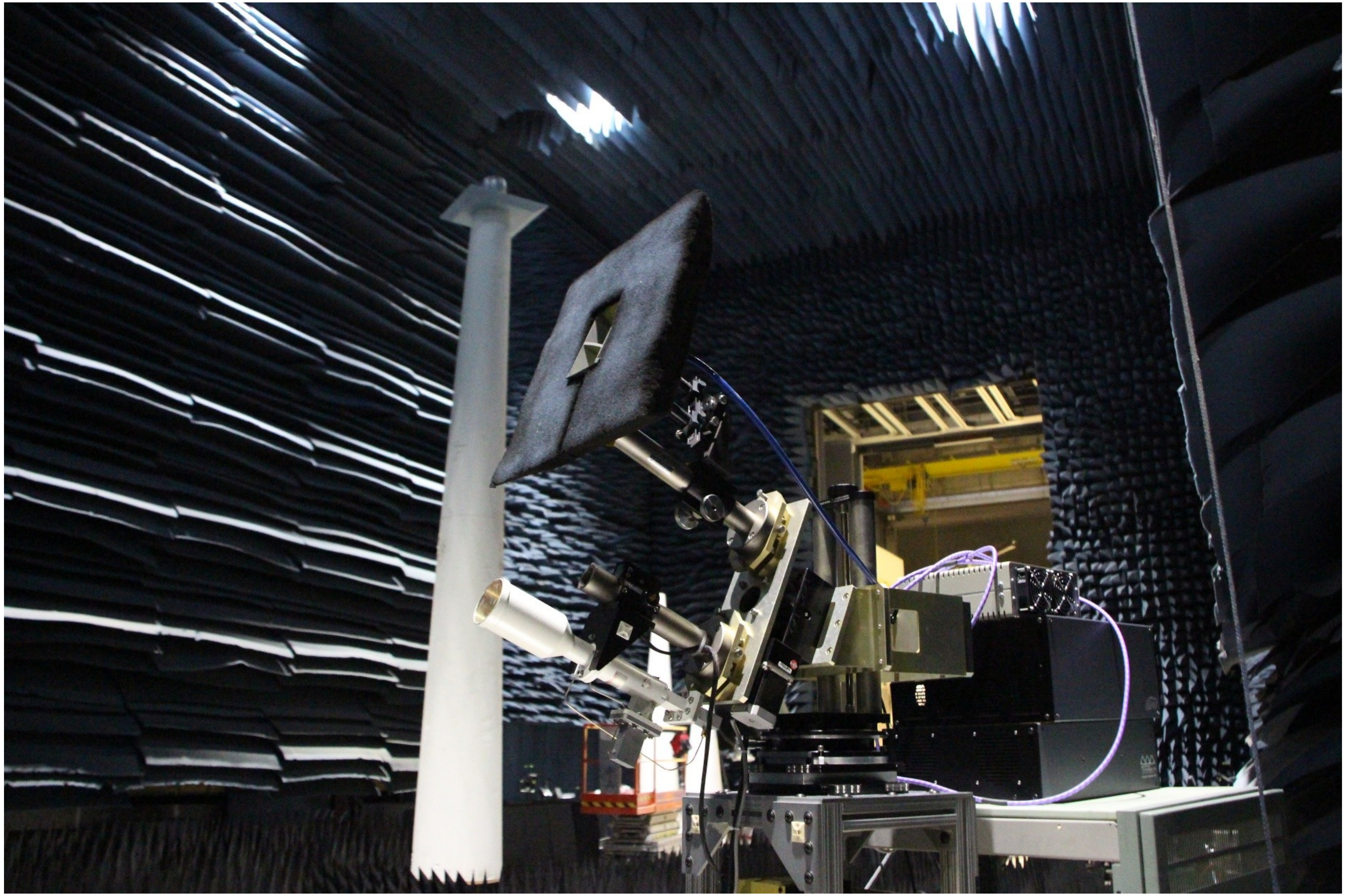
Commercial Airborne Radar Evaluation & Recommendations



April 23, 2021
George Szatkowski D320
Larry Ticatch D319
Christopher Morris D320
Chester Dolph D201
Mahyar Malekpour D320
Angelo Cavone D304

Outline

- Radar Performance Specifications
- Free Space Propagation Loss
- Transmitting Antennas
- 2018 Radar Cross Section (RCS) Measurements
- 2018 Antenna Measurements
- Doppler Rail Measurements
- 2019 -2021 Flight Data Assessments
- Conclusions & Recommendations

Radar Specifications

Object Detection parameters	
Object RCS	-50 to +100 dBsm ;0 dBsm target at 2500 meters
Range	Minimum 20 meters, Maximum 5987 meters operational
Range Resolution	Waveform dependent
Velocity Resolution	Waveform dependent
Angular Resolution	±1° Az and ±3° El in Search Mode, smaller for tracked targets
Search & Track	
Search	User configurable scan volume
Track acquisition	New tracks acquired in < 1 sec
Track updates	10 updates /sec (for each track)
Max Tracks	20 simultaneous tracks dynamically allocated via i-SCAN
Modes	Search & Search-While-Track
Operation center frequency	24.45-24.65 GHz (Default – FCC Radio Navigation Band) Unit will function from 24.0 to 24.7 GHz in any 200MHz sector
Operating bandwidth	Baseline Configuration: Mode A1 (45MHz swept BW Channel A1-A 24.4675 to 24.5125 GHz (Fc=24.49 GHz / 45MHz swept BW) Channel A1-B 24.5275 to 24.5725 GHz (Fc = 24.55 GHz / 45MHz swept BW) Channel A1-C 24.5875 to 24.6325 GHz (Fc = 24.61 GHz / 45MHz swept BW) **Note: All channels fully functional.** Note: NTIA spectrum mask allows for about 15MHz overshoot on each edge.

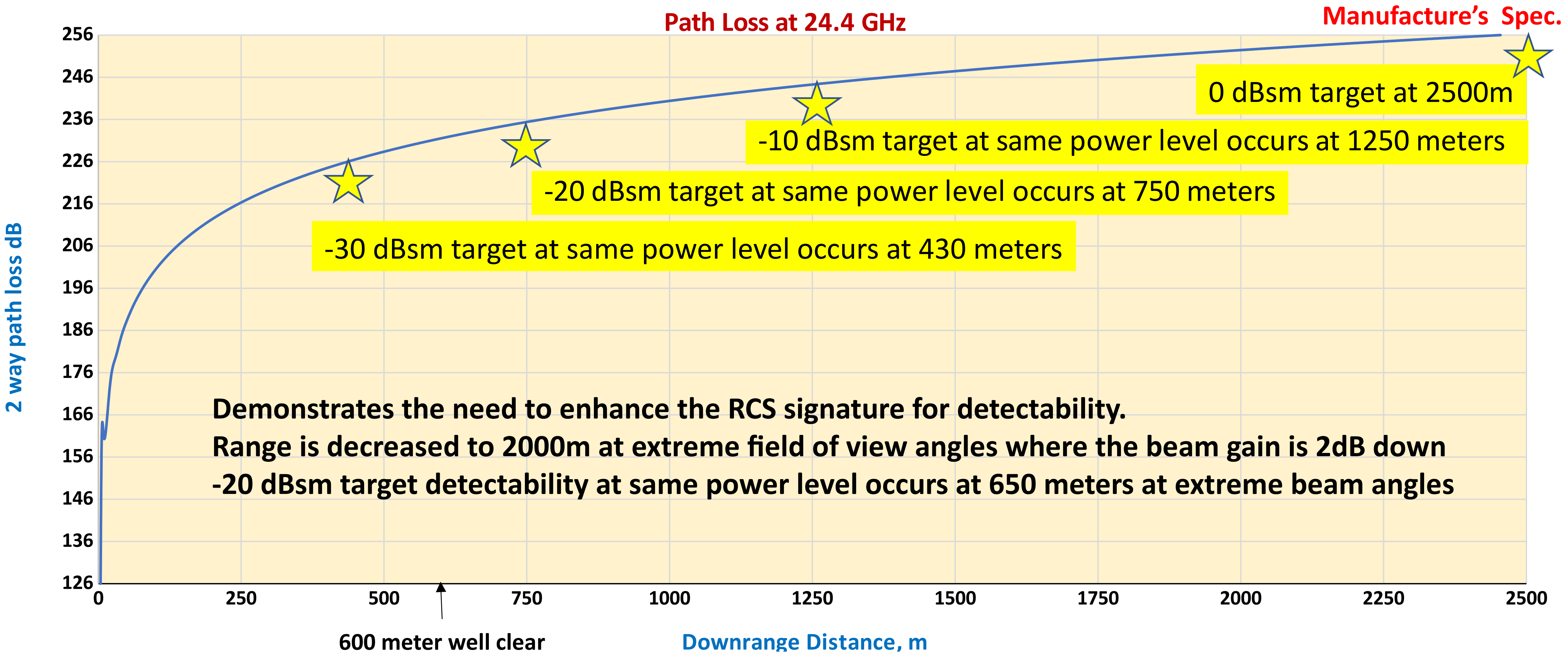
Free Space Propagation Loss – Radar Equation

Path loss in dB:

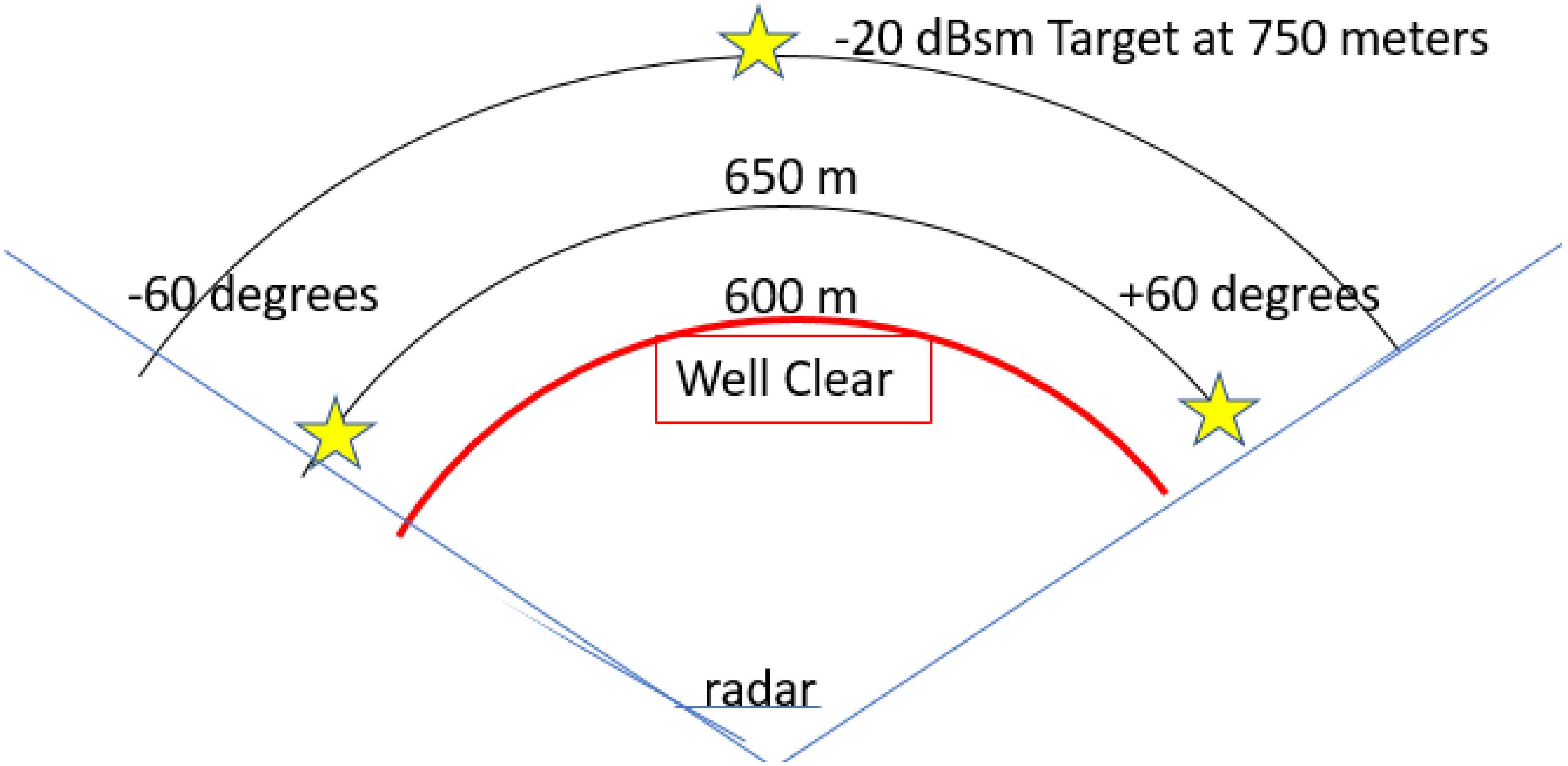
$$L = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right)$$

- Power density at a range R from an isotropic antenna $= \frac{P_t}{4\pi R^2}$ W/m²

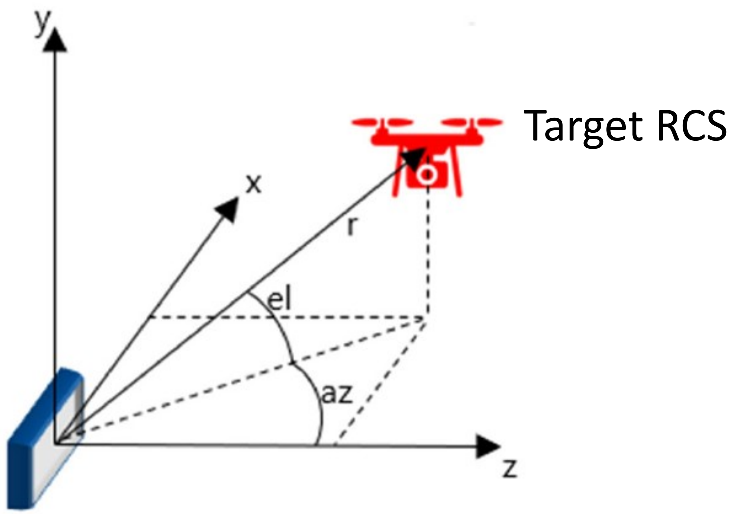
$$P_r = \frac{P_t G^2 \lambda^2}{(4\pi)^3 R^4}\sigma$$

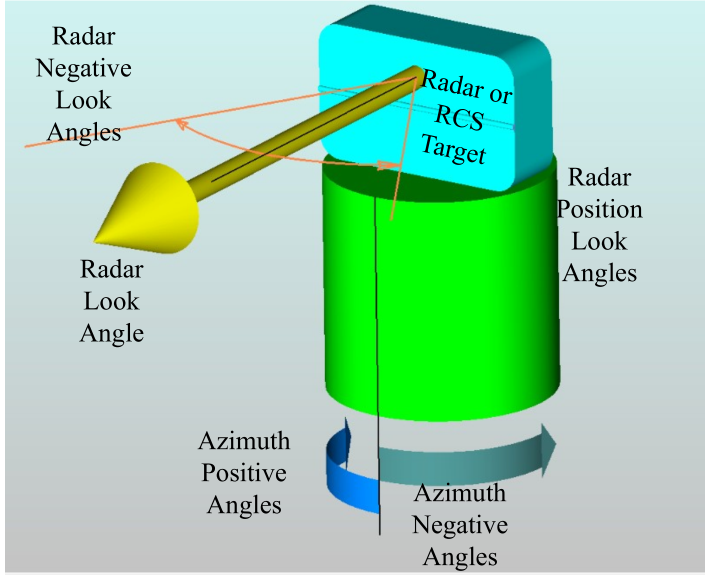


Detection range for -20 dBsm target



Coordinate System

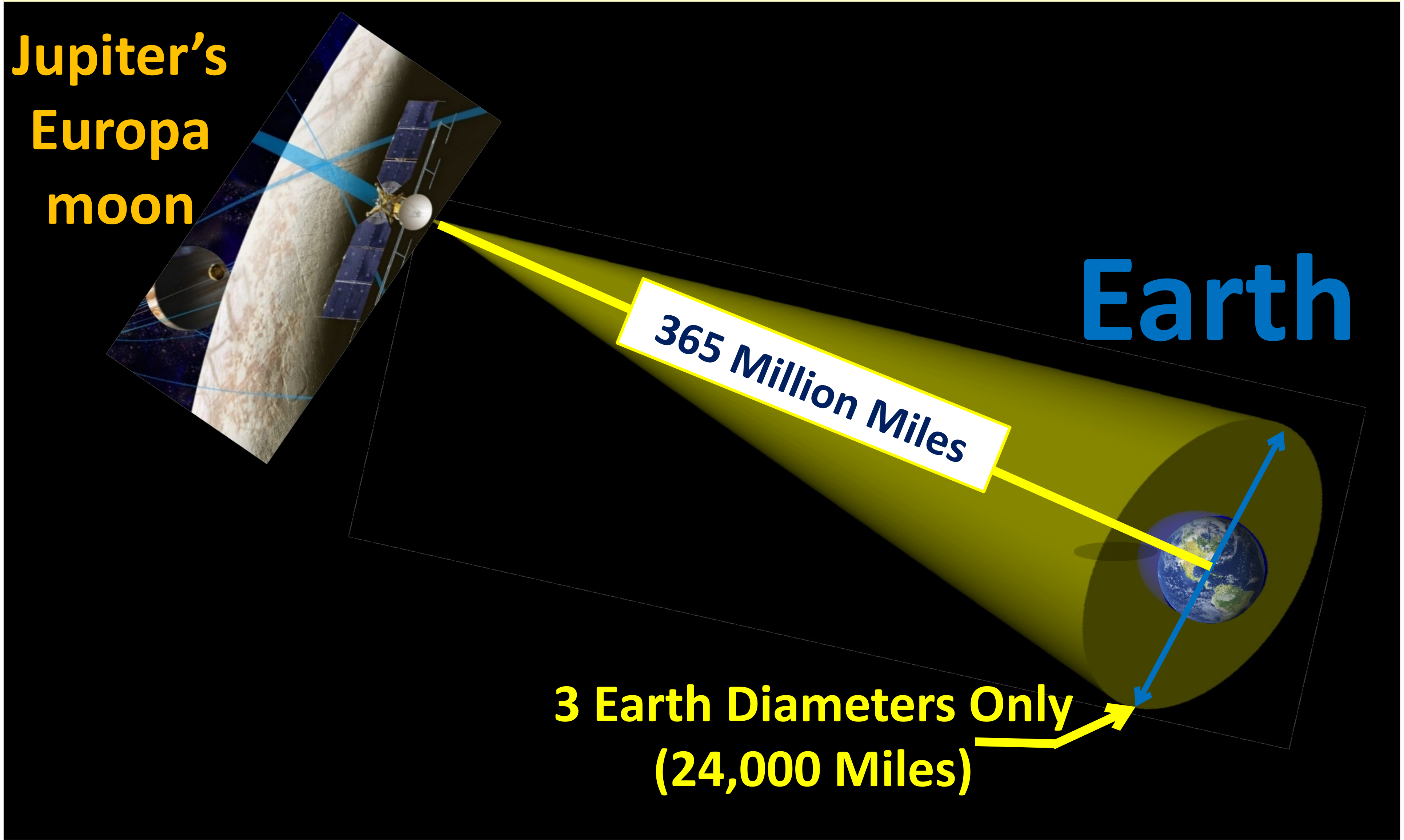




Coordinate system for azimuth cuts.

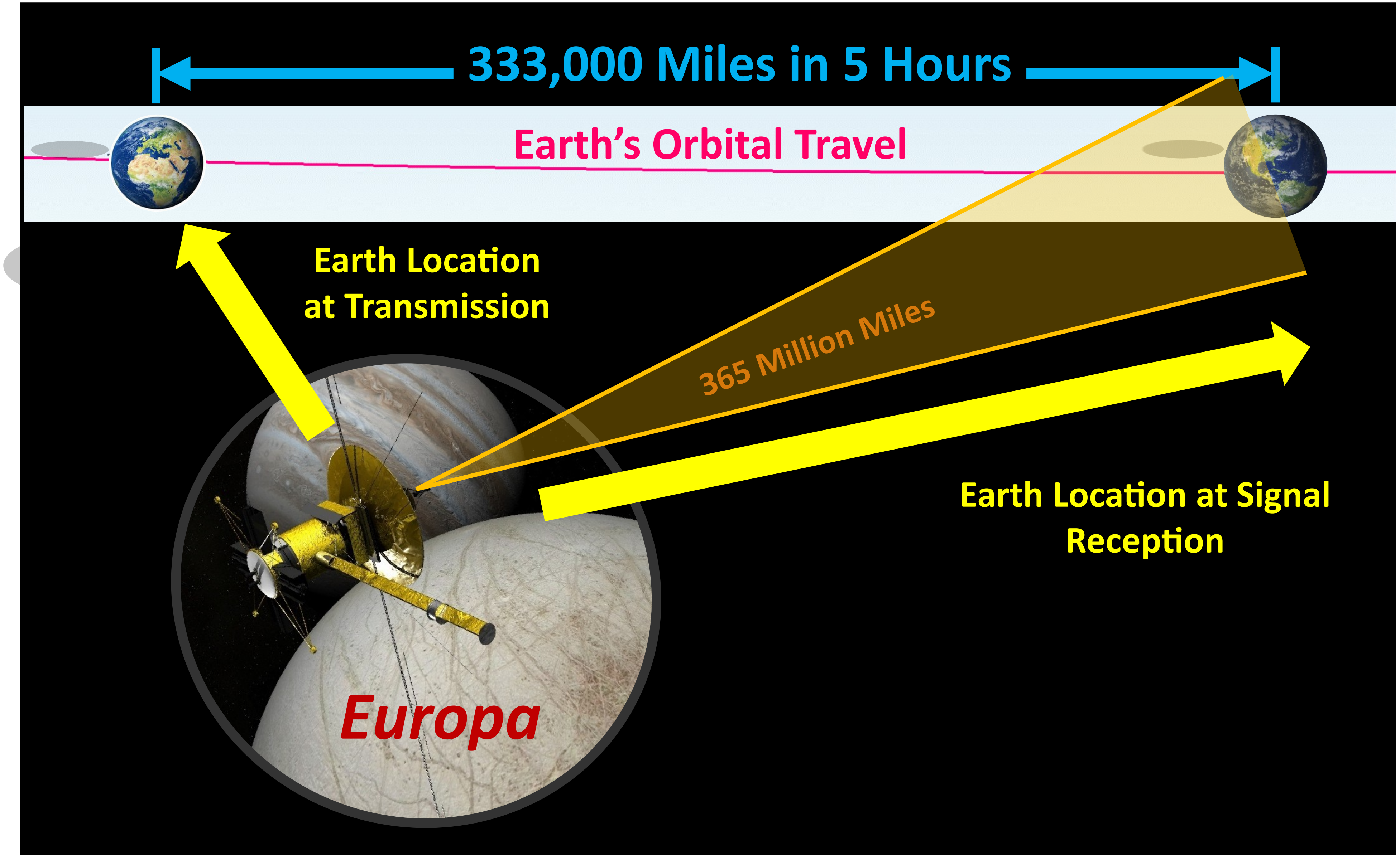
Rotational measurements with 2 axes require understanding the differences between Great circle and Conical cut rotations. Need same axis of rotation.

Understanding High Gain Antenna Measurements

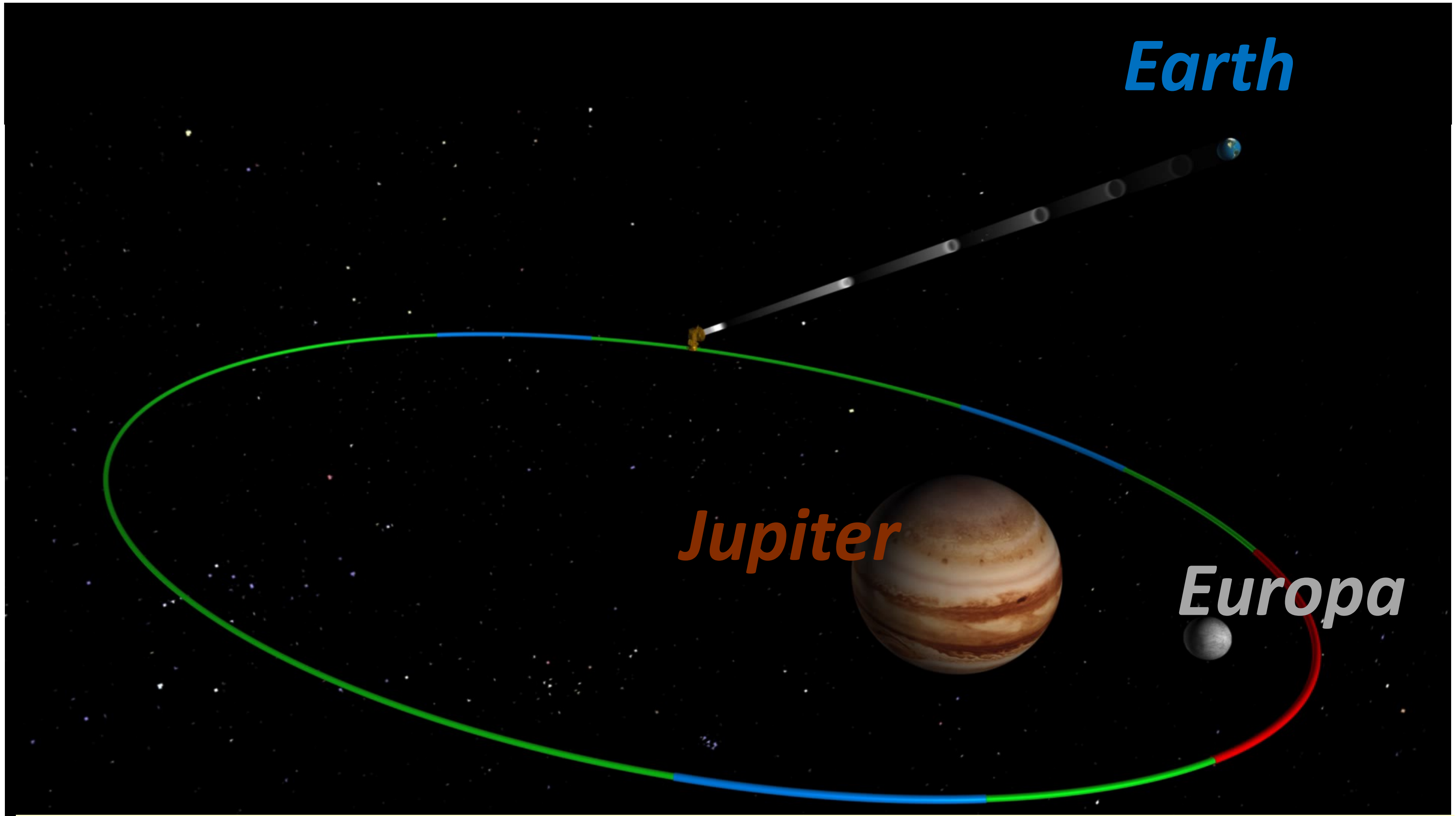


Transmitting Antennas

Understanding High Gain Antenna Measurements in Motion



Transmitting Antennas

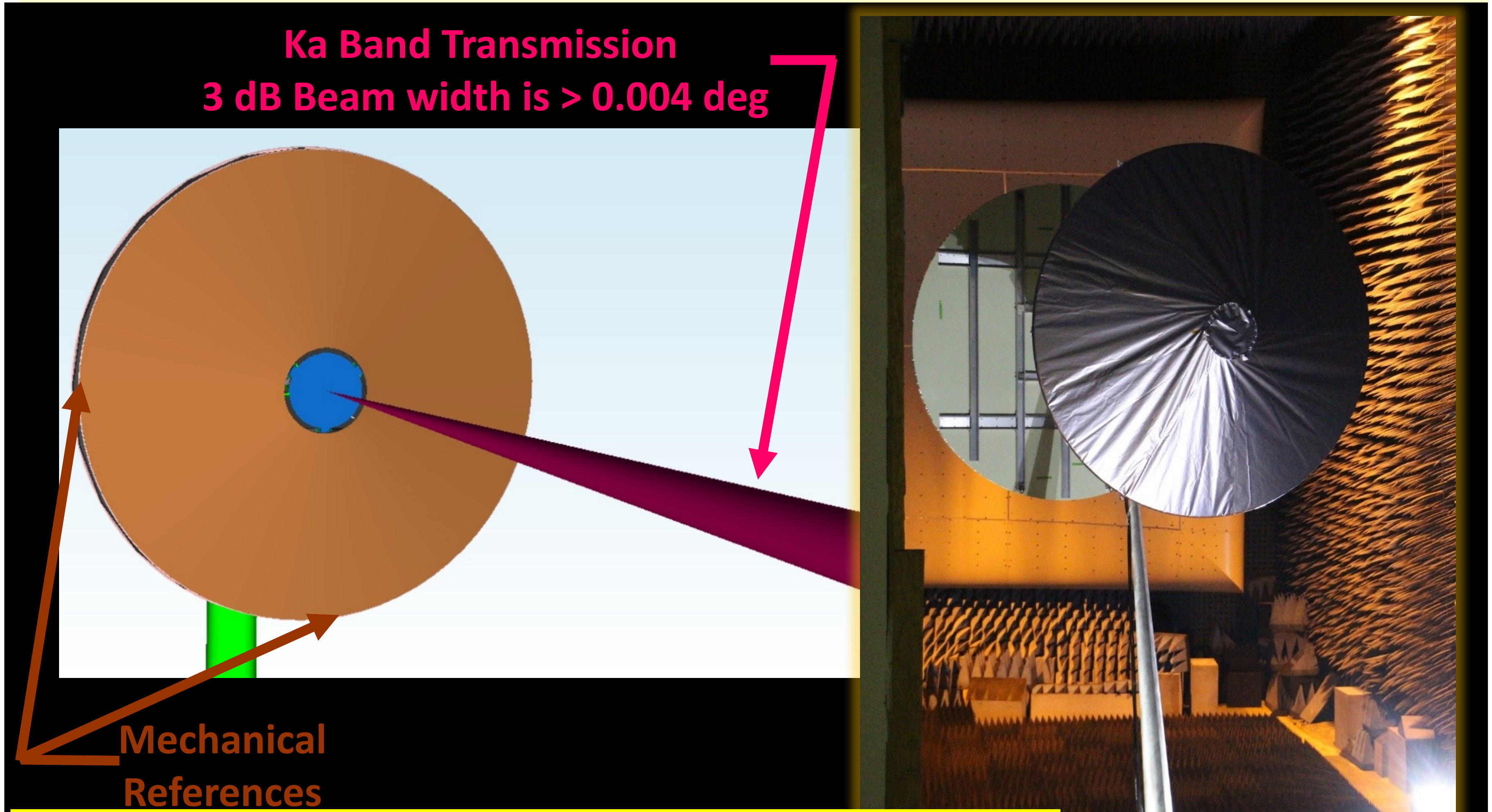


Europa Clipper Transmission to Earth

PLAY

Transmitting Antennas

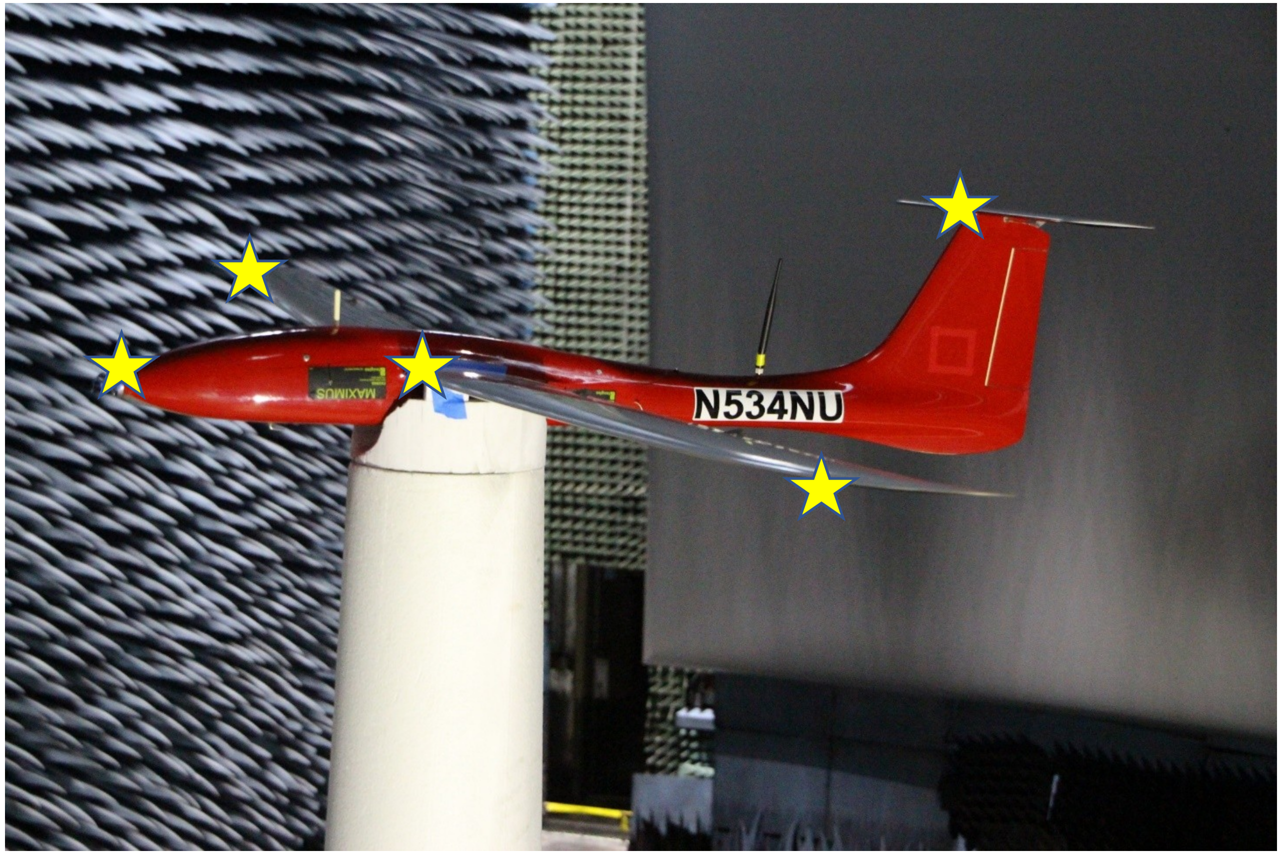
Antenna radiation pattern must be documented.



1. Schulze, Ron; Bray, Matthew; Ticatch, Larry A; Szatkowski, George; Cavone, Angelo; Flores, Nate; VanDelinder, Chris; Ayers, Matthew; Draszt, Michael; Boucher, Rick; Rooks, John: ***"Resurfacing the NASA Langley Experimental Test Range Reflector."*** IEEE **ISSN:** 2474-2740, November, 2018.

Radar Cross Section

RCS in dBsm is a function of frequency. 0 dBsm at 24.5 GHz
This radar produces RCS estimates are Range bin Amplitudes
Not a coherent sum of the scattering points at a frequency.



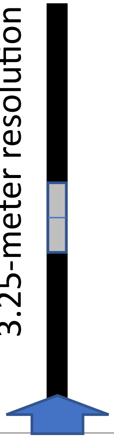
- Horizontal E field illuminates leading edges - Vertical E field illuminates trailing edges
- Specular returns are best – perpendicular alignment of a broadside surface, nose on, tail on.

Radar Size Imagery

www.uml.edu/Research/STL/

delta x = c / (2 * delta f)

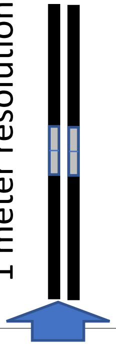
3.25-meter resolution



45 MHz Bandwidth Radar

https://apps.dtic.mil/dtic/tr/fulltext/u2/a462278.pdf

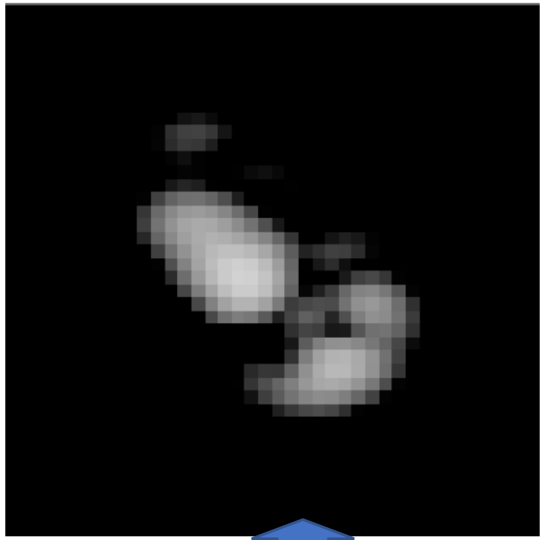
1 meter resolution



170 MHz Bandwidth
&
2 Passive Antennas

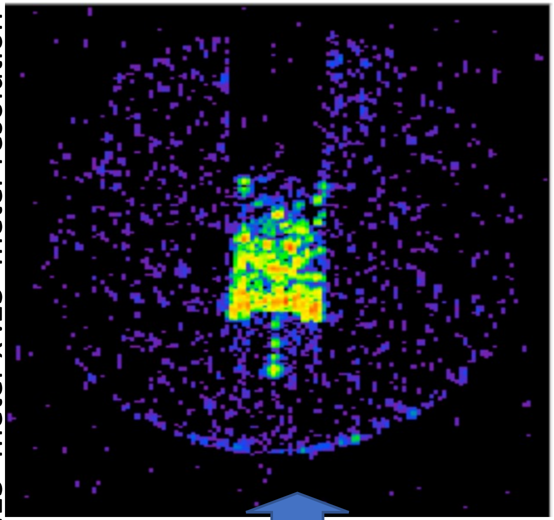
https://apps.dtic.mil/dtic/tr/fulltext/u2/a461644.pdf

1 meter x 1 meter resolution



171 MHz Bandwidth Radar

.15- meter x .15- meter resolution



2 GHz Bandwidth Radar

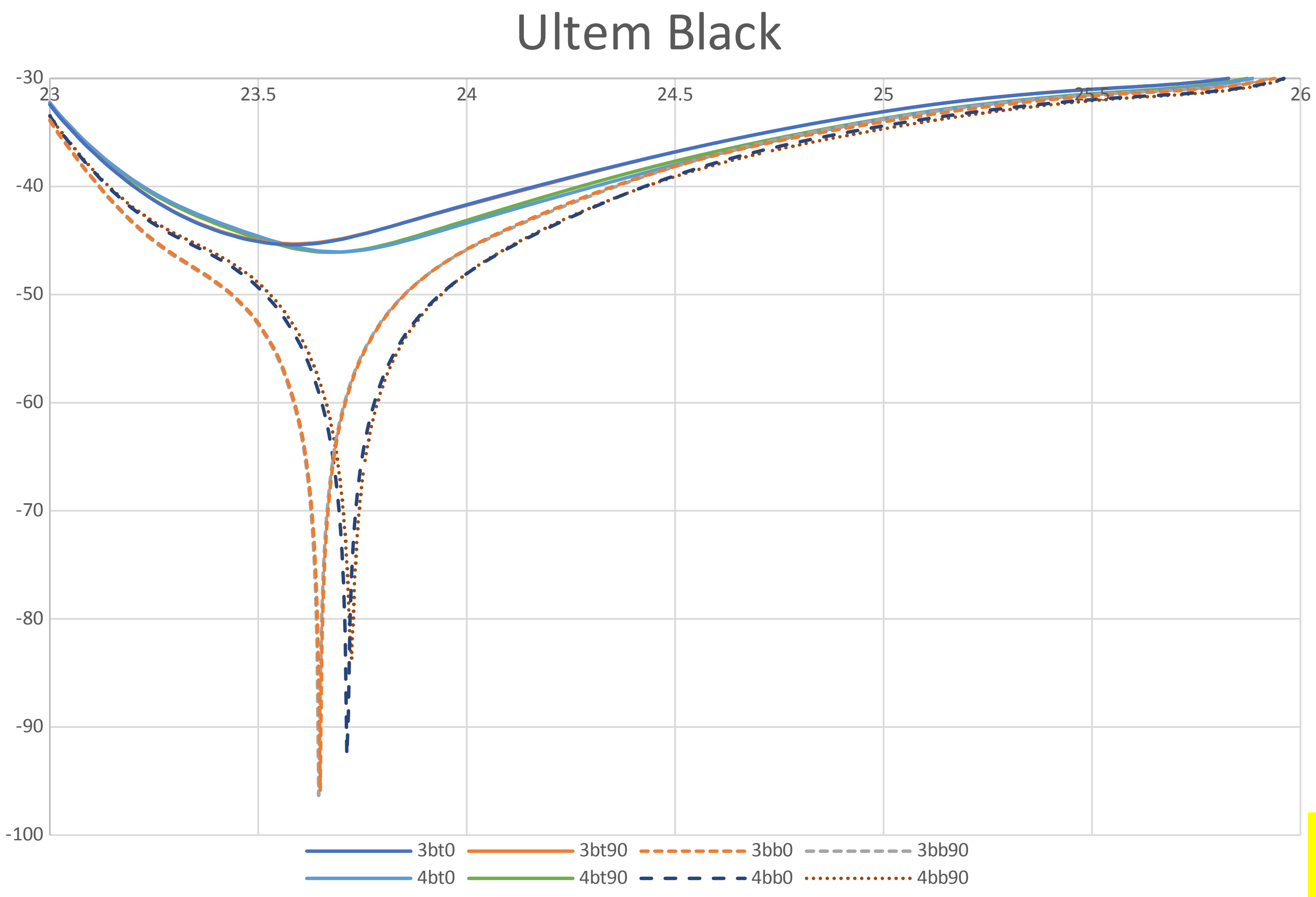
Frequency Bandwidth versus Range Resolution

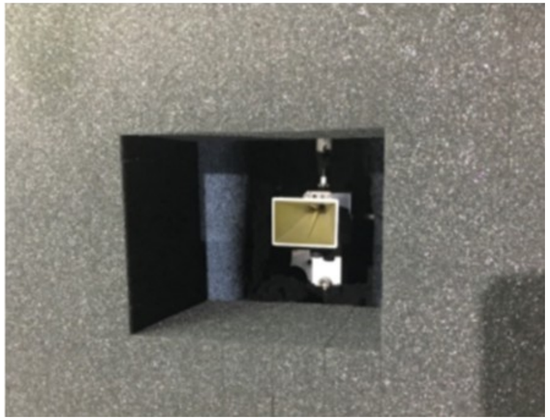
Radar waveform parameters	Radar performance
32 chirps, 45MHz bandwidth, 24.4Khz frequency step 1842 pts	*3.25 m range resolution, 5987 m range extent, .91m/s radial velocity*
32 chirps, 200MHz bandwidth, 10Khz frequency step 4500 pts	*1 m range resolution, 4500 m extent, .91m/s radial velocity*

Radar is susceptible to interference from other like radars operating within 5 kilometers

- *Interference track range and radial velocity are across all beam look angles.*
- *UAS radars would benefit from linking to form a multi-static system.*
- *Poor detection range performance could partially be compensated by regional connectivity.*

Radome Materials





Bottom side measurement resonance null is dependent upon coupon thickness

Szatkowski, George; Ticatch, Larry A: ***“Evaluation of Ultem 1000, 1010, and 9085 for Radome Applications at24.5 GHz.”*** NASA/TM-2019-220287, June, 2019

UAS in the NAS, 8 week effort, 1FTE, 50K procurement

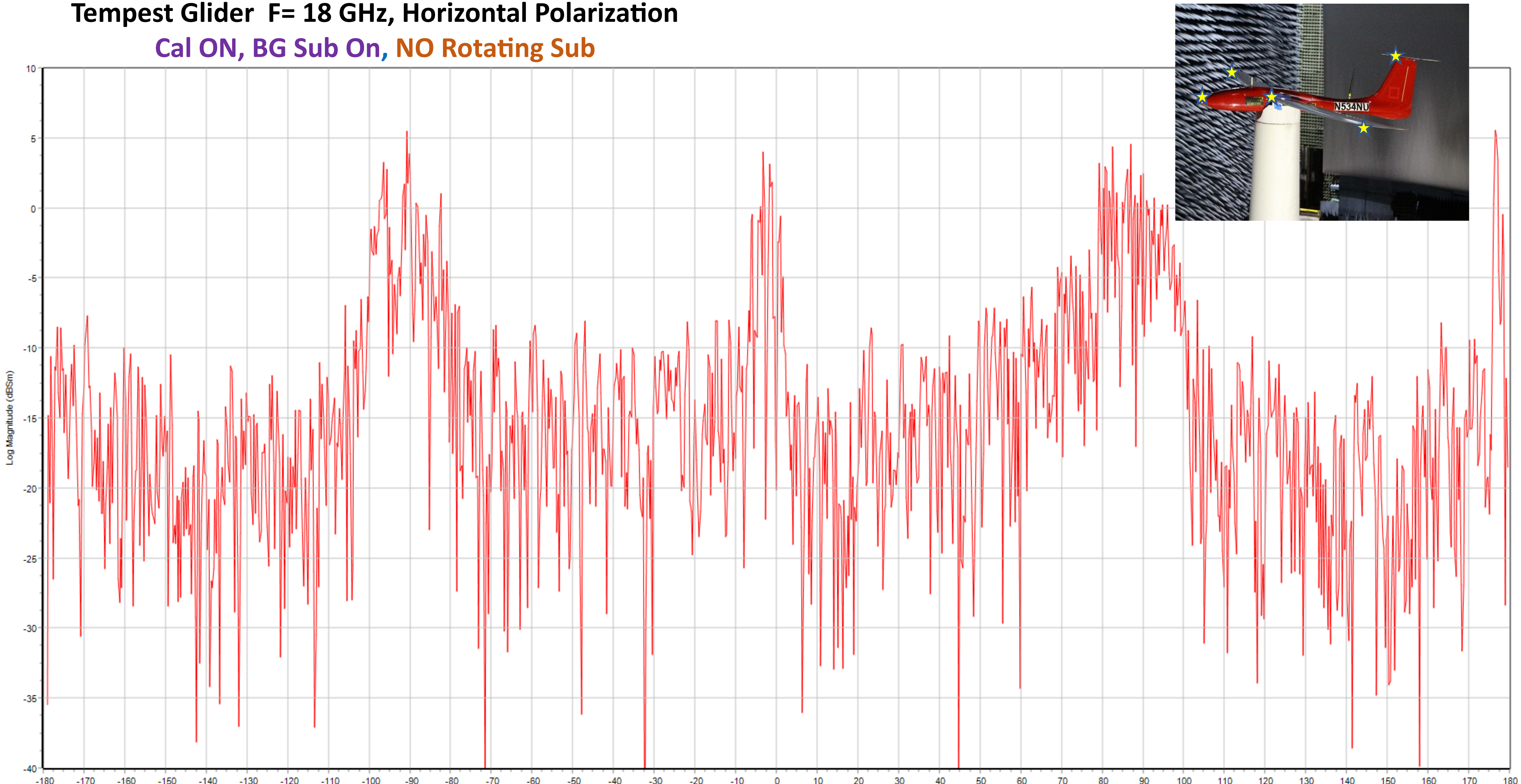
Radar Cross Section Measurements in ETR

UTM-2018; 8-10 week effort 1FTE 1.5 WYE
50K Procurement -Unpublished data

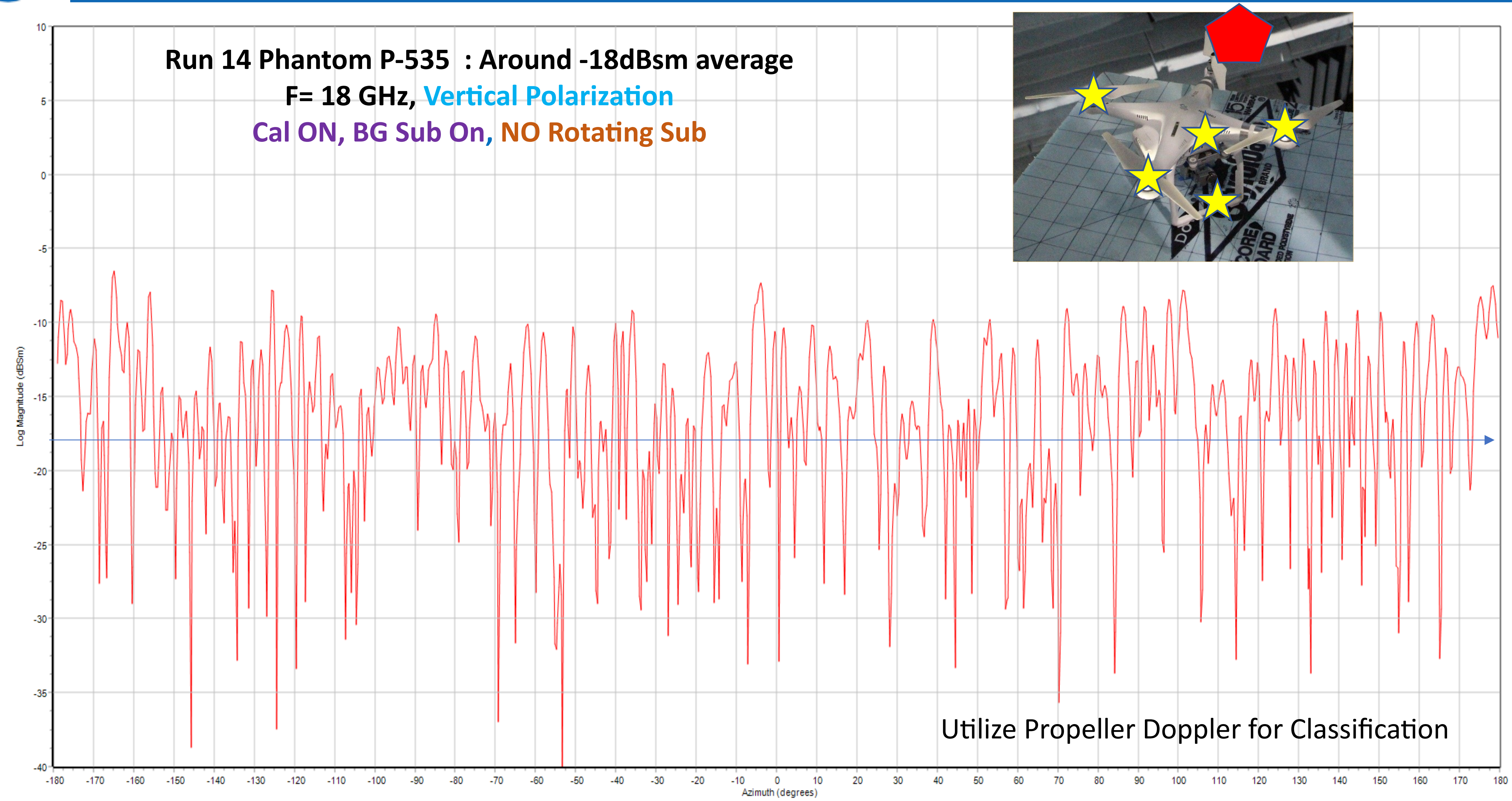
Radar Cross Section Measurements in ETR

Tempest Glider F= 18 GHz, Horizontal Polarization

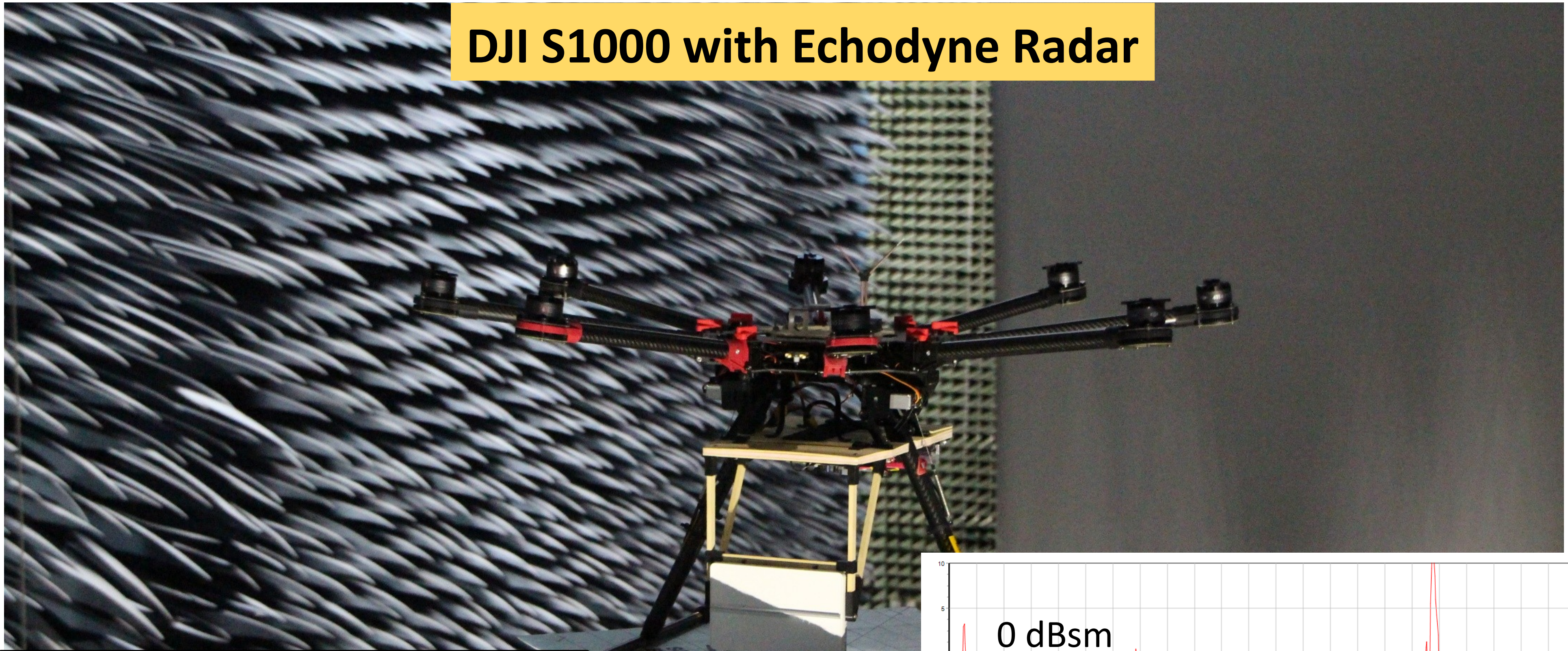
Cal ON, BG Sub On, NO Rotating Sub

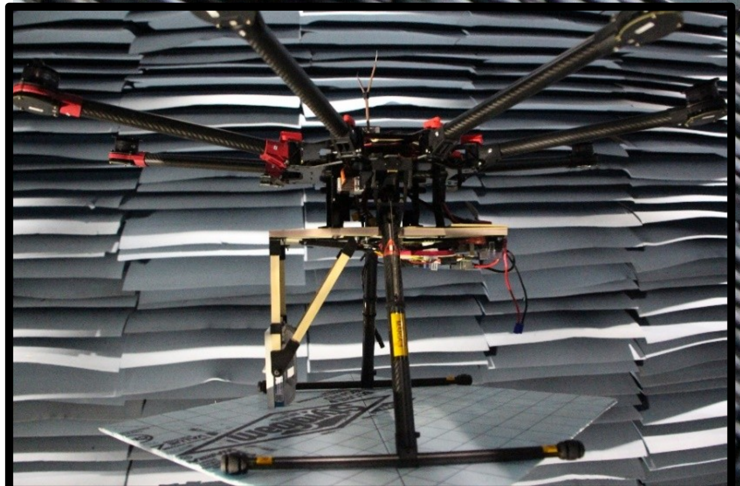


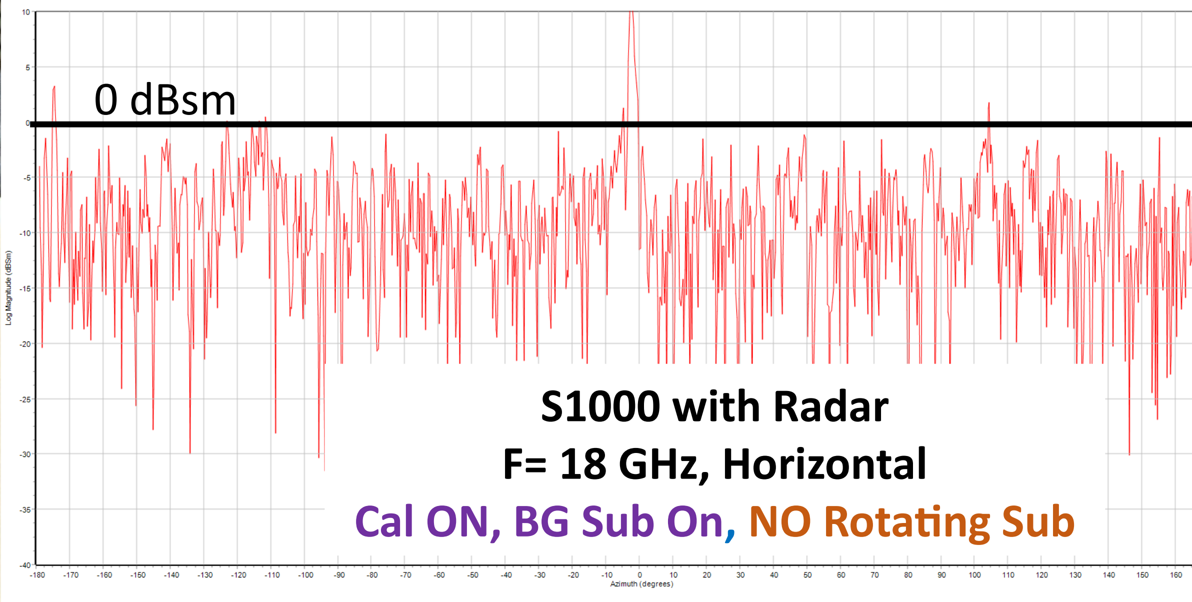
Radar Cross Section Measurements in ETR



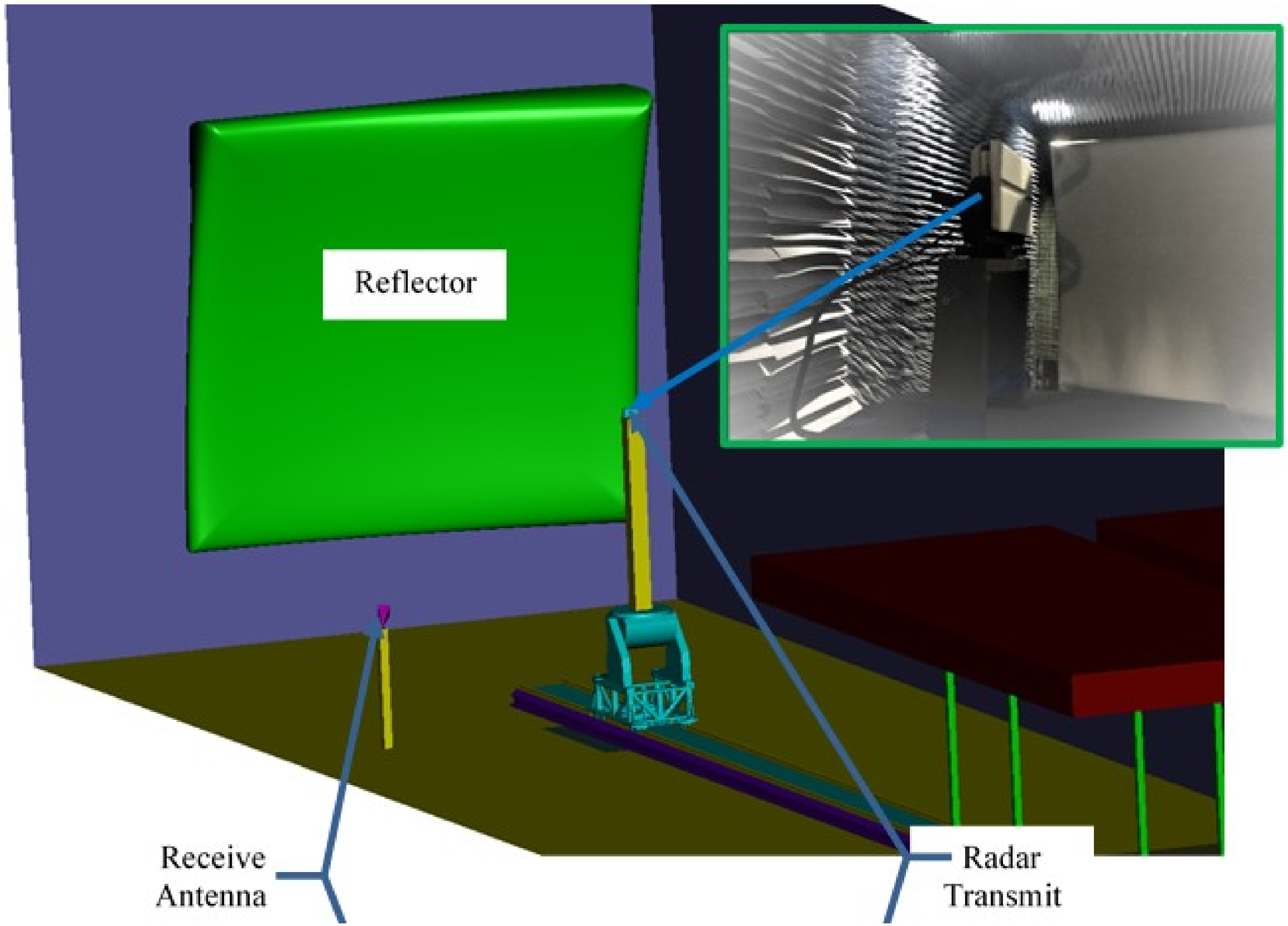
DJI S1000 with Echodyne Radar

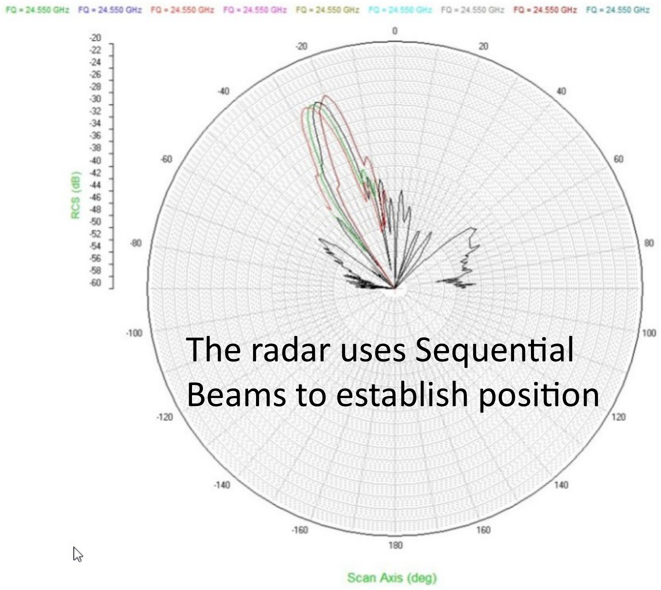




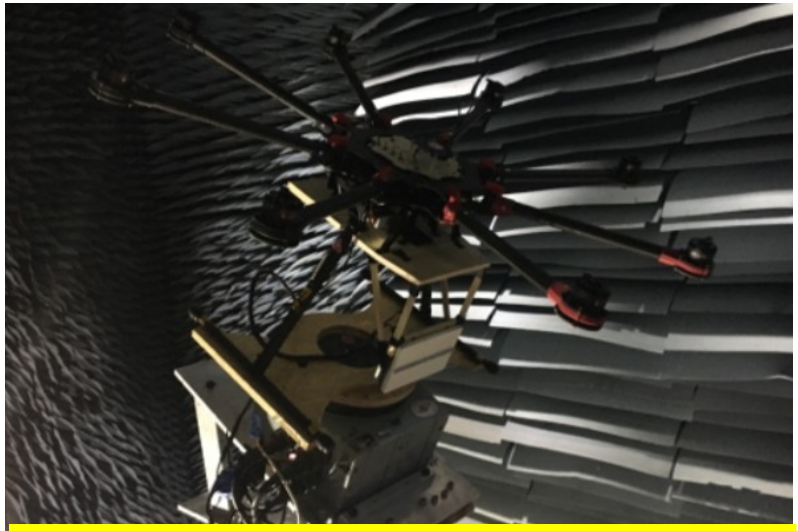


Antenna Measurements in ETR



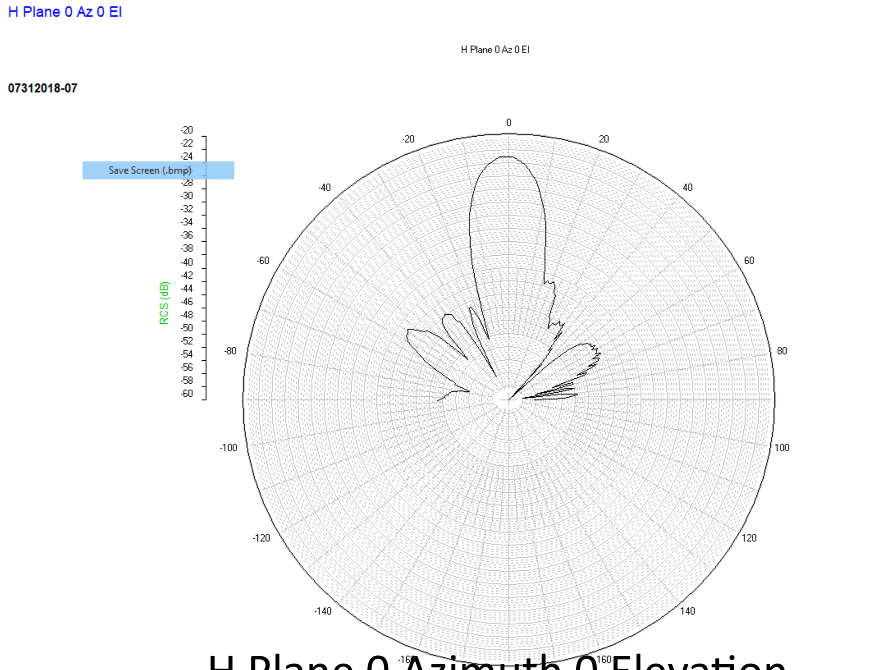


Radar Transmission is recorded on spectrum analyzer from the 24GHz antenna at the reflector focal point. Assume reciprocity.

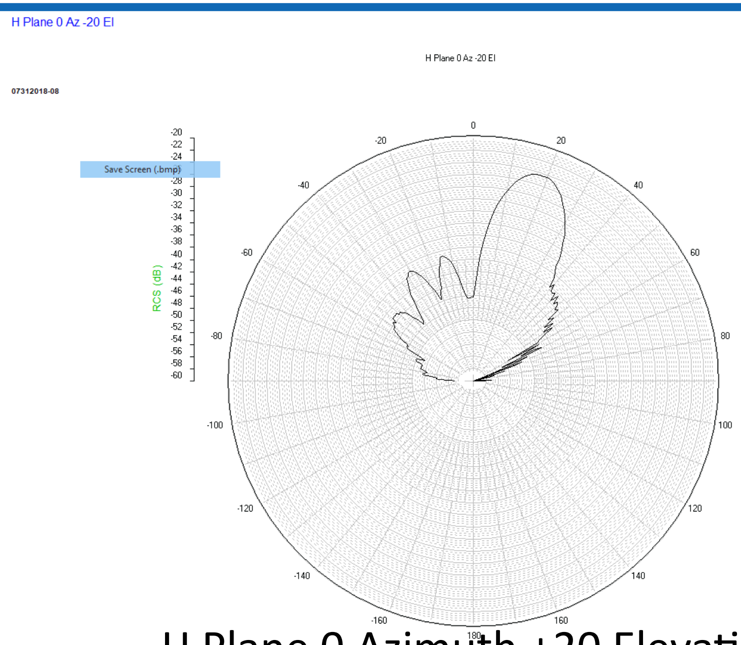


8-10 week activity, 1 FTE, 2 WYE reported in Doppler document

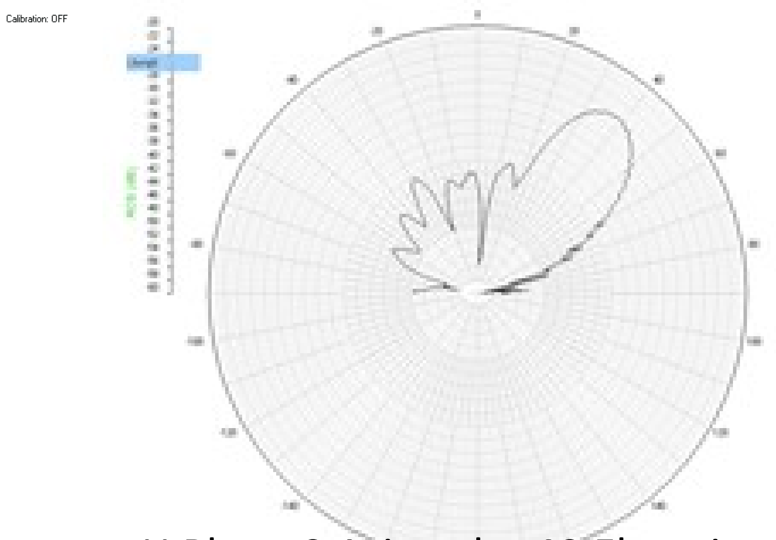
Antenna Measurements in ETR



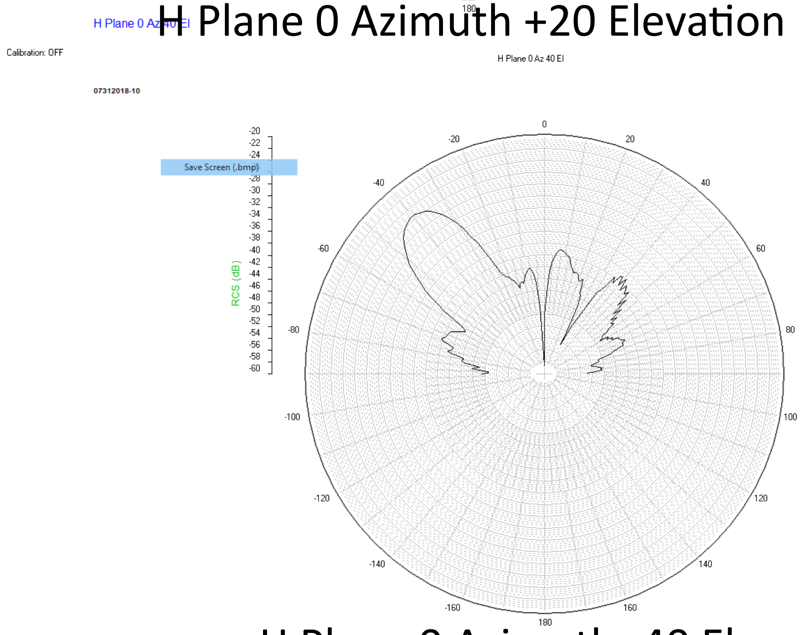
H Plane 0 Azimuth 0 Elevation



H Plane 0 Azimuth +20 Elevation



H Plane 0 Azimuth +40 Elevation

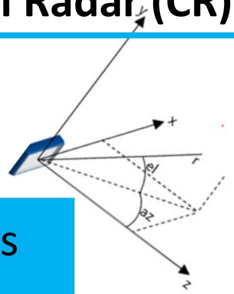


H Plane 0 Azimuth -40 Elevation

Control Radar (CR)

Target is detected by Radar

Multi-Static Radar Opportunities



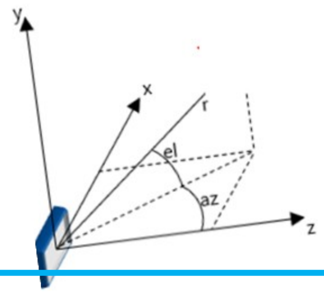
- Don't rely on sequential lobbing to define position
- Add a rf referenced PSR to locate a target
- Knowing the radiation pattern will enable target isolation
- Scan the PSR in elevation during radar beam dwell
- Add second rf referenced PSR for cross range imagery.

CR Detections
& RF
Reference Link

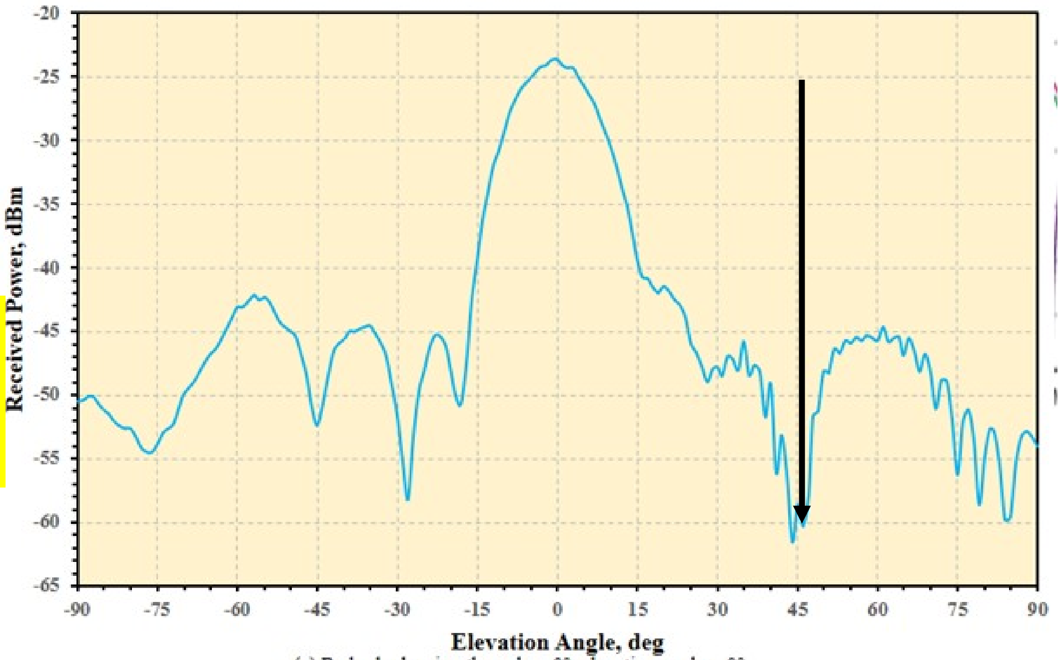
– CR Detection coordinates reported to PSR

Use the Null rather than the peak for establishing location

Could improve angular resolution and increase field of view for targets closest to the radar



Passive Scanning Receiver (PSR)

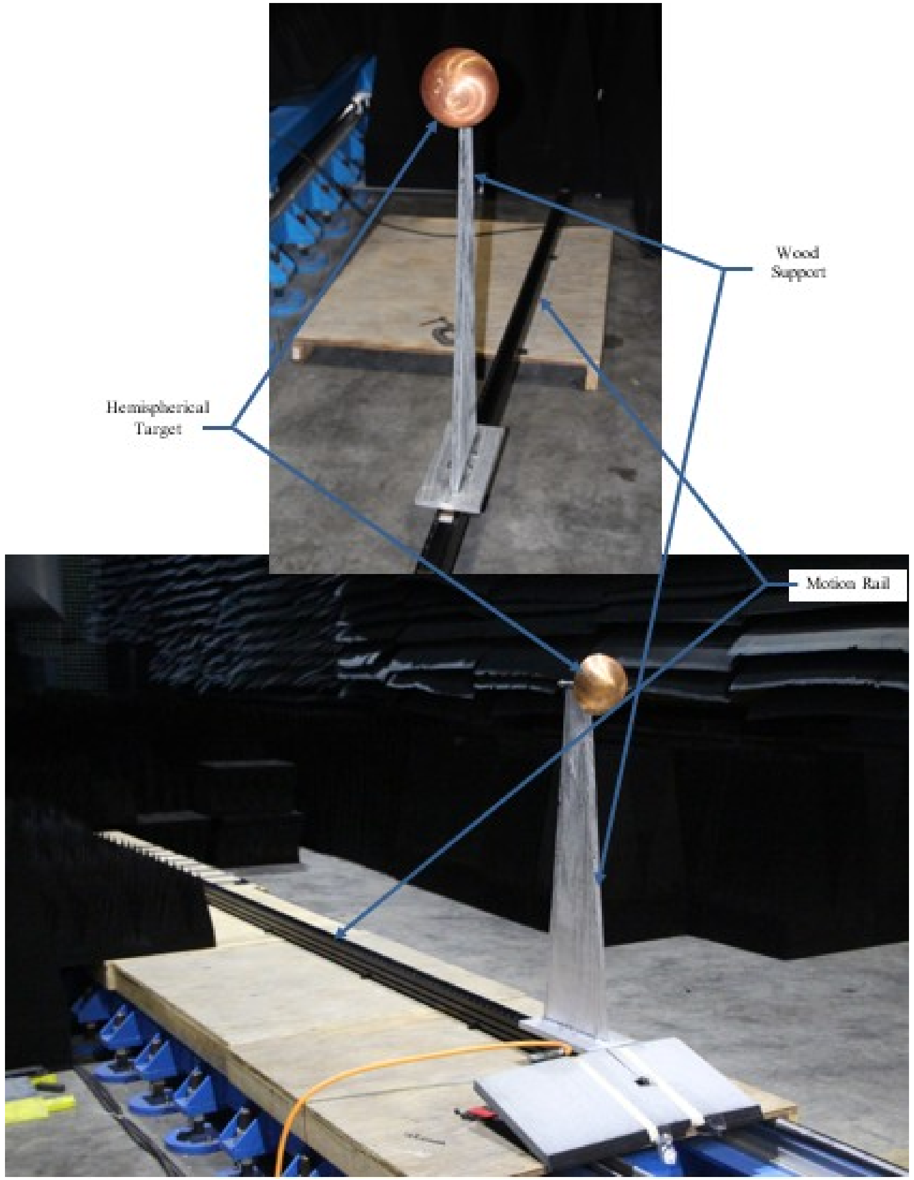


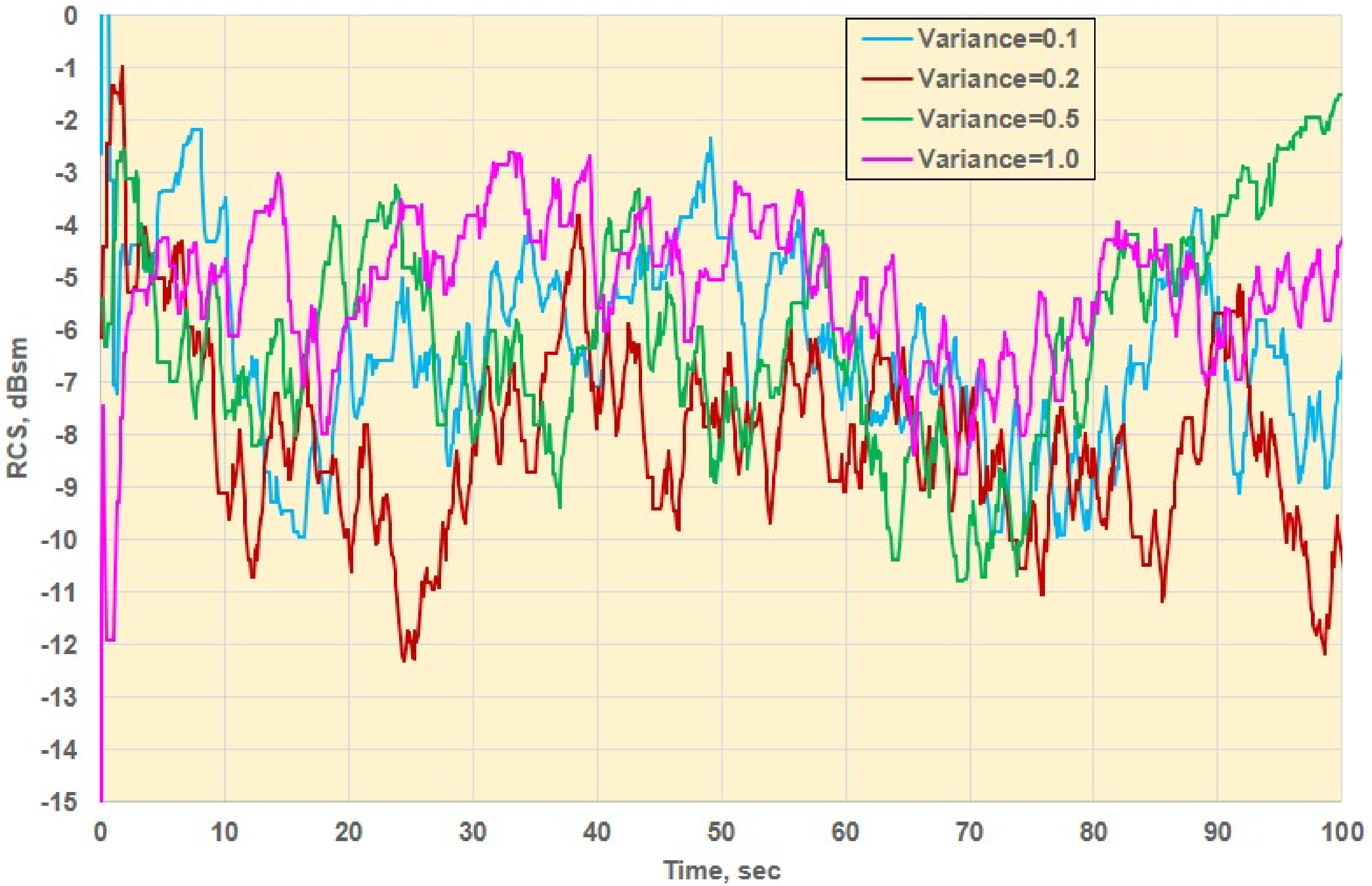
(a) Radar look azimuth angle = 0°, elevation angle = 0°.

Figure 13. Radar transmit antenna pattern in H-Plane.

Doppler Rail Measurements in ETR

1. Szatkowski, George; Ticatch, Larry A; Morris, Christopher M.; Cavone, Angelo A.: ***"Indoor Ground Testing of a Small UAS Sense and Avoid Airborne Doppler Radar."*** NASA/TM-2019-220280, May, 2019.



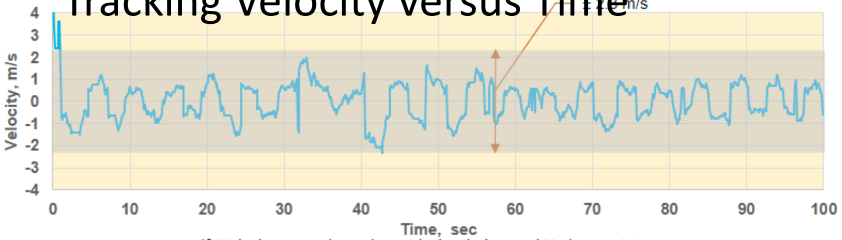


(a) RCS versus time using a 6 in. hemisphere.
Figure 8. Track data measurements for a 6 in. hemisphere with variance settings of 0.1, 0.2, 0.5, and 1.0.

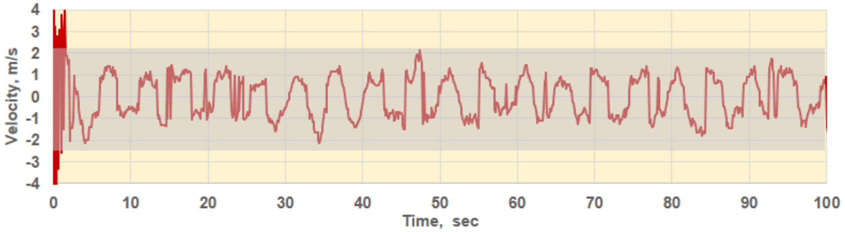
UTM 2018; 8-10 week effort 1 FTE 2.5 WYE, 50K procurement

Doppler Rail Measurements in ETR

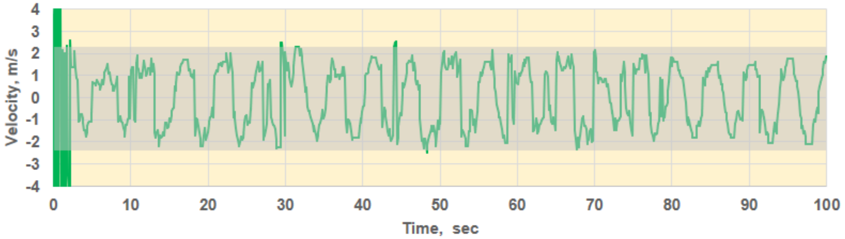
Tracking Velocity versus Time



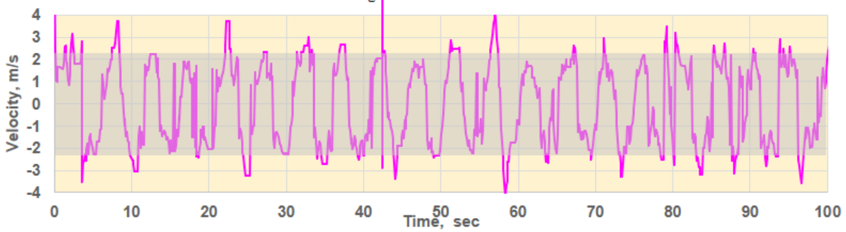
(f) Velocity versus time using a 6 in. hemisphere and Variance = 0.1.
Figure 8. Continued.



(g) Velocity versus time using a 6 in. hemisphere and Variance = 0.2.
Figure 8. Continued.

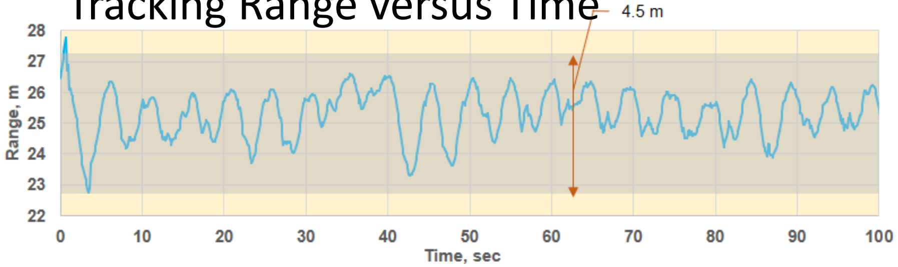


(h) Velocity versus time using a 6 in. hemisphere and Variance = 0.5.
Figure 8. Continued.

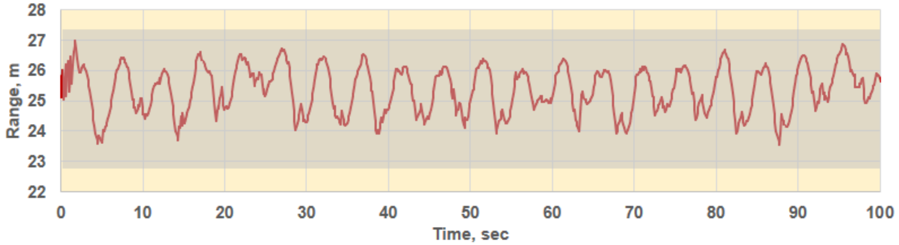


(i) Velocity versus time using a 6 in. hemisphere and Variance = 1.0.
Figure 8. Concluded.

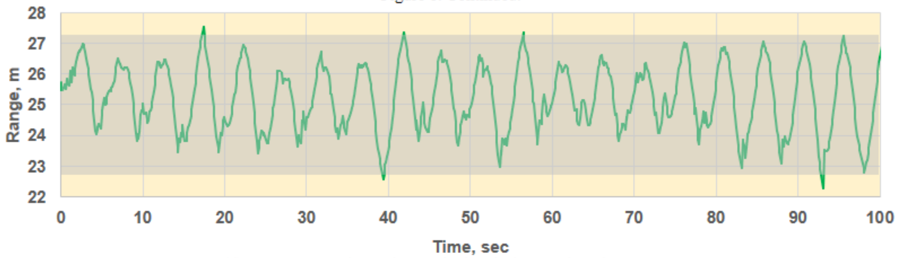
Tracking Range versus Time



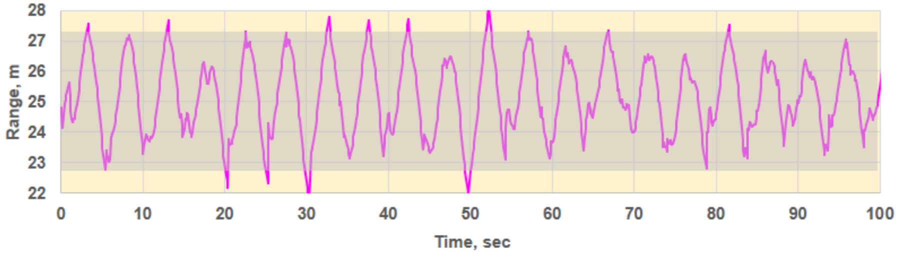
(b) Range versus time using a 6 in. hemisphere and Variance = 0.1.
Figure 8. Continued.



(c) Range versus time using a 6 in. hemisphere and Variance = 0.2.
Figure 8. Continued.



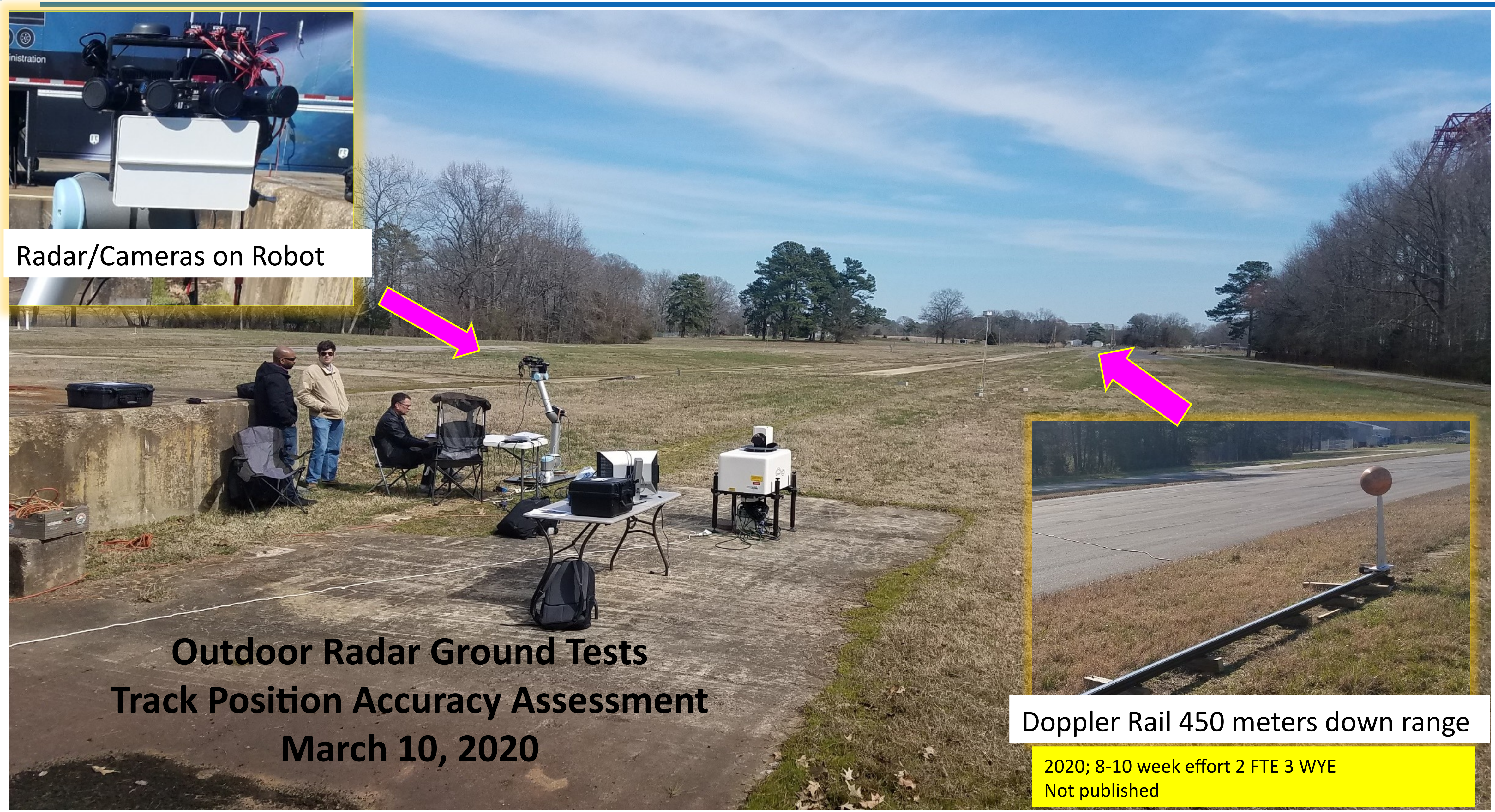
(d) Range versus time using a 6 in. hemisphere and Variance = 0.5.
Figure 8. Continued.



(e) Range versus time using a 6 in. hemisphere and Variance = 1.0.
Figure 8. Continued.

Kalman Filter settings influence Tracked velocity and range
Dynamic Data Driven Tracking is needed.

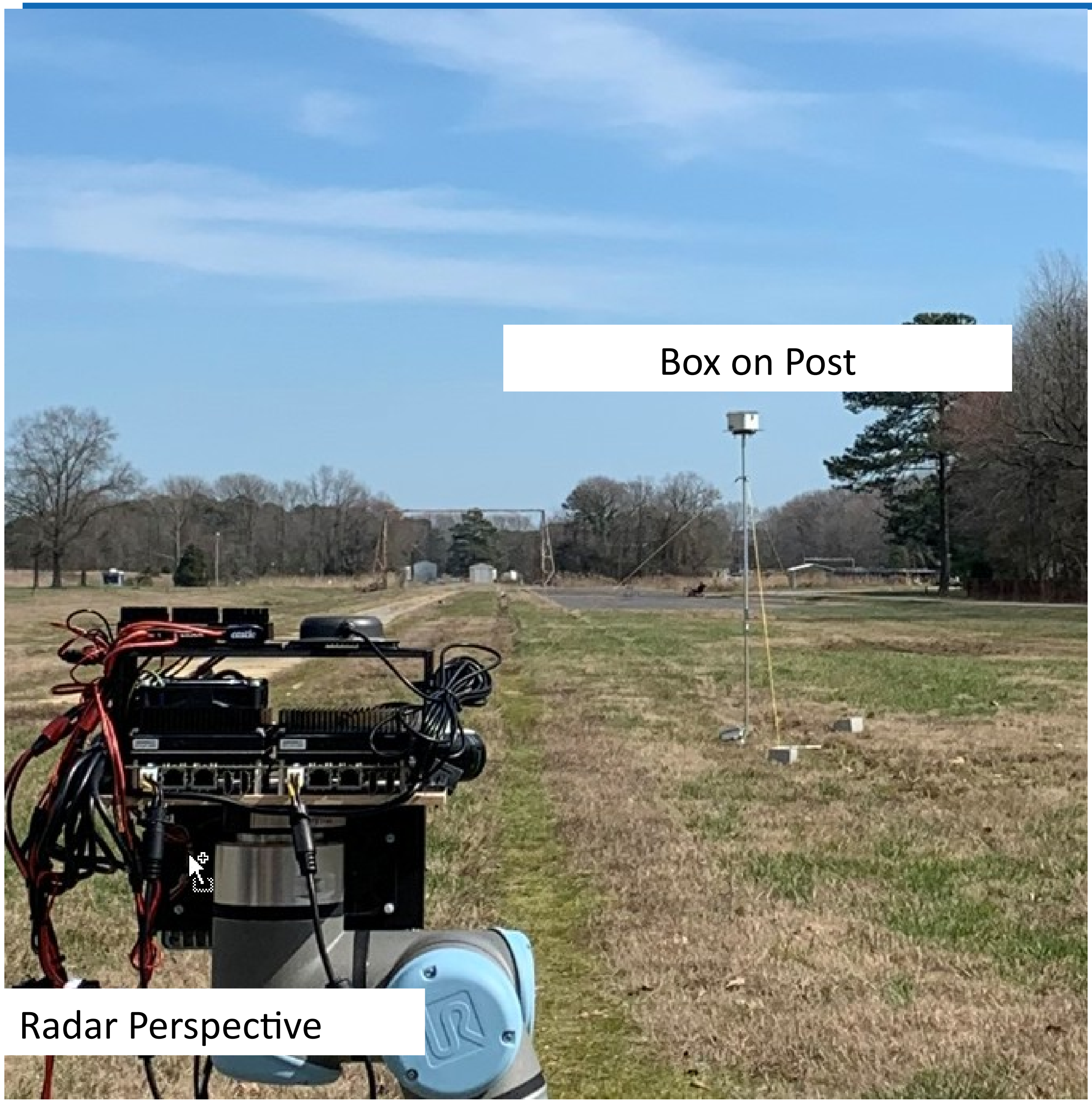
Doppler Rail Measurements at Certain Range March 2020



Doppler Rail Measurements at Certain Range March 2020

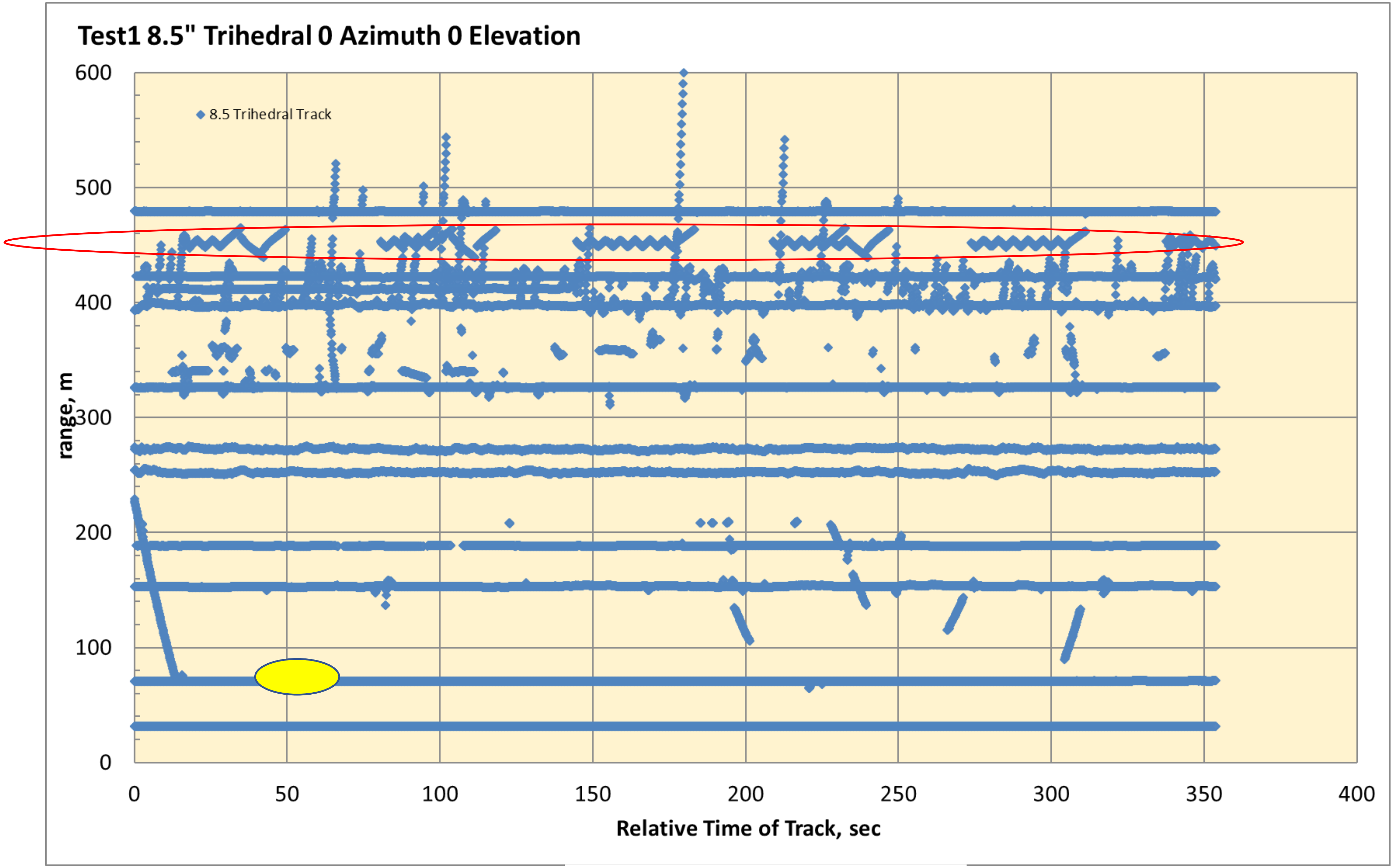
Radar Doppler Targets

Doppler Rail Measurements at Certain Range March 2020

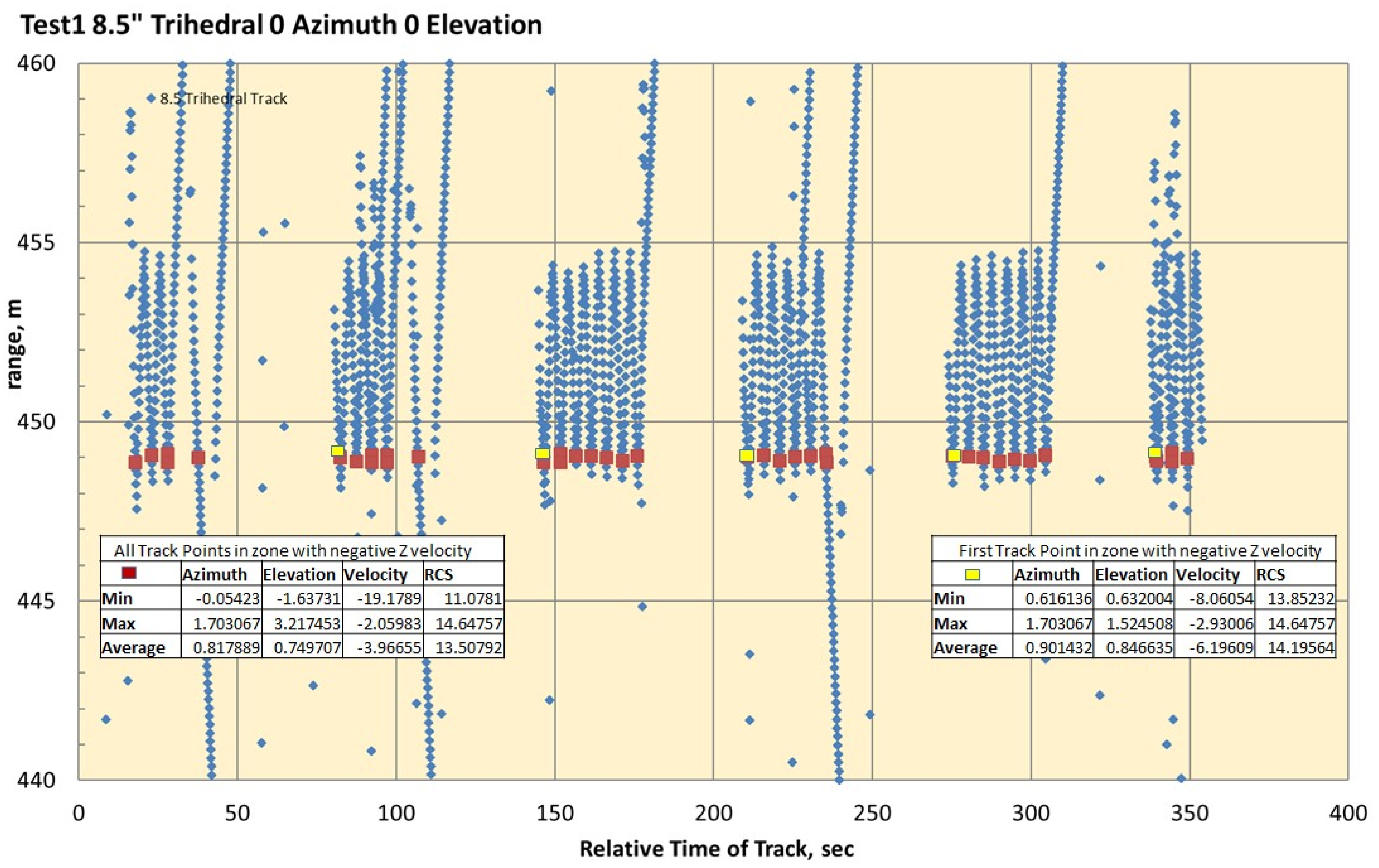


Doppler Rail Video

Doppler Rail Measurements at Certain Range March 2020



Doppler Rail Measurements at Certain Range March 2020



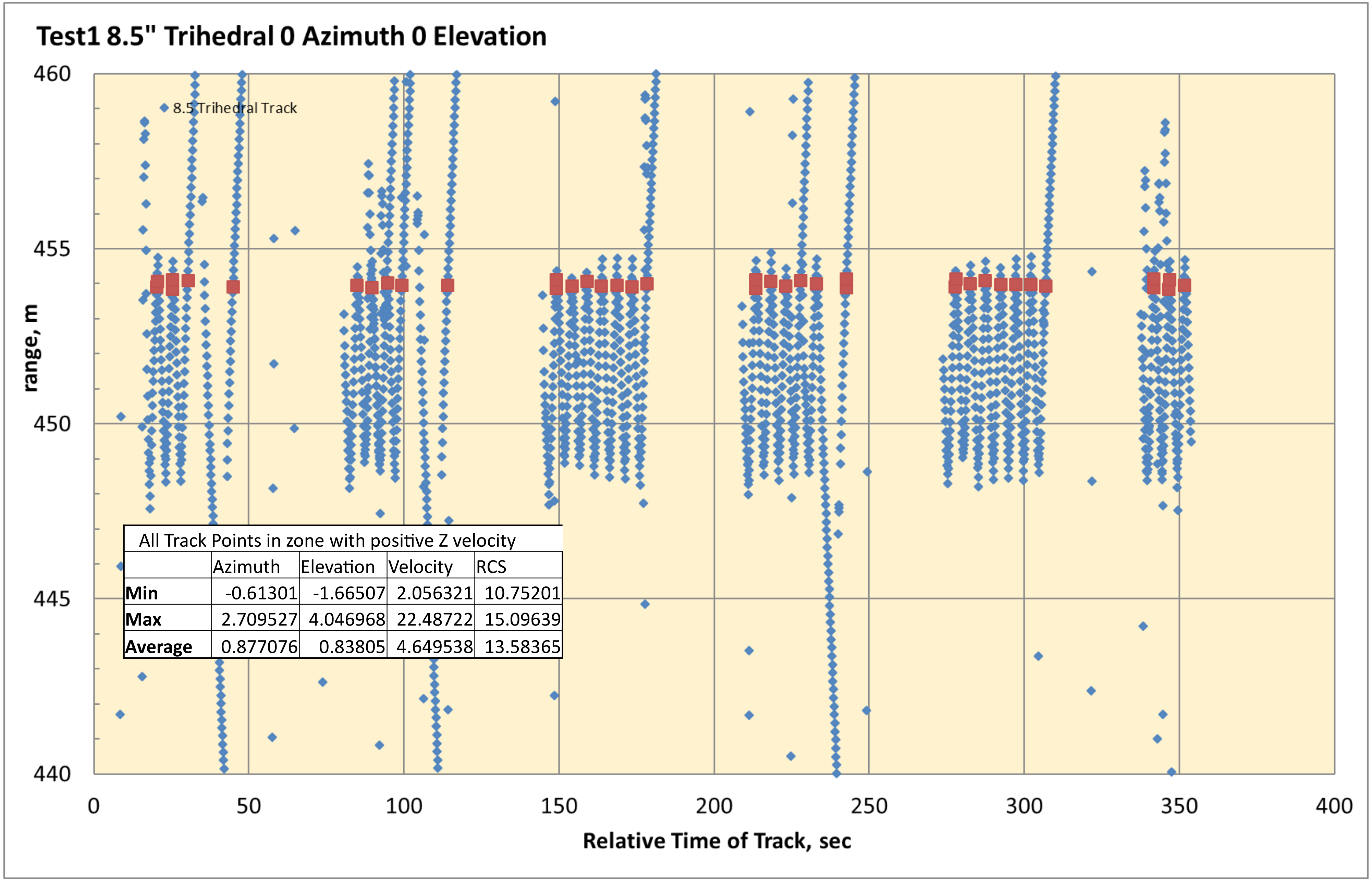
All Track Points in zone with negative Z velocity

	Azimuth	Elevation	Velocity	RCS
Min	-0.05423	-1.63731	-19.1789	11.0781
Max	1.703067	3.217453	-2.05983	14.64757
Average	0.817889	0.749707	-3.96655	13.50792

First Track Point in zone with negative Z velocity

	Azimuth	Elevation	Velocity	RCS
Min	0.616136	0.632004	-8.06054	13.85232
Max	1.703067	1.524508	-2.93006	14.64757
Average	0.901432	0.846635	-6.19609	14.19564

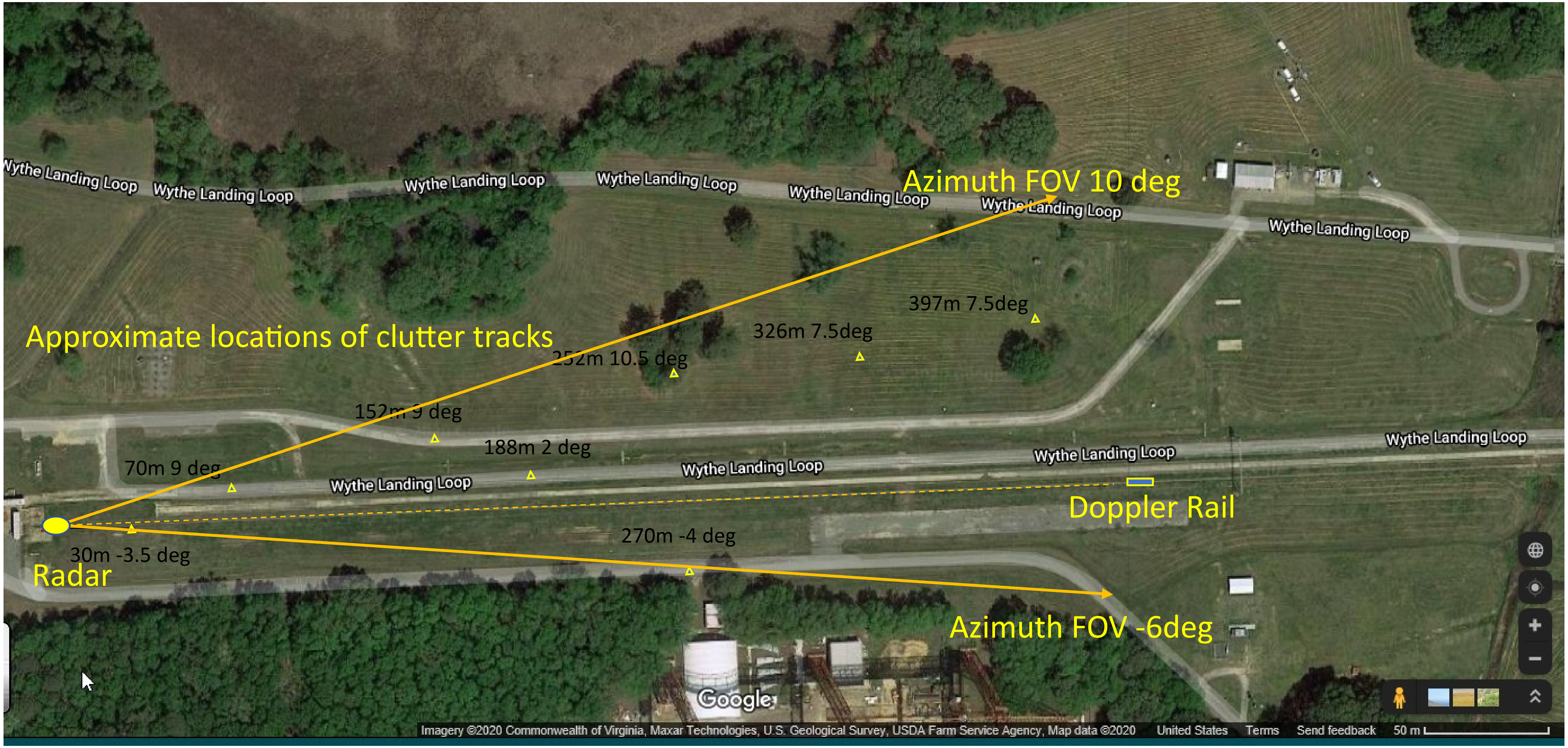
Doppler Rail Measurements at Certain Range March 2020



All Track Points in zone with positive Z velocity

	Azimuth	Elevation	Velocity	RCS
Min	-0.61301	-1.66507	2.056321	10.75201
Max	2.709527	4.046968	22.48722	15.09639
Average	0.877076	0.83805	4.649538	13.58365

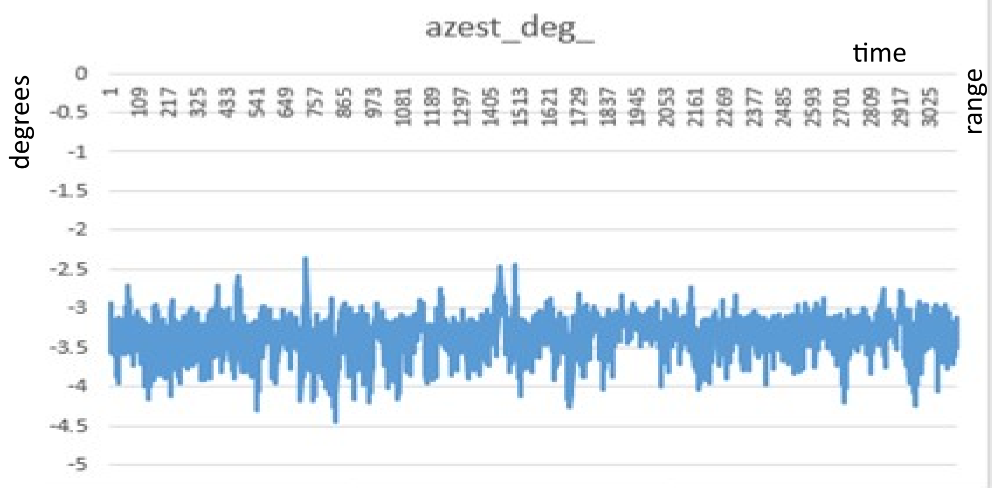
Doppler Rail Measurements at Certain Range March 2020

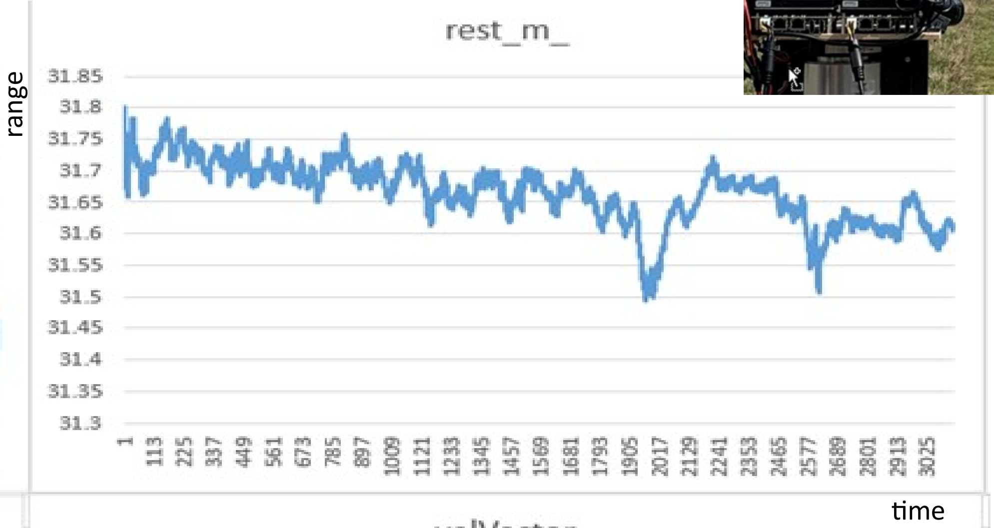


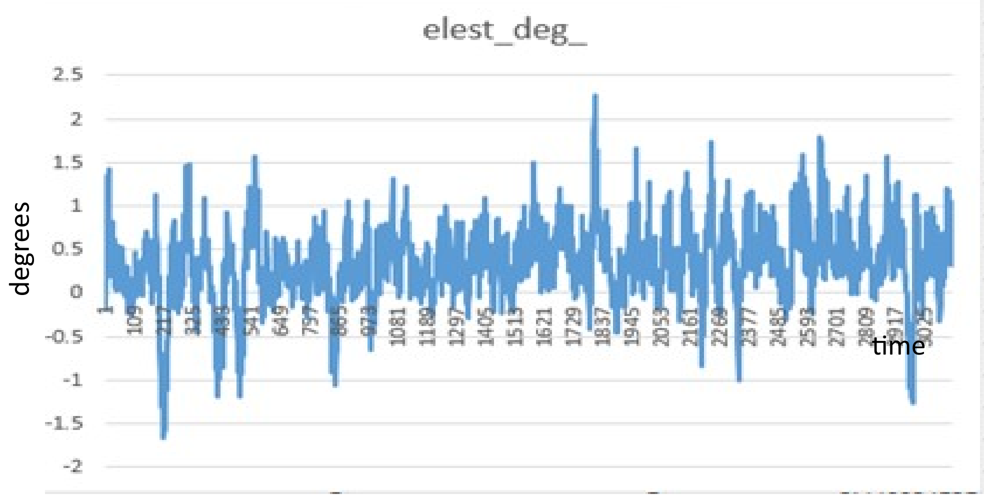
Box on a Post at Certain Range March 2020

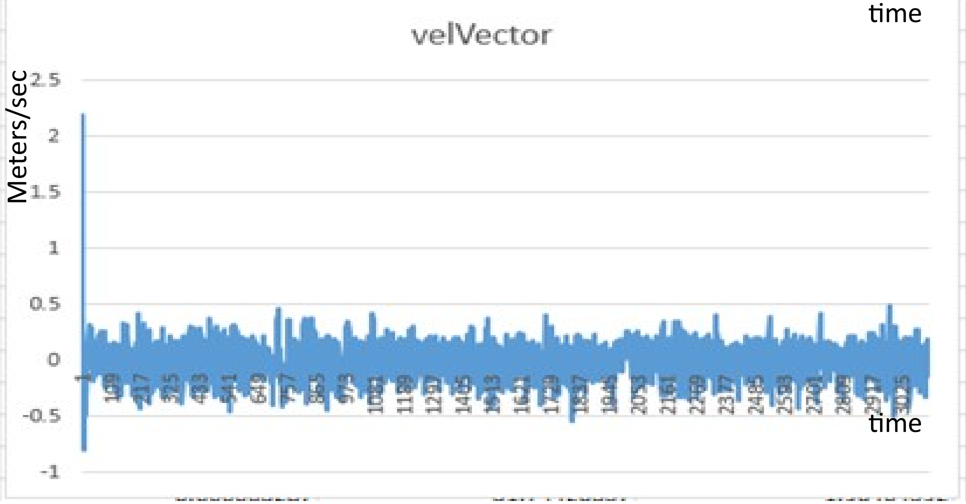
Box contained a 5G Network Router

TEST 1 Track 1 at 30 Meters -3.5 deg Az





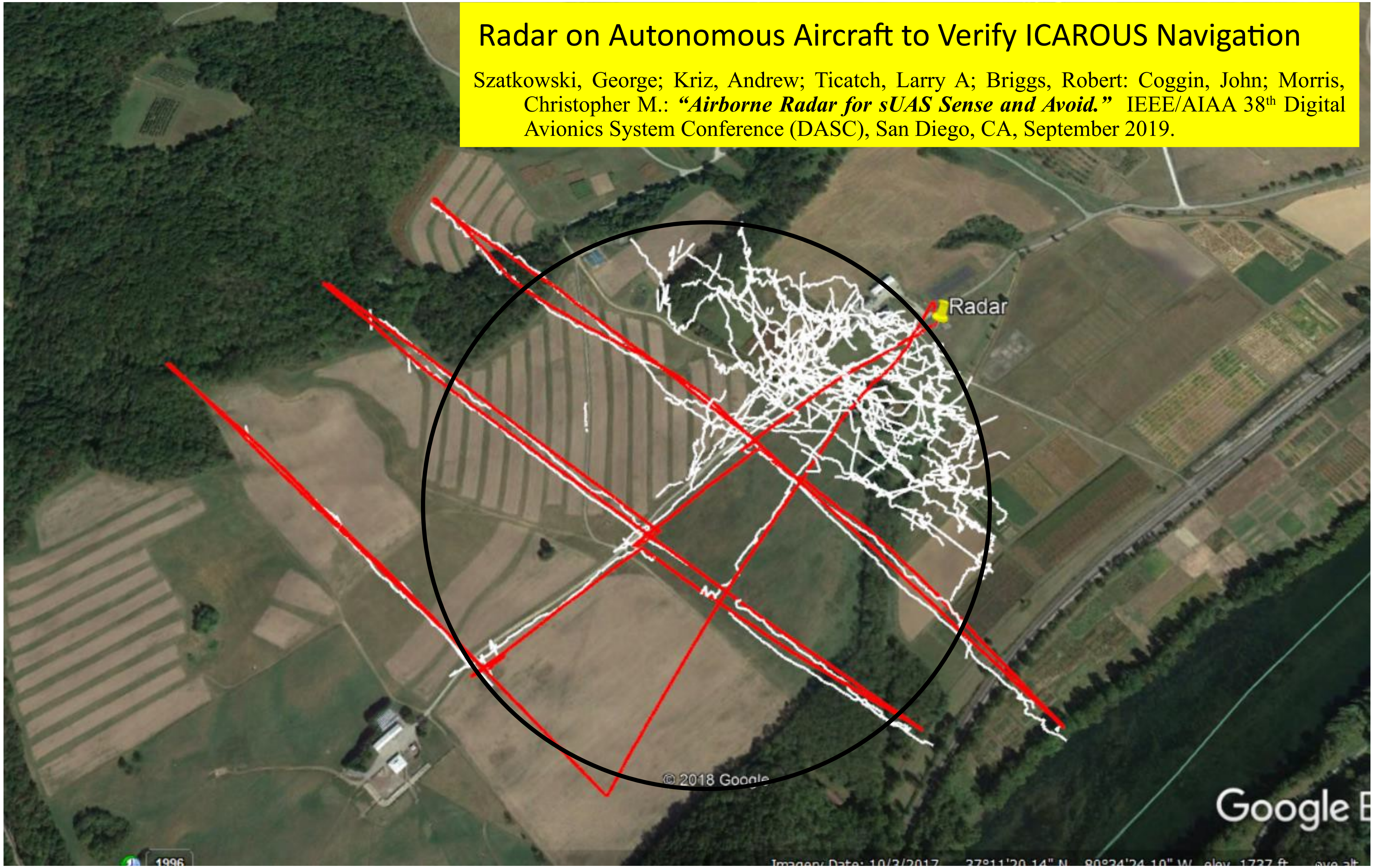




Ground Data Assessments at Kentland Farms, VA Feb 2019

Radar on Autonomous Aircraft to Verify ICAROUS Navigation

Szatkowski, George; Kriz, Andrew; Ticatch, Larry A; Briggs, Robert: Coggin, John; Morris, Christopher M.: ***"Airborne Radar for sUAS Sense and Avoid."*** IEEE/AIAA 38th Digital Avionics System Conference (DASC), San Diego, CA, September 2019.



Flight Data Assessments with ICAROUS operational at Kentland Farms, VA August 2019

Radar on Autonomous Aircraft to Verify ICAROUS Navigation

NASA Team
- Lou Glaab
- Swee Balachandran
- Kyle Smalling
- Dave Hare
- Dave Bradley
- Brenden Duffy
- Angelo Cavone

TPSAS #34996
TITLE: NASA RAAVIN Final Report
FIRST AUTHOR: Andrew Kriz, VA Tech

https://shemesh.larc.nasa.gov/fm/ICAROUS/ICAROUS_ISAAC.mp4

NASA RAAVIN - Radar on Autonomous Aircraft to Verify ICAROUS Navigation

Slide Narrative: Head-on encounter with C-172. BFD ownship initially avoids false track (123) then avoids the C-172 intruder track (224). After C-172 passes the ownship returns to destination waypoint.

BFD Multirotor with Echodyne Radar and NASA ICAROUS automated alerting and guidance

Current Work

1. Dolph, Chester V.; Szatkowski, George; Holbrook, Henry; Morris, Christopher M.; Ticatch, Larry A; Malepour, Mahyar; McSwain, Robert: ***"Aircraft Classification Using RADAR from small Unmanned Aerial Systems for Scalable Traffic Management Emergency Response Operations."*** AIAA, August 2021.

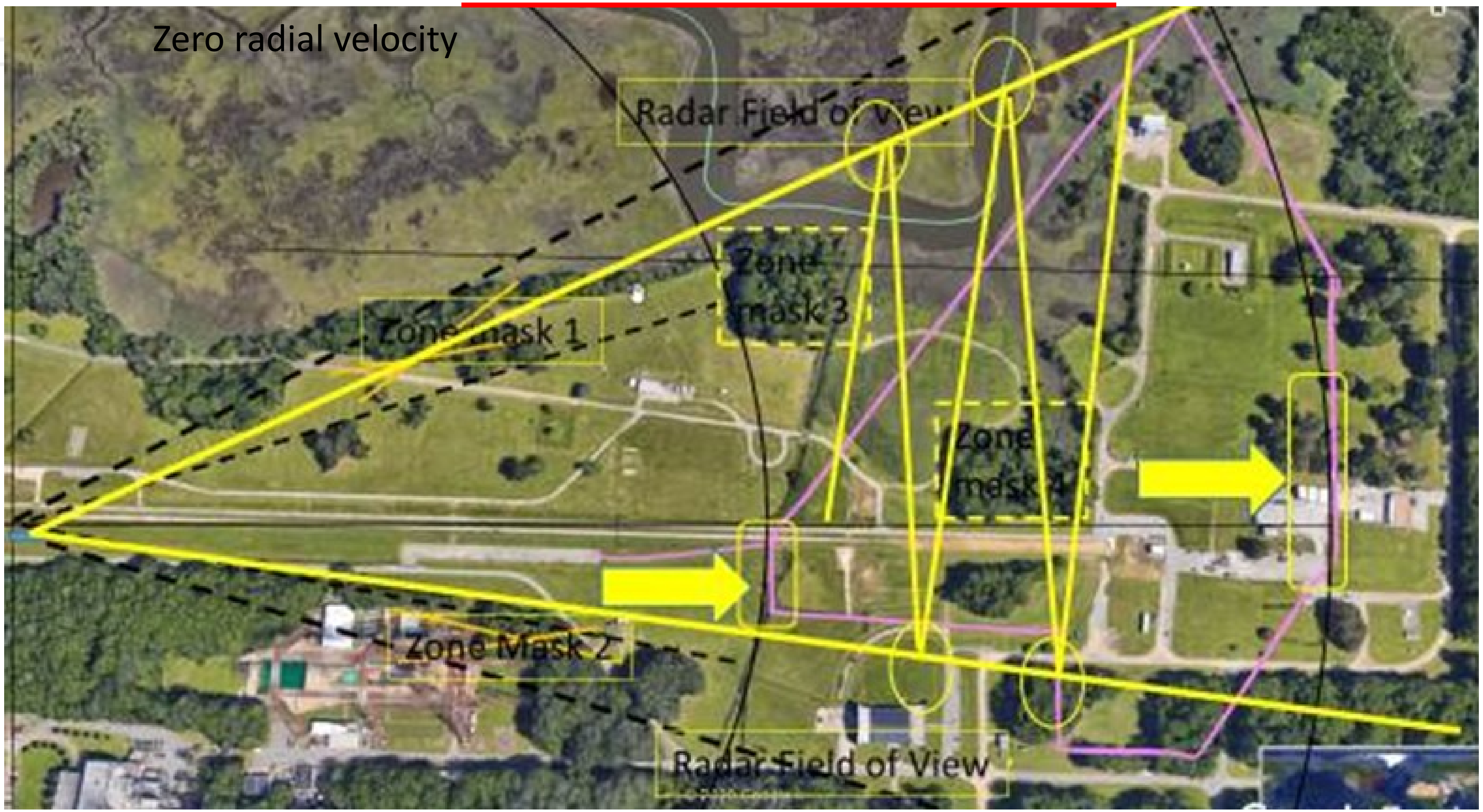
- Field testing of RADAR with ICAROUS avoidance system generated perfect Recall (ICAROUS avoided all aircraft) but low precision (RADAR generated trajectories caused ICAROUS to activate not-an-aircraft). Precision of 50% poses a challenge for successful sUAS missions that aim to optimize onboard resources (battery, time, complete a waypoint mission)
- This work proposes adding a layer of AI between the RADAR and ICAROUS to identify aircraft trajectories using machine learning and thus mitigate for unnecessary activations of ICAROUS
- Preliminary results using a Support Vector Machine (SVM) look promising
- A Neural Network (variational autoencoder) is being developed for comparison in the AIAA 2021 Aviation paper

Pre-Flight Data Assessments at Certain Range March 2021

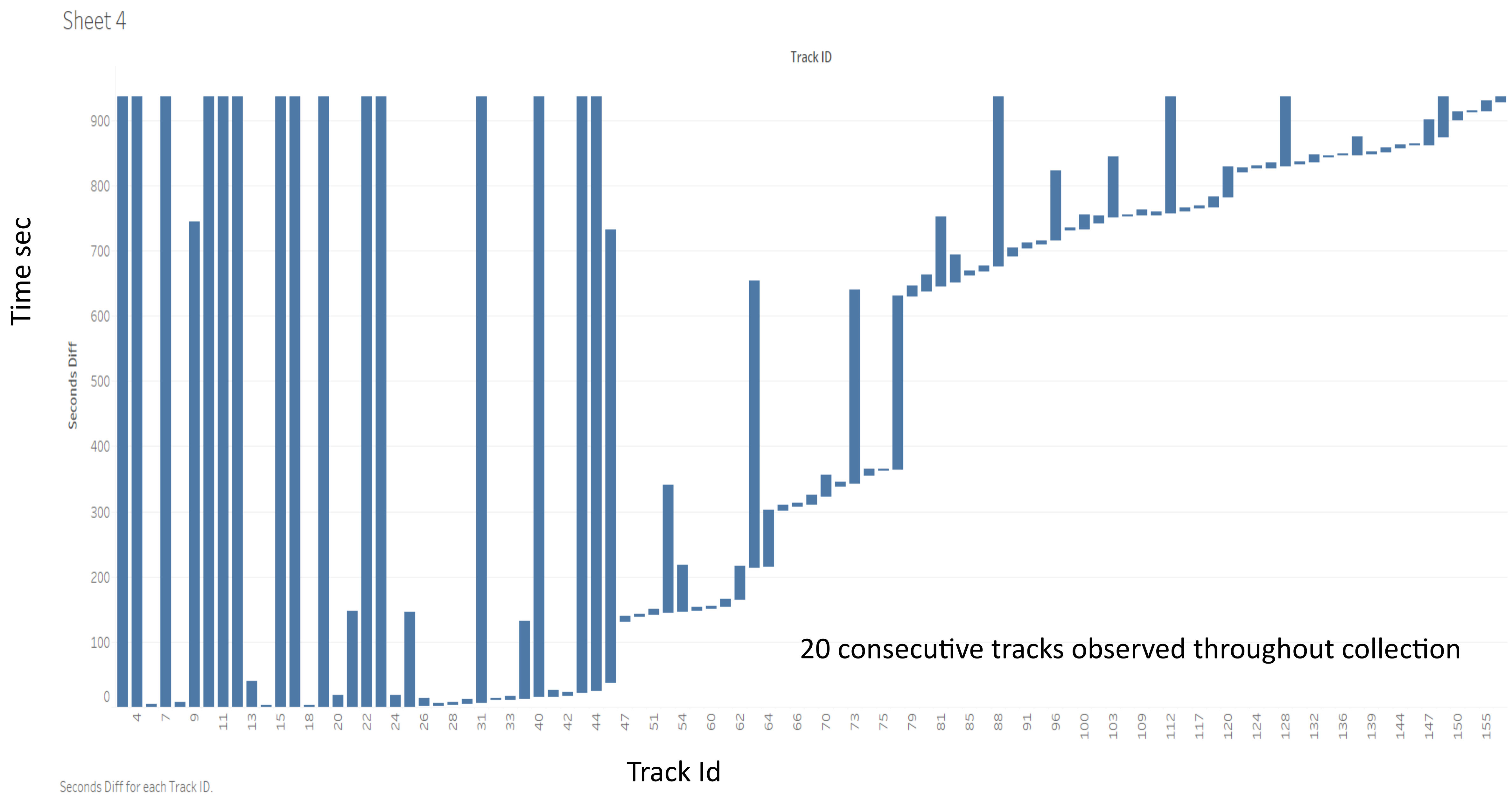
Elevation_0_phase2.txt

Elevation_0_phase2.txt

```
RESET:PARAMETERS
enable_rvmap
enable_detection
enable_status
enable_track
enable_measurements
enable_rvmap_logging
enable_detection_logging
enable_status_logging
enable_track_logging
enable_measurements_logging
OUTPUT:EXTENDEDPACKET:ENABLE TotemLake TRUE
MODE:SWT:OPERATIONMODE 0
MODE:SWT:TRACKER:MINREPORTINGCONFIDENCE TotemLake 30
MODE:SWT:SEARCH:ELFOVMIN 4
MODE:SWT:SEARCH:ELFOVMAX 32
MODE:SWT:TRACK:ELFOVMIN 4
MODE:SWT:TRACK:ELFOVMAX 32
MODE:SWT:SEARCH:AZFOVMIN -30
MODE:SWT:SEARCH:AZFOVMAX 30
MODE:SWT:TRACK:AZFOVMIN -30
MODE:SWT:TRACK:AZFOVMAX 30
RANGE:MASK TotemLake 0,281,2047,0,31
RANGE:MASK TotemLake 1,528,2047,0,31
ZONE:MASK:CLEAR TotemLake
RSP:Cluttermask TotemLake 3
ZONE:MASK:ENABLE TotemLake TRUE
ZONE:MASK TotemLake 0 -30 -10 4 32 20 540
ZONE:MASK TotemLake 1 18 30 4 32 20 420
SYSPARAM? TotemLake
```



Pre-Flight Data Assessments at Certain Range March 2021



Conclusions/Recommendations

- Target classification requires better range resolution.
- 24.5 GHz 200Mhz spectrum allocation is operationally problematic
- Current 32 chirp dwell is sufficient to capture this data effectively.
- Effective operational surveillance volume is compromised by 20 track limit./Use AI to filter
- Tracker produces data based on Kalman filter variance settings./Dynamic filtering
- Beam angle error could be improved by using a referenced second antenna/receiver.
- Incorporate 2 passive scanning receivers to generate unfocused cross range imagery
- Operational field of view could be expanded with add on passive scanning receivers.
- Explore multi-static radar system to generate additional intelligence
- Add +10dBsm shroud to sUAS body for signature enhancement
- Regional assignment to enable more effective operational utilization is recommended
  - Use spectrum smarter enabling higher confidence multi-static surveillance
  - Embrace Spread Spectrum

- Data not needed by you does not mean it is not needed. – road conditions, flood, fire, rain, etc
- Use sidelobe radiation to help establish detections as a side benefit to them being there.
- Understand airspace congestion and turbulence by monitoring radar transmissions
- Radar cross section signature is less valuable than physically sizing an aircraft