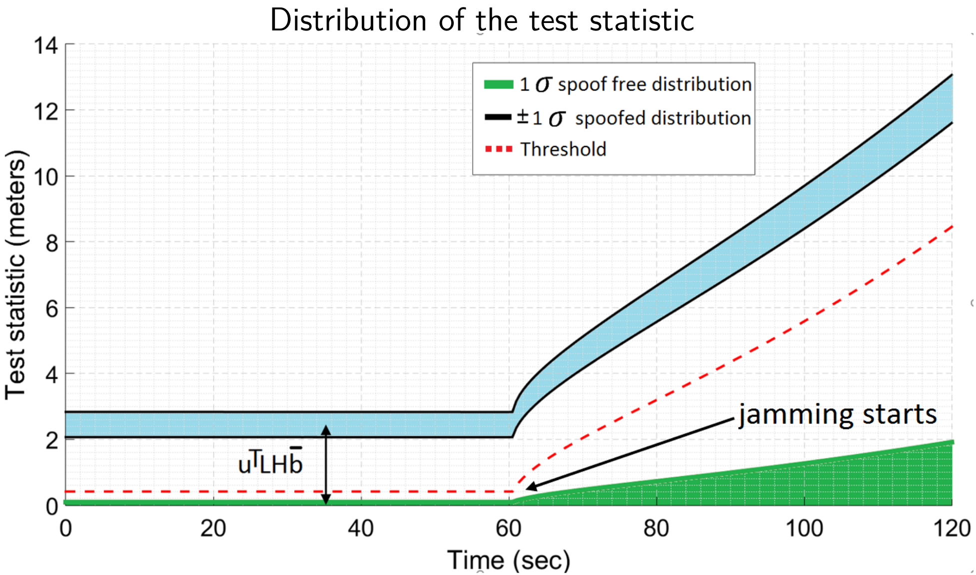
- Within ADS-B, aircraft sends out
  - Navigation Accuracy Category for Position (NAC_P)
  - Navigation Integrity Containment (NIC)
- NAC_P specifies with 95% probability bound on the reported ADS-B position error.
- To operate in civil airspace a minimum nominal NAC_P level of 8 is required, which corresponds to 92.6 m. ($NAC_P(8)$).[3] So the aircraft needs to ensure that,

$$\mathbf{u}^T \bar{\mathbf{b}}_k + 2\sqrt{\mathbf{u}^T \hat{\mathbf{P}}_k \mathbf{u}} \leq NAC_P(8)$$

- While coasting during jamming NIC and NAC_P values will need to be updated to account for increasing position covariances, and ADS-B position offsets.

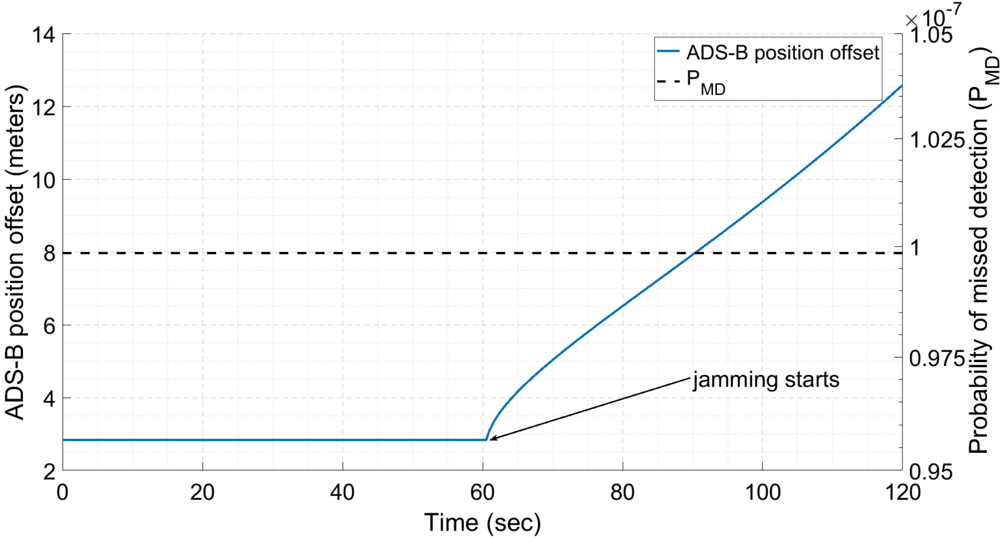
[3] Advisory Circular, Department of Transportation, Federal Aviation Administration: Subject: Airworthiness Approval of Automatic Dependent Surveillance - Broadcast (ADS-B) Out Systems: AC-20-165.

Example Results

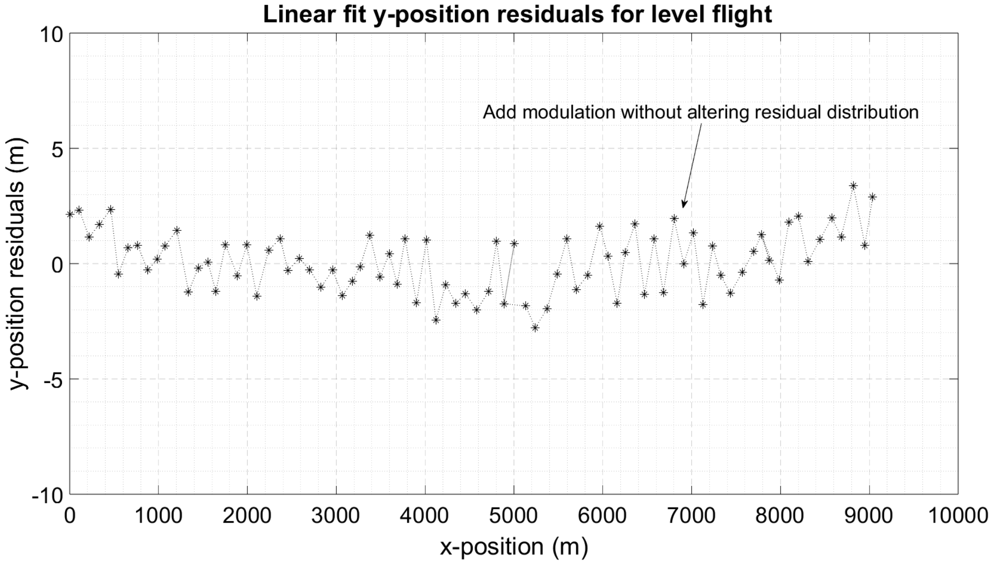


Example results

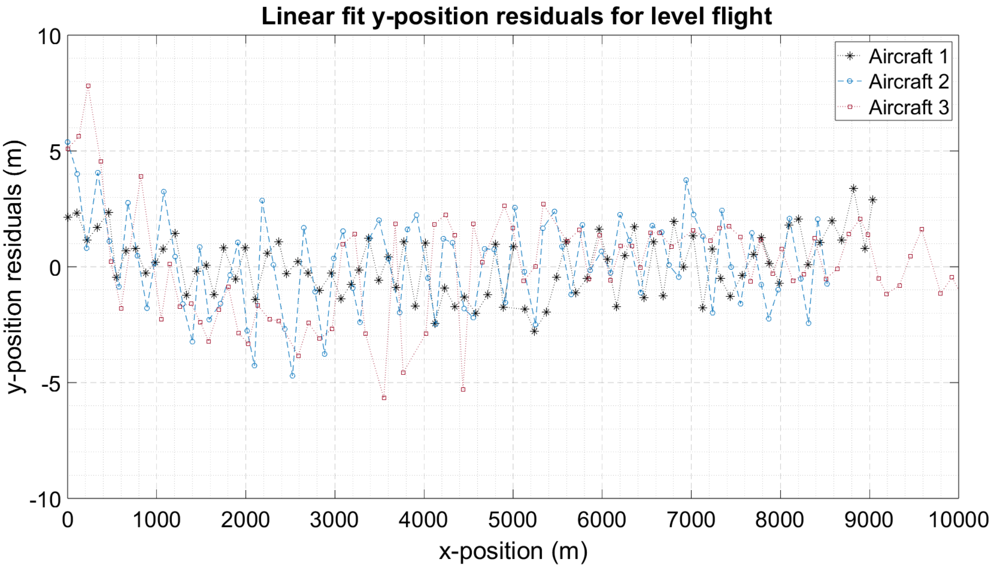
Probability of missed detection and ADS-B position offset



Future work - ADS-B variable modulation



Future work - ADS-B variable modulation



Summary

- ADS-B increases **spoofing vulnerability** of an aircraft.
- Spoofers with access to ADS-B can easily and accurately track aircraft, enabling generation of **false GNSS trajectories that can go undetected** at aircraft even with INS aiding.
- **Adding modulated offsets to ADS-B Out position** reports can be highly effective anti-spoofing measure for INS-equipped aircraft.
- A **position domain-innovation monitor** can detect spoofed GNSS signals created using the offset ADS-B.
- The **jamming-then-spoofing** scenario is also addressed by ADS-B modulation
- Future work includes evaluating and protecting against potential spoofer countermeasures-e.g., attempts to “de-bias” using random counter-offsets.