

Analyzing the Effects of Detected GNSS Spoofing Patterns on an Aircraft

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April 13-16, 2026



Bottom Line Up Front (BLUF)

- Many different GNSS spoofing patterns are now seen worldwide with circular tracks of various sizes and speeds being the most common
- Developed a simulation model to test the effects of different patterns and levels of GNSS dependency has on UAV
- Spoofing patterns/parameters result in the different UAV behavior – with some causing a crash. Having independent heading was useful for preventing crashes



Outline

- 1. GNSS Spoofing Worldwide Today
- 2. Example Worldwide Patterns
- 3. Simulation Development, Set up & Scenarios
- 4. Results from Selected Spoof Patterns



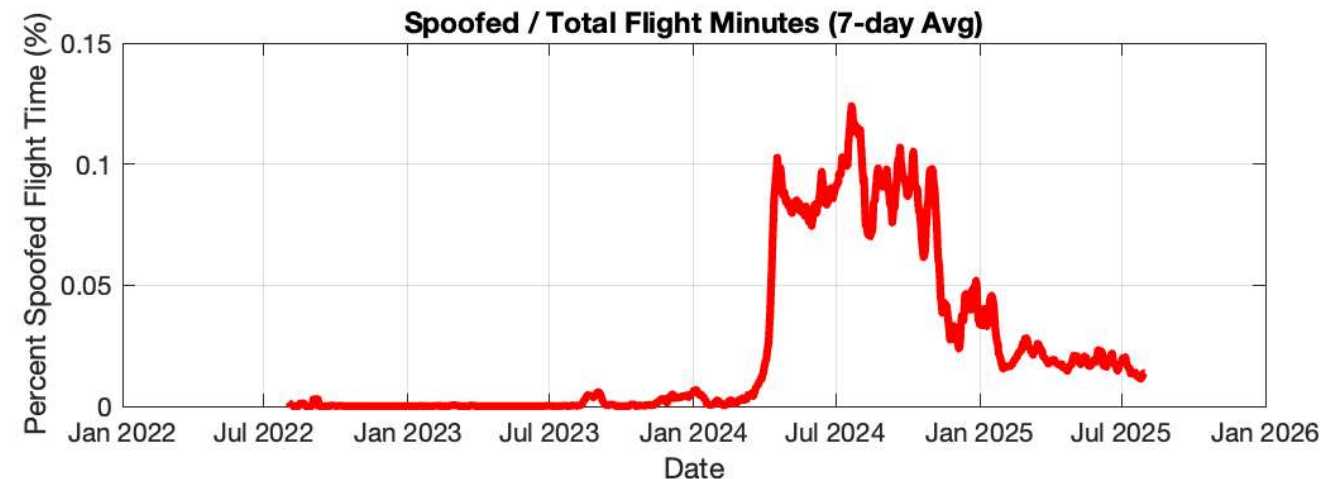
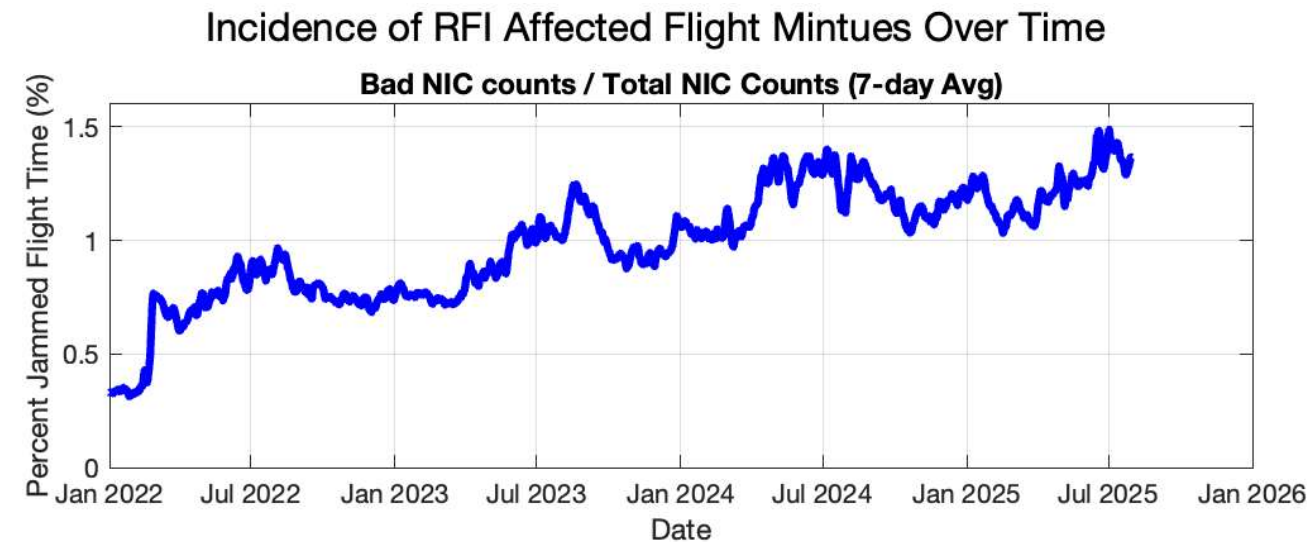
1. World GNSS RFI Events are Increasing – Percentage of Minutes with Jamming & Spoofing

➤ More widespread worldwide – GNSS RFI increased in 2024 & 2025

- Significant increase in spoofing
- Percent of flight minutes of spoofing affecting aircraft decreased between 2024 & 2025
- Perhaps reduced spoofing in Israel

➤ ADS-B data helps us quantify the change in several ways

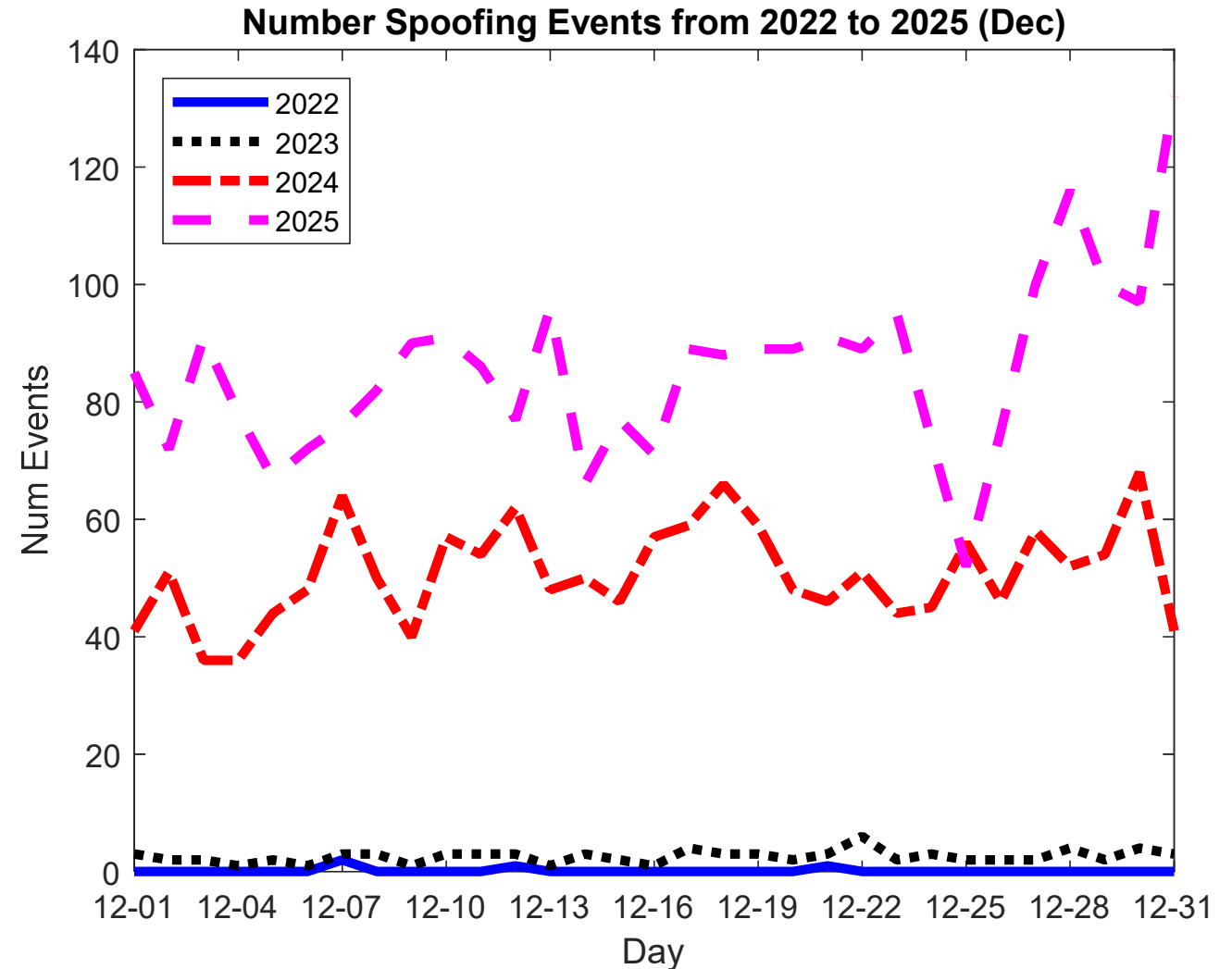
- Flight minutes (% of total) of RFI
- Identifying and quantifying events
- Type, extent & characteristics of events



GNSS Spoofing is Increasing in Number & Sophistication

- Number of events has been increasing
 - More places in the world with spoofing
 - Myanmar, India/Pakistan (Fall 2024)
- Increase use and diversity of dynamic spoofing tracks

Number of Daily Spoofing Events (Dec 2022-2025)



GNSS Spoofing No Longer Limited to Static Positions



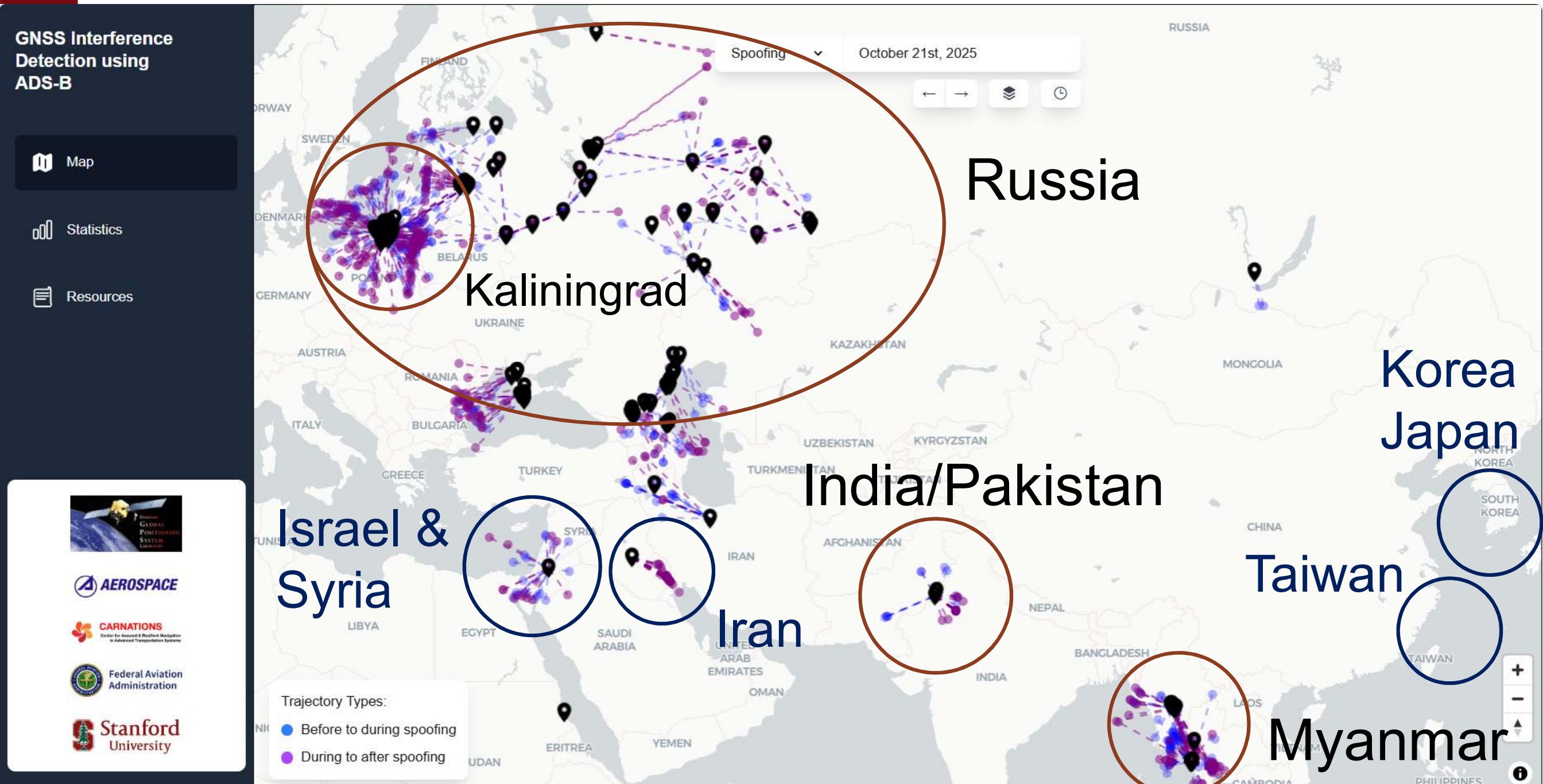
Static spoofing to airport likely targeting consumer drones with geo-fences to force them to land

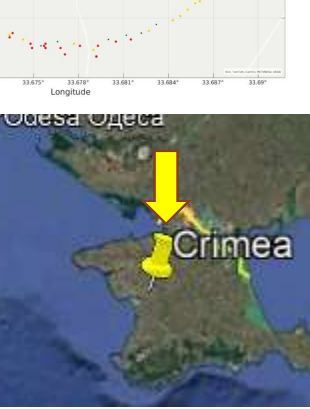
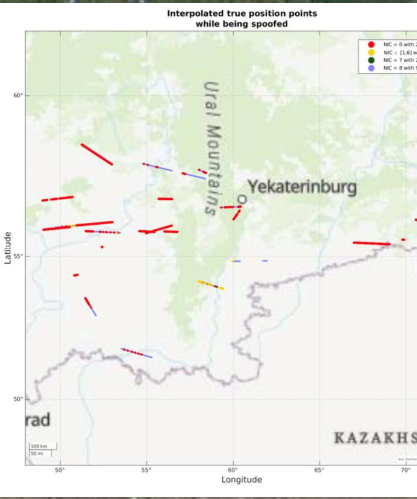
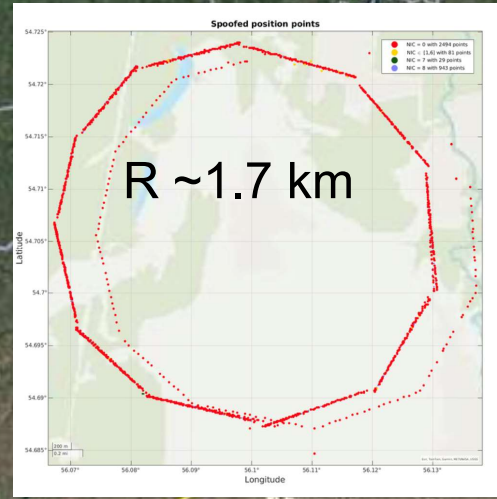
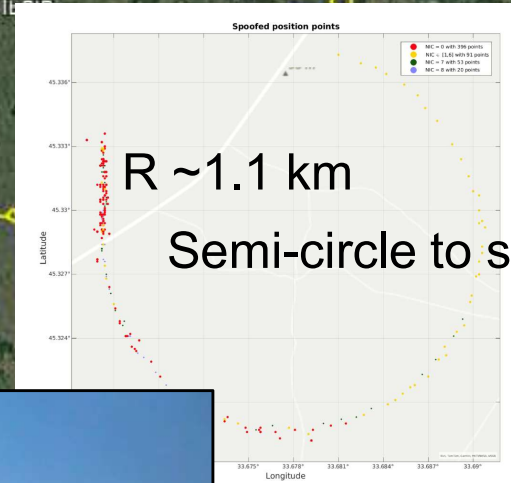
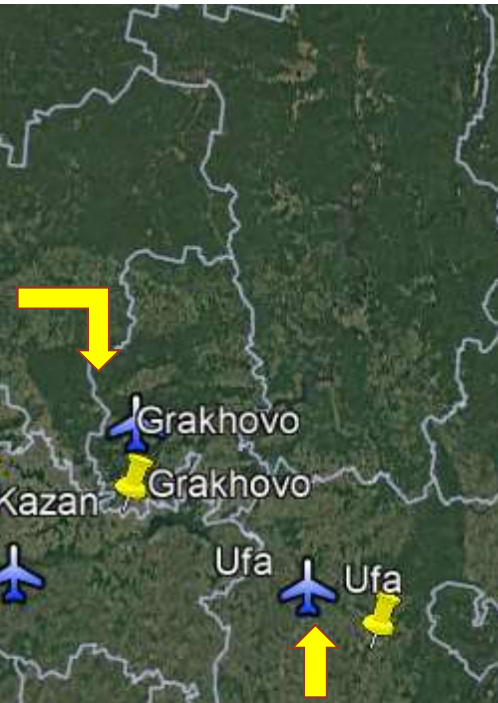
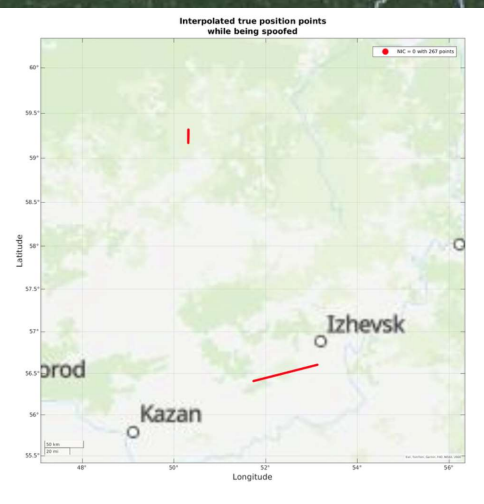
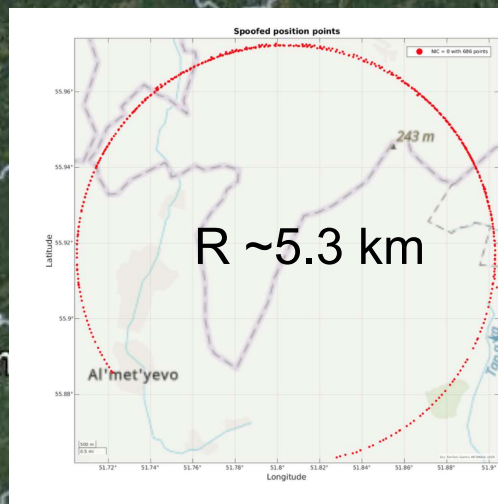
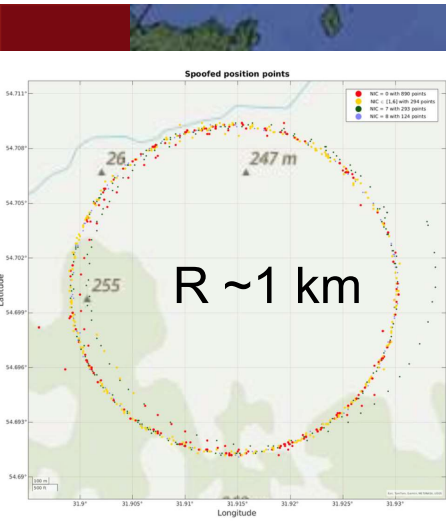
What are the effects of observed spoofing dynamic tracks autonomous aircraft?

Image generated by chatgpt



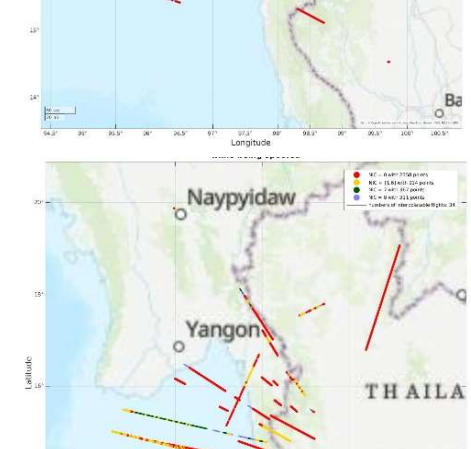
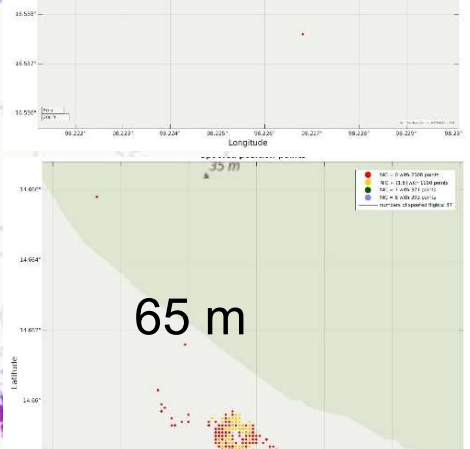
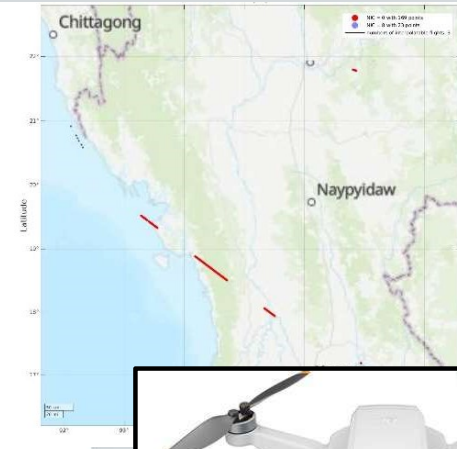
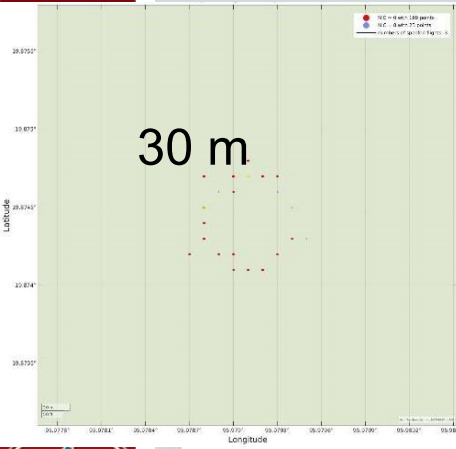
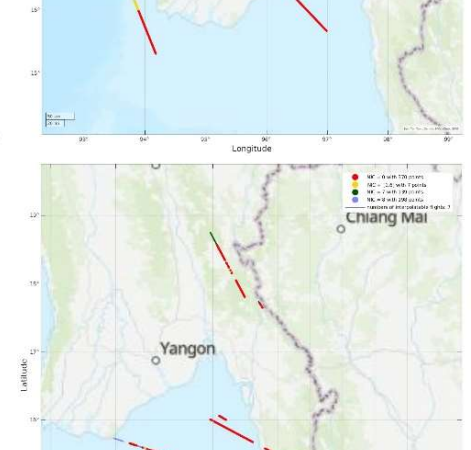
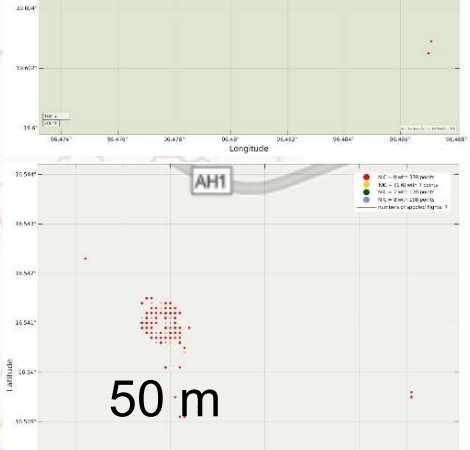
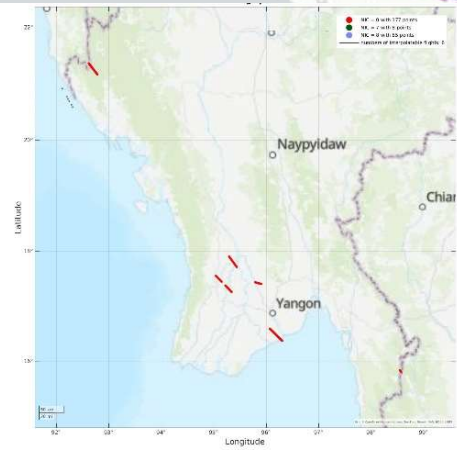
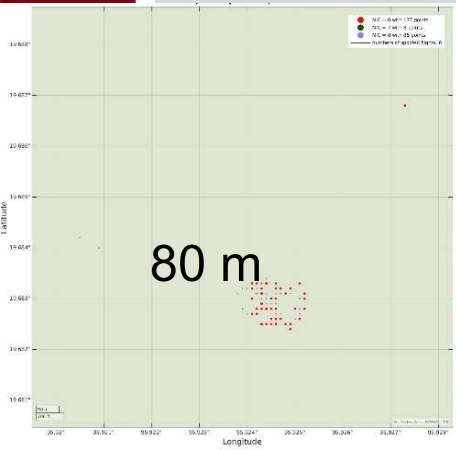
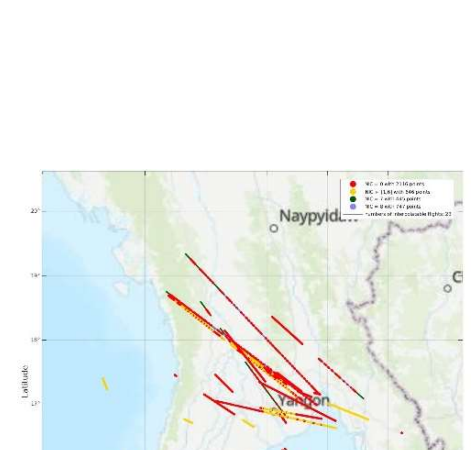
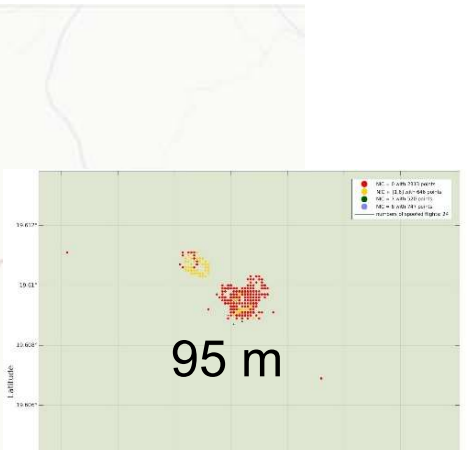
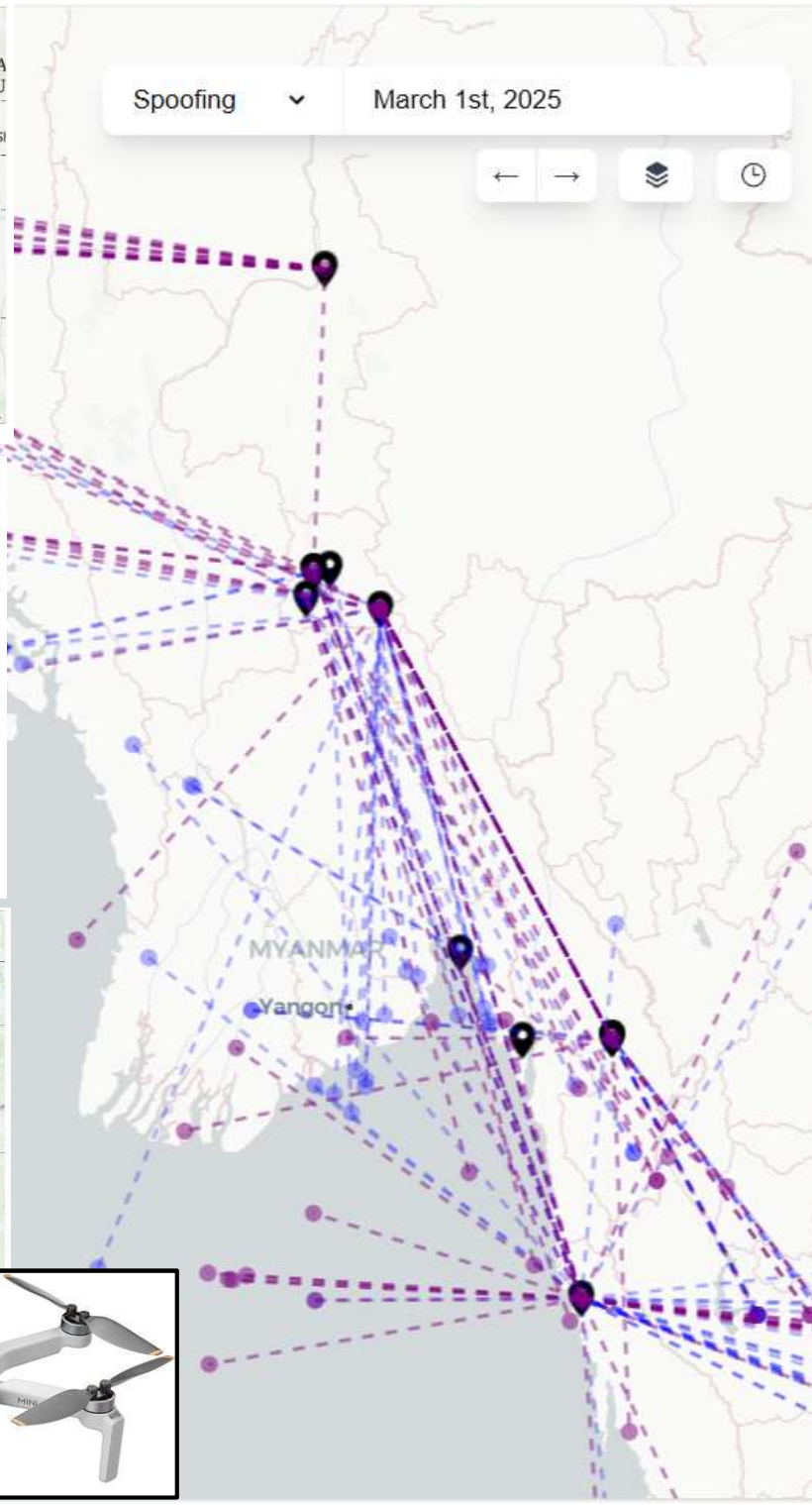
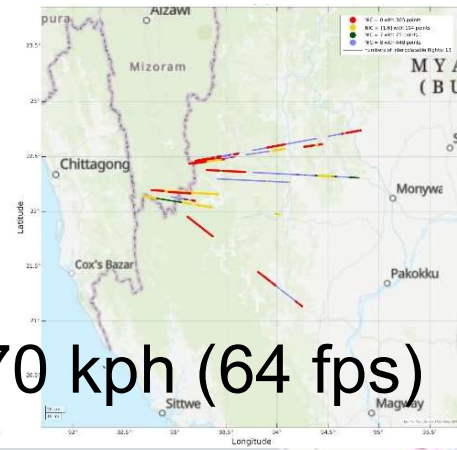
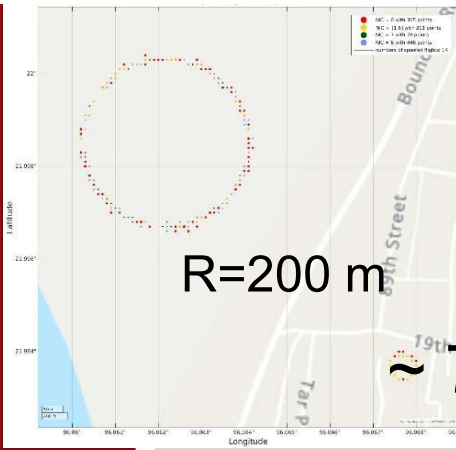
2. Worldwide Spoofing Patterns (2025)





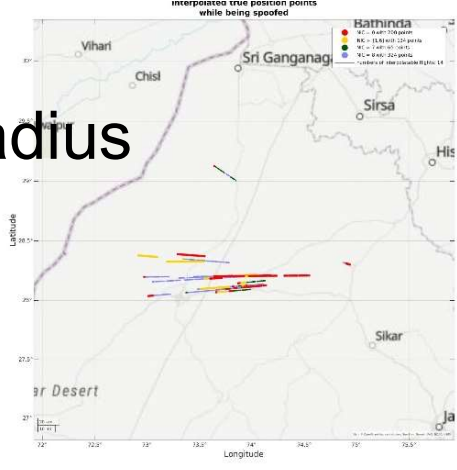
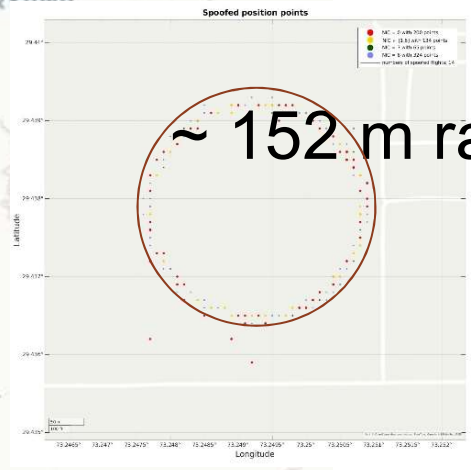
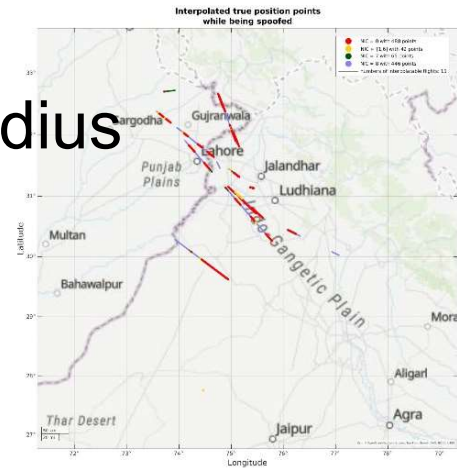
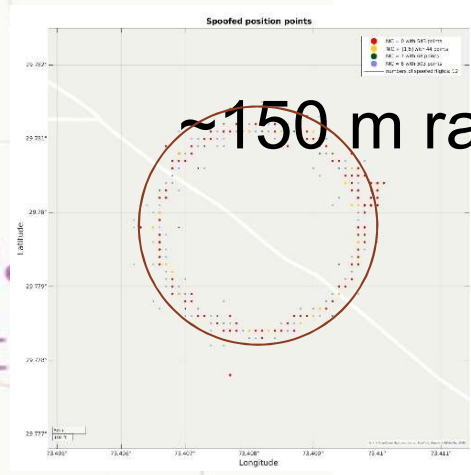
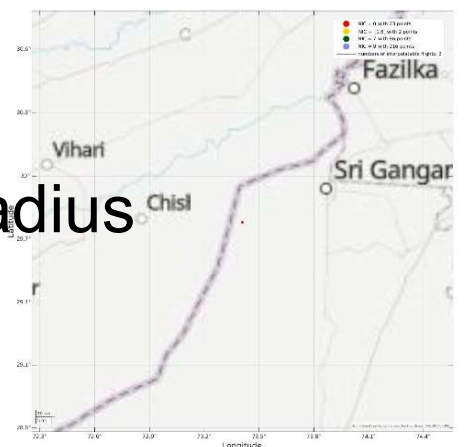
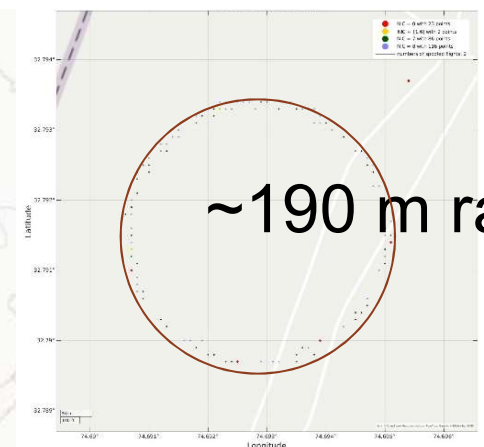
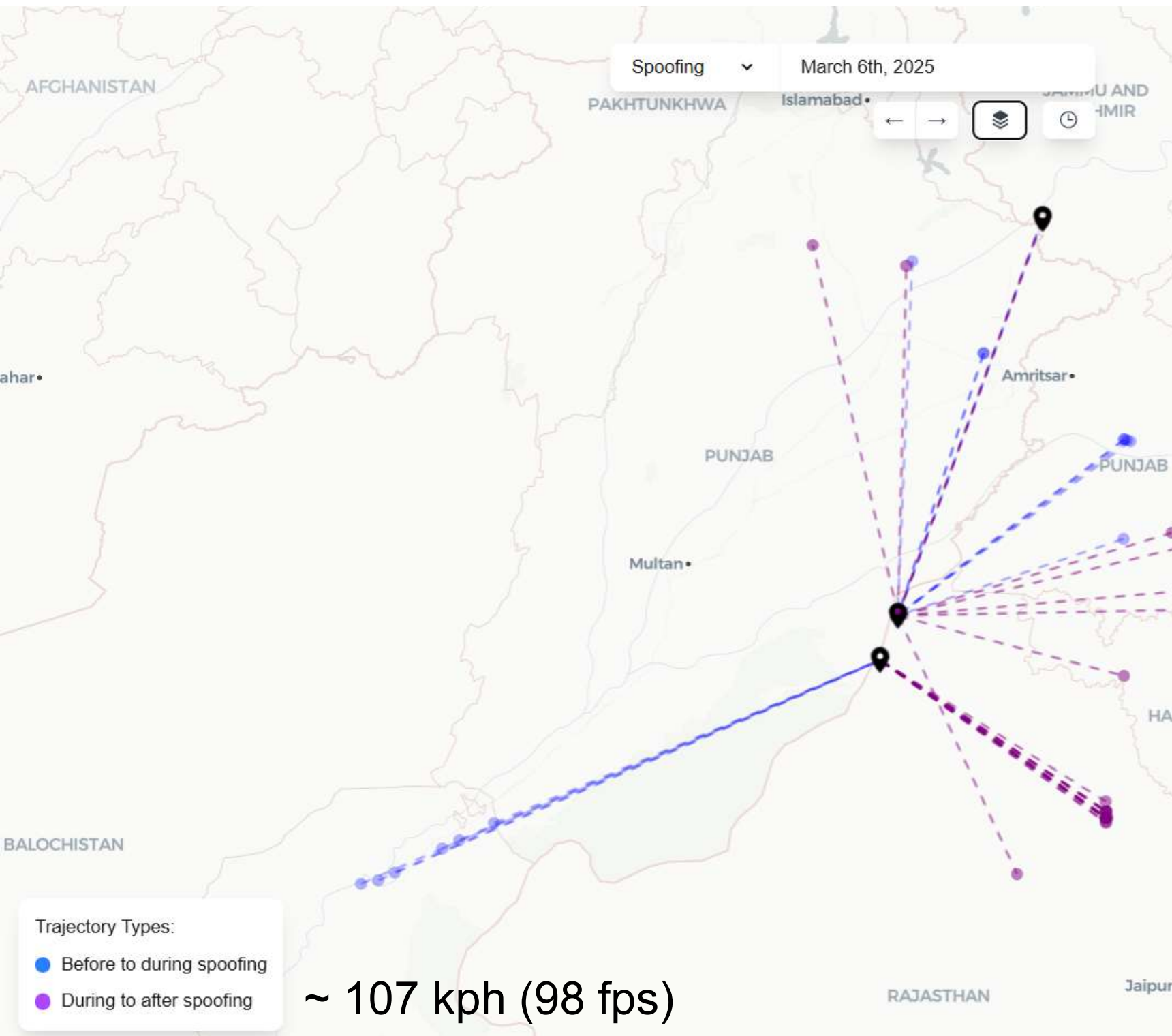
$\sim 200 \text{ kph (182 fps)}$ at Smolensk





● Before to during spoofing
 ● During to after spoofing





3. Simulation Model for Testing Spoof Pattern Effects

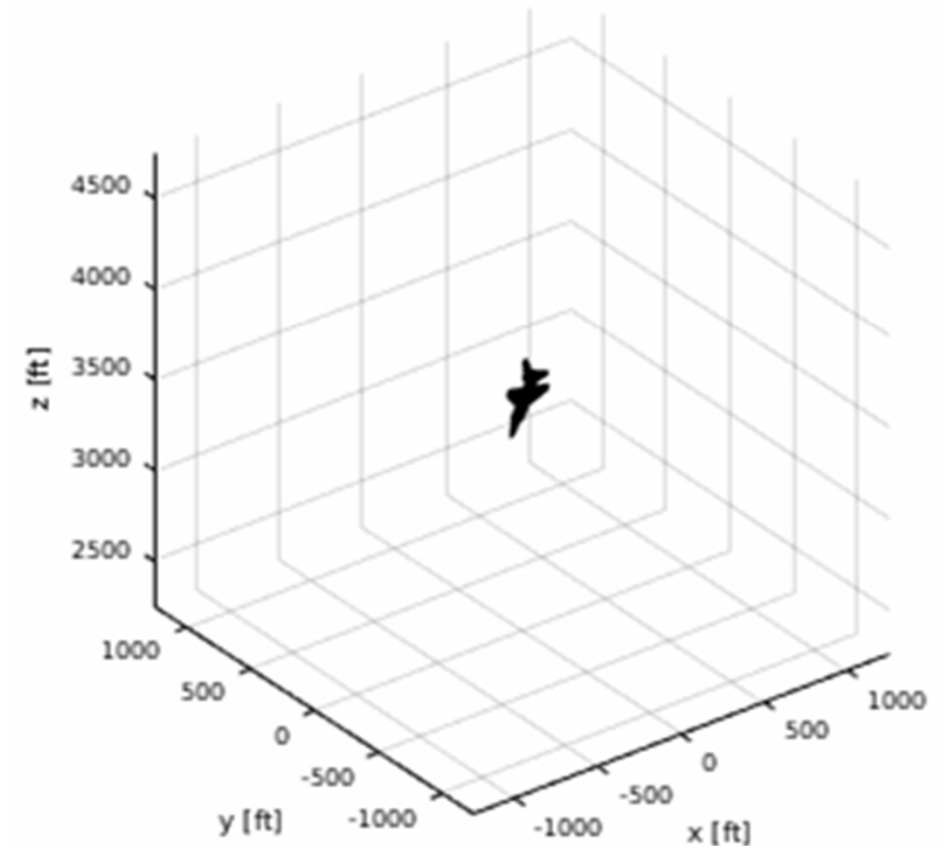
➤ AeroBenchVV F-16 simulator

- F-16 dynamics model – fixed wing aircraft
- Built to model ground collision avoidance
- “Simple” but nonlinear dynamics models
- Built-in control system and variable flight limits
- Able to follow waypoints
- Autonomous maneuvers

➤ Simulation model modified to test

- Different levels of GNSS dependency (Information provided primarily by GNSS)
- Different flight tracks/target location relative to spoof
- Different spoof patterns (circle, polygon, figure 8, approach)

t = 0.00 sec Waiting
h = 3500.00 ft V = 540.00 ft/s
 $\alpha = 2.12$ deg $\beta = 0.00$ deg
 $N_z = 0.17$ g $p_s = 0.00$ deg/s
 $[\phi \theta \psi] = [45.0, -72.0, -45.0]$ deg



Caveats

- F-16 simulation model may not represent the target vehicle(s)
 - Scale up spoof trajectory speed to be comparable to F-16 flight speed
- Simple sensor models – no fusion with GNSS, cross checking, no sensor error
- Simple binary spoofing effects (either completely genuine or completely spoofed)

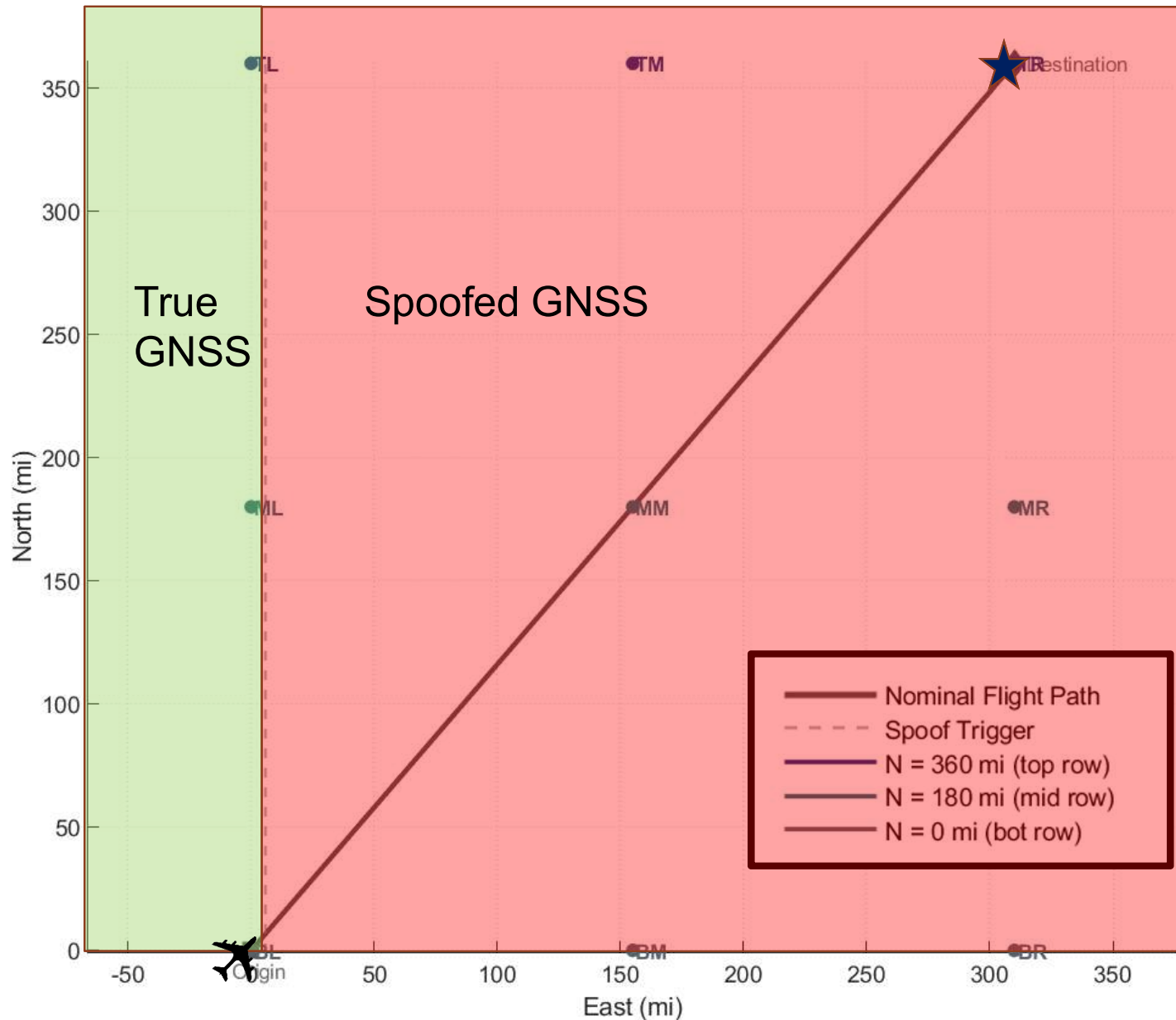


Cases for Information Spoofed

- P = spoofed GNSS horizontal position used
 - V = spoofed GNSS velocity used
 - H = heading generated using spoofed GNSS position
 - A = altitude from spoofed GNSS vertical position
-
- If the letter is present, that information is from the spoofed GNSS and used by the aircraft guidance navigation & control (GNC)
 - i.e. PVA means that the aircraft GNC uses spoofed position (horizontal, vertical) and velocity from GNSS



Flight Scenario Overview



- Spoofed information is used once aircraft crosses spoof line
- Several spoofed locations are tested (examples use location TM)

4. Example Scenarios Presented

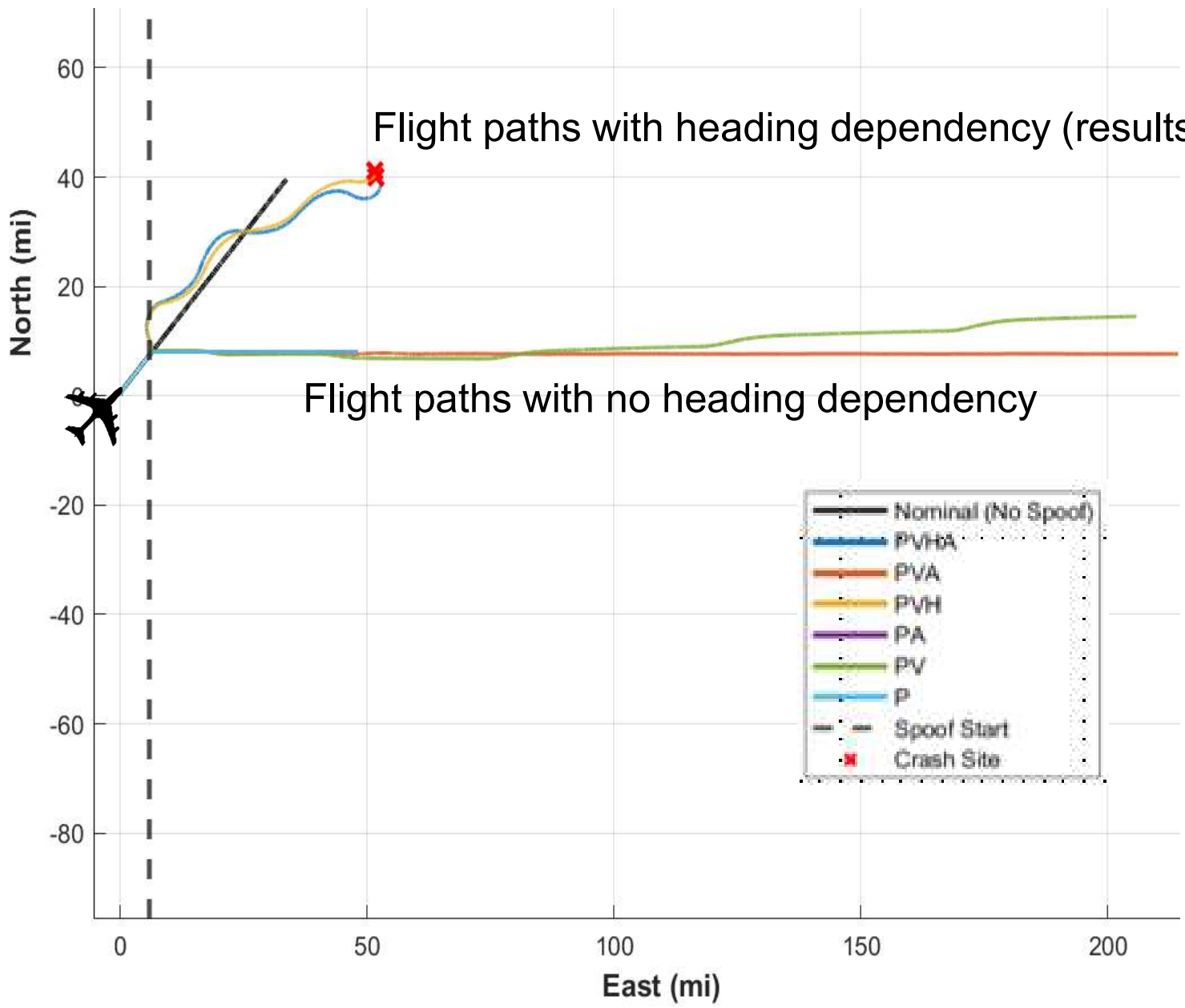
- Circle of different radius
- N sided regular polygon
- Approach & landing
- Figure 8

- Velocity, Radius increased from those seen due to F-16 model
 - F-16 cruises at around 850 ft/s; stall speed of ~330 ft/s

Spooft Shape	Parameter Name	Sweep Values (Imperial)
1. Circle Pattern	Orbit Velocity	[300, 550, 800, 1100] ft/s
	Orbit Radius	[1000, 5000, 15000, 30000] ft
	Orbit Direction	Clockwise, Counterclockwise
2. Polygon Pattern	Vertex Count	[3, 4, 6, 8, 12]
	Polygon Radius	[2500, 10000, 25000, 40000] ft
	Track Velocity	[300, 550, 800, 1100] ft/s



Scenario: Circle Spoofed Track Example



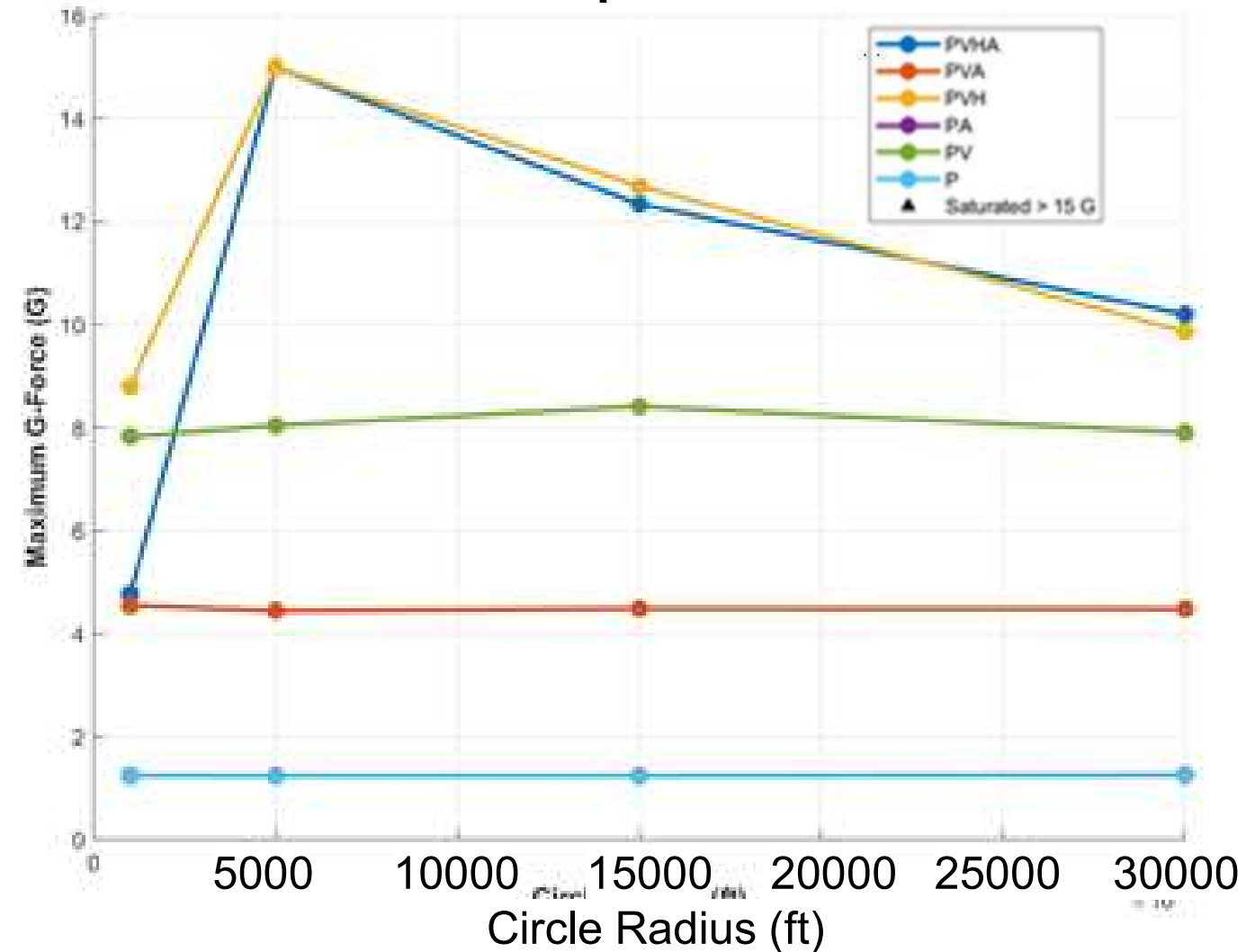
All crashes (mostly stalls) with this spoofing had a dependency on GNSS for heading (H). There are no cases an aircraft having true heading crashes



Effect of Circle Size/Radius

- Increasing radius generally results in reducing maximum G force on cases where spoofed heading is used
- Radius does not affect maximum G load in cases where true heading is known

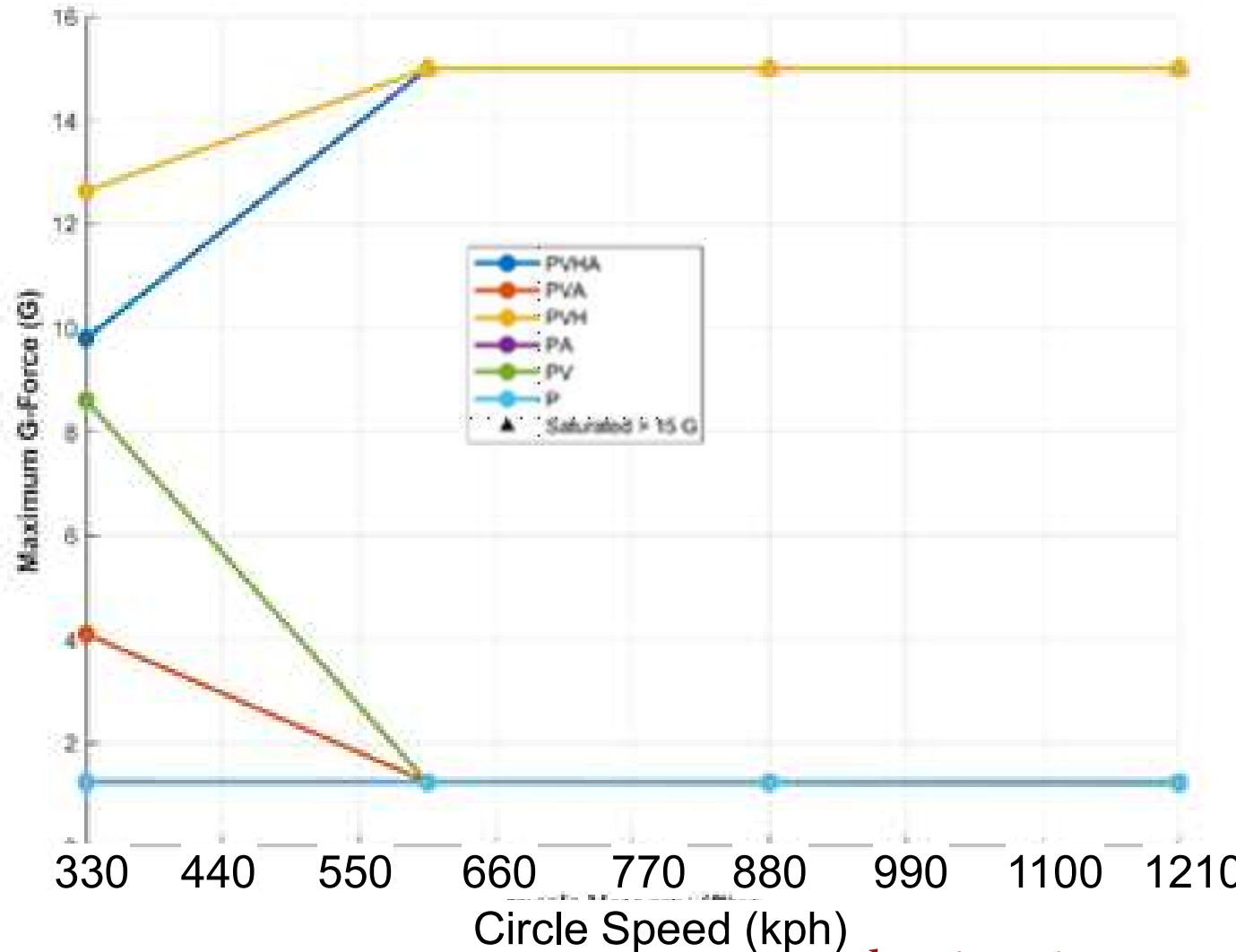
Max G Force Experienced vs Circle Radius



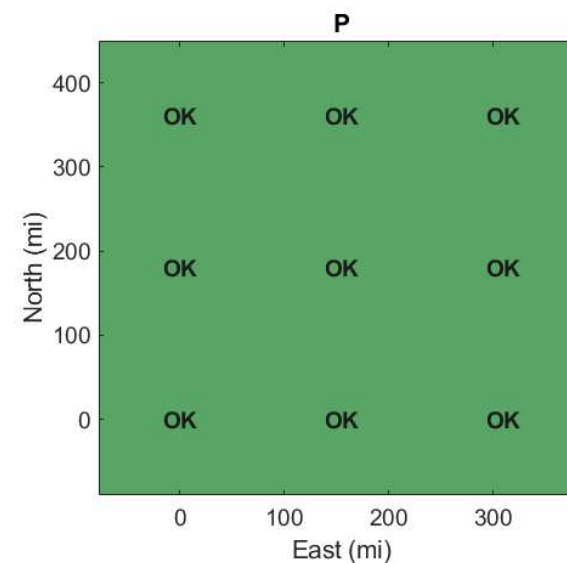
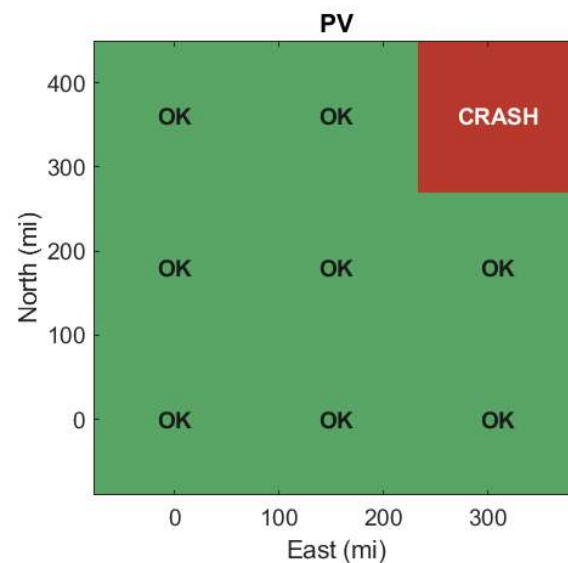
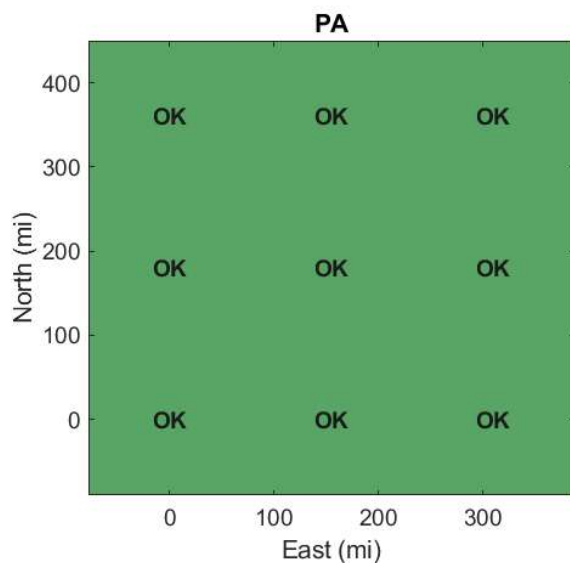
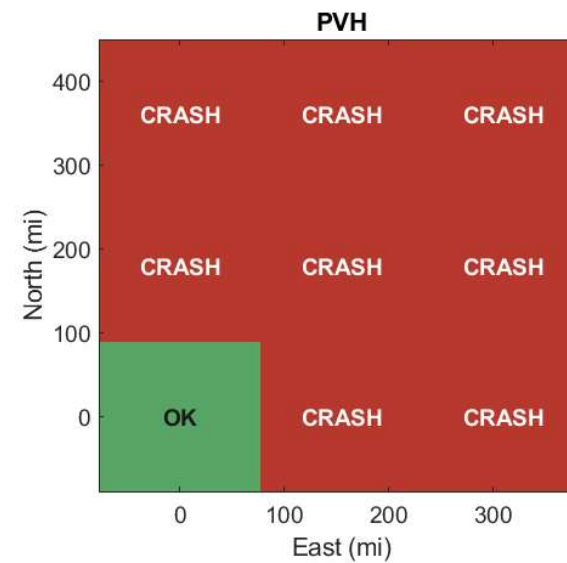
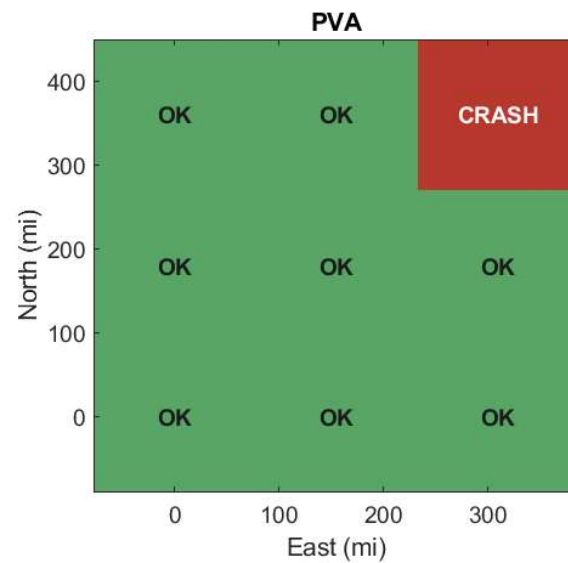
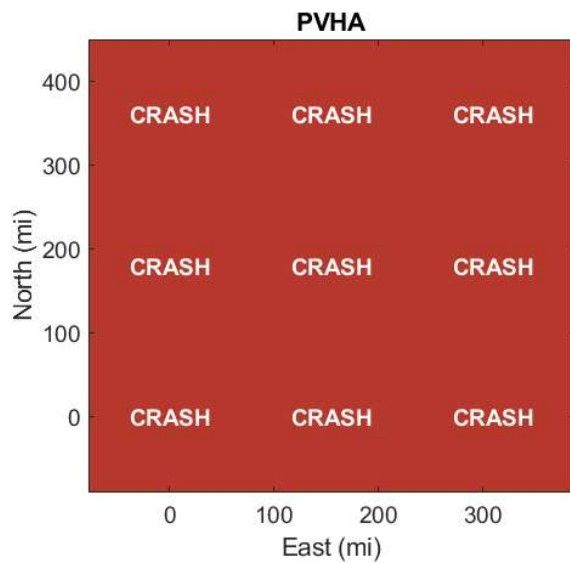
Effect of Spoofed Speed (Circle Track)

- Generally higher G forces at low speed – due to aircraft being below stall speed
- At higher speeds, low G load unless true velocity/heading is not known
 - PVH, PVHA lead to crashes

Max G Force Experienced vs Circle Trajectory Speed



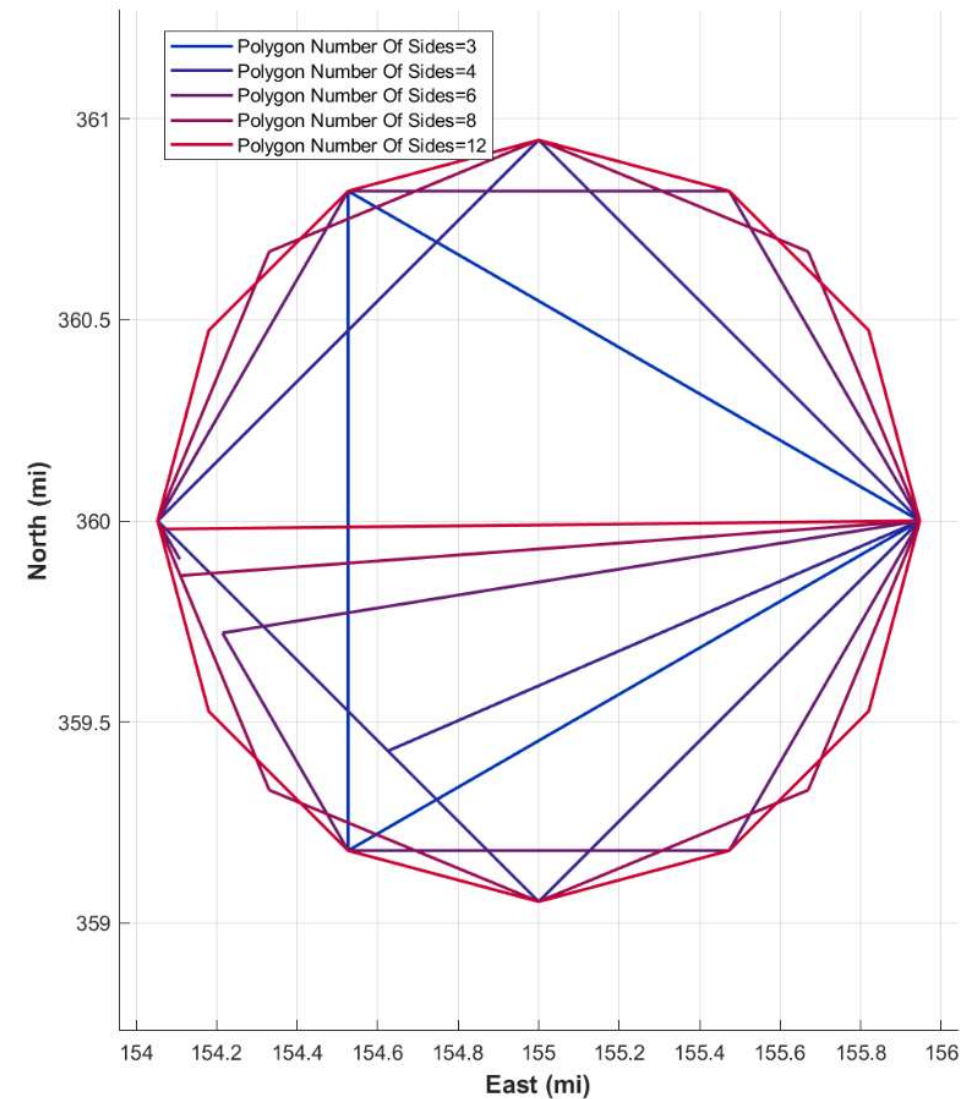
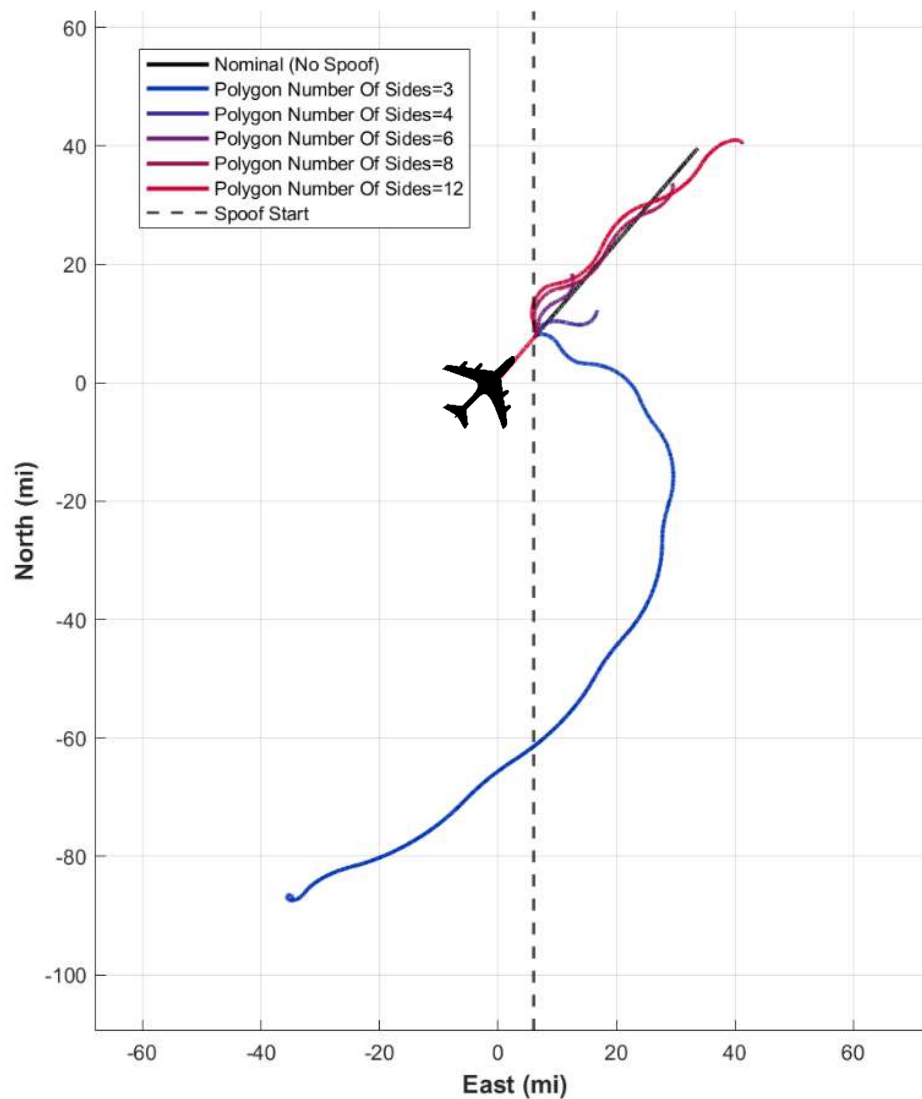
Circle Spoofing Crash as a Function of Spoof Location



- $R = 5,000 \text{ ft}$
- $V = 500 \text{ ft/s}$
- Spoofed position doesn't determine IF you crash... heading dependency does
- Spoofed position determines how fast you crash. Time to Crash (TTC) varied (56s to 207s) for the same sensor mode and same circle parameters
- TTC for different radius varied from 56s to 200s
- TTC for different speeds varied from 59s to 111s



Scenario: Regular Polygon under condition PVH (R = 5000 ft)



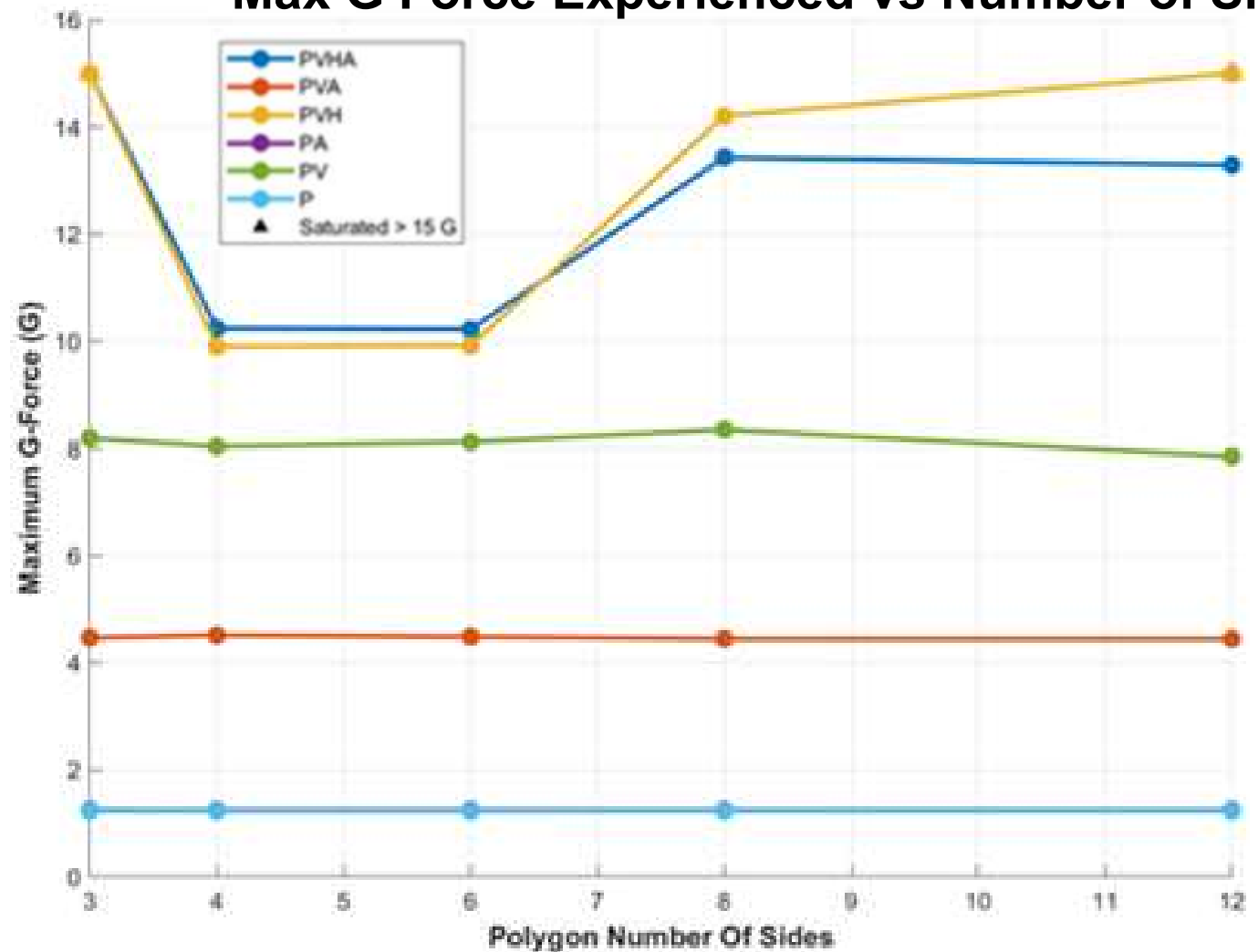
All crashes with this spoofing had a dependency on GNSS for heading (H) (every case) whereas no cases with true heading has a crash.



Effects of Polygon Shape (Number of Sides)

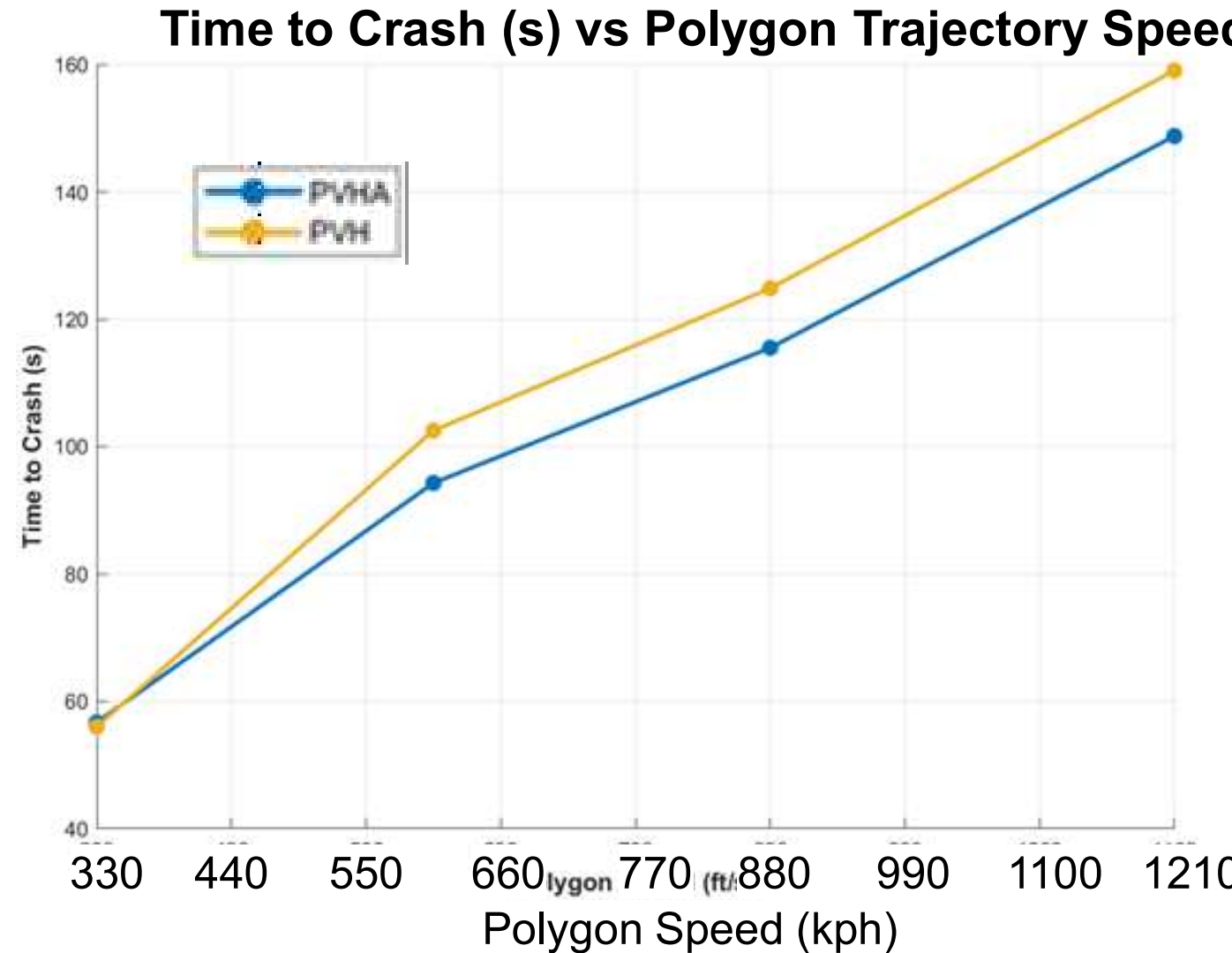
- Effect of different number of sides of polygon
 - Same flight spoofed flight speed, radius (& center)
- Maximum G force relatively constant as a function of number of sides IF heading is not spoofed
- Maximum G varies if spoofed GNSS derived heading is used

Max G Force Experienced vs Number of Sides



Effect of Spoofed Speed (Hexagon Track)

- Slower spoof speed results in faster crashes since aircraft tries accelerate to increase speed
- Without true velocity/heading this increase speed results in stall and crashes



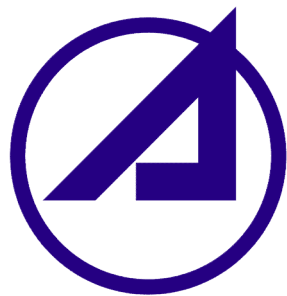
Summary

- Many different GNSS spoofing patterns are now seen worldwide with circular tracks of various sizes and speeds being the most common
- Developed a simulation model based on F-16 to test the effects of different patterns and levels of GNSS dependency has on aircraft
- Different spoofing patterns/parameters and aircraft GNSS dependency affects whether it is misdirected or crashes
 - Aircraft with independent heading source for GNC avoided crashing
 - Parameters of spoofing affects (location, speed, etc.) how fast the crash occurs
 - Highlights importance of cross-checks and careful integration



Acknowledgements & Disclaimer

- The authors gratefully acknowledge the support of the FAA, The Aerospace Corporation, and CARNATIONS/Department of Transportation.
- The views expressed herein are those of the authors and are not to be construed as official or any other person or organization.



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