

Leveraging Metamaterials Antennas for Low-Cost Phased Array Radar Solutions in Atmospheric and Sea Surface Sensing

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Phased Arrays for Ground-based, Airborne, and Spaceborne Atmospheric Science

Phased arrays offer unique degrees of freedom for sampling the 2D angular space:

- Arbitrarily steer main lobe from dwell-to-dwell within the array's accessible field of view (e.g., 90-120 degree cone)
- (Digital arrays) Simultaneous pencil beams illuminating different parts of the atmosphere or spoiled beam Tx operation with Rx digital beamforming (DBF)

Ground-based:

- Can increase time resolution of NEXRAD VCP-like sampling if using DBF, but not necessarily the optimal strategy
- Ability to simultaneously sample isolated convective features spread across array FOV is a key differentiator versus mechanically rotating reflectors

Airborne:

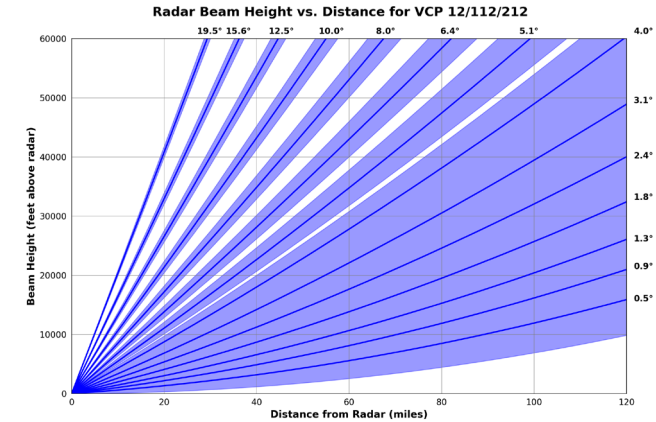
- Unique multi-modal sampling of atmosphere and sea surface
- Doppler winds, adaptive sampling for improved sensitivity / resolution / science quality, sea surface scatterometry and altimetry

Spaceborne:

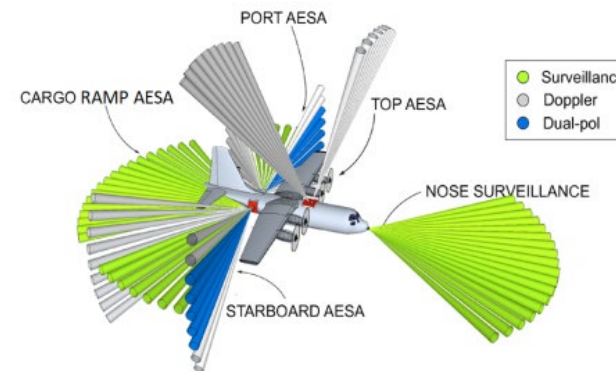
- Demanding sampling constraints from orbit make phased arrays highly attractive for precipitation mapping (e.g., GPM DPR)

Technological Challenges

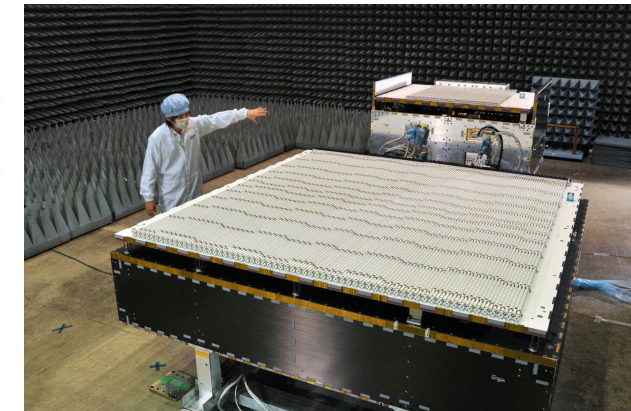
- Calibration is challenging (more so with dual-pol)
- Traditional PAR system complexity drives **cost – arguably the principal (often ignored) challenge in realizing widespread PAR adoption for atmospheric sensing**



Example NEXRAD VCPs (accessed at https://www.noaa.gov/jetstream/vcp_max Jan 2026)



Original NCAR APAR architecture (accessed <https://www.eol.ucar.edu/research-development/apar/msri-2-airborne-phased-array-radar-apar> Feb 2026)

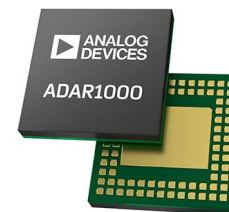


GPM DPR (accessed <https://gpm.nasa.gov/resources/images/building-dpr-jaxa> Feb 2026)

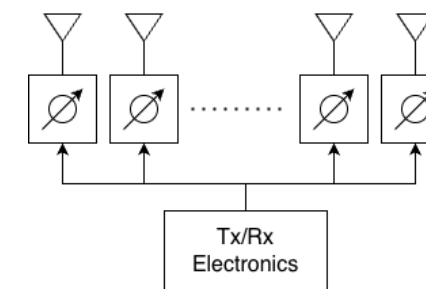
Addressing the Atmospheric PAR Cost Elephant: Metamaterials

- X-band 2D active electronically steered array (AESA) cost challenges for 1 m circular aperture ($\sim 2^\circ$ beam)
 - 1 beamforming integrated circuit and 4 Tx/Rx front-end modules for every 4 elements (optimistically $\sim \$1k$)
 - For $\lambda/2$ spacing, total element count $N \sim 3000 \Rightarrow \$750k$ just for beamformers and front ends (2x for dual-pol)
- Passive phased arrays are a general alternative to AESA that greatly simplify system complexity
 - E.g., frequency steered arrays, corporately fed phase shifter networks, 1D series fed arrays with 1D AESA steering
- Metamaterials are a newer realization of a passive phased array offering extremely low-cost relative to AESA with modest sacrifice in performance
 - Characterized by densely distributed element configuration with binary (on/off) element control
 - Pattern synthesis tools developed and validated for ruggedized satcom and target tracking radar commercial applications
 - Supports dual-polarization architectures – but none developed for commercial applications yet
 - Software-definable polarization (arbitrary linear, LH/RH circular)

ADAR1000 8-16 GHz 4-channel beamforming IC



Simplified passive array diagram (corporate feed)



Metamaterials array quadrant (top), polarization control scheme (bottom left) and holographic beamforming depiction (bottom right)

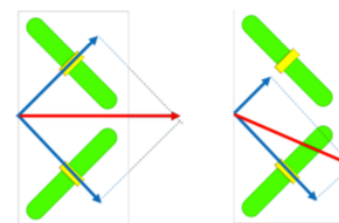
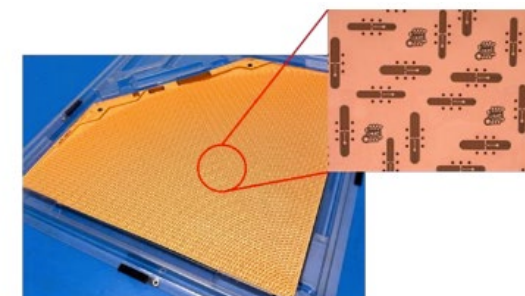


Fig. 4. Resultant E-field vectors from an equivalent modulation state (left) and rotated modulation state (right)

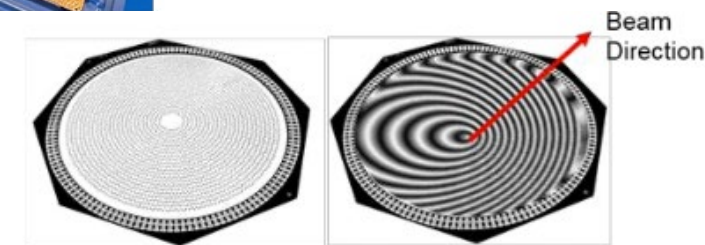


Fig. 3. Diffraction pattern on a cylindrical metasurface

ROARS – The Rain, Ocean, Atmosphere Radar System

A first-of-its-kind multimodal radar for atmospheric and sea surface sensing

- Based on commercially available, metamaterials electronic steering antennas (ESAs)
- ESA mated with Agile Radar’s custom RF electronics and a reconfigurable digital IF transceiver, or software-defined radar (SDR)
- Can be operated as a weather surveillance radar, sea surface altimeter, radar scatterometer, precipitation profiler, and/or target tracking radar
 - Inherently supports multi-modal operation
- Real-time electronic beam stabilization using on-board inertial navigation system (INS) for ground and airborne deployments
- **Drastically lower cost** than an AESA equivalent (at least 10x)
- Metamaterials = *passive phased array* ⇒ robust RF transceiver calibration = *robust far-field calibration*



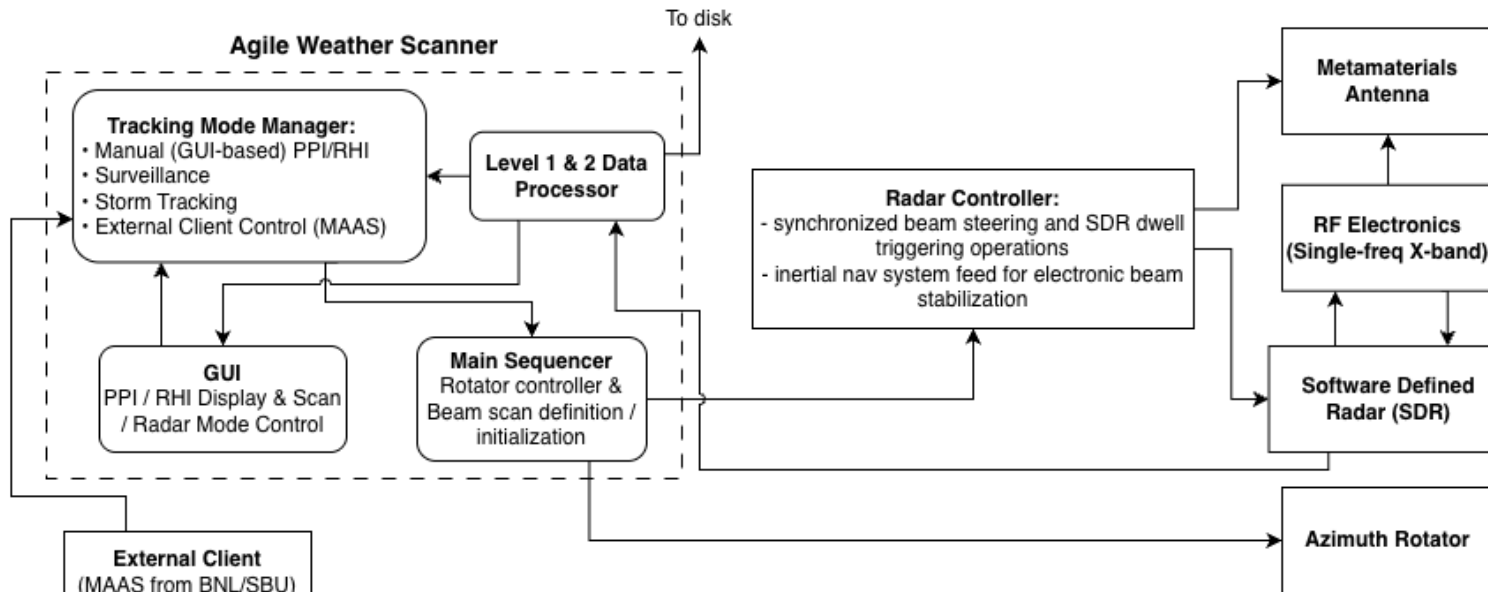
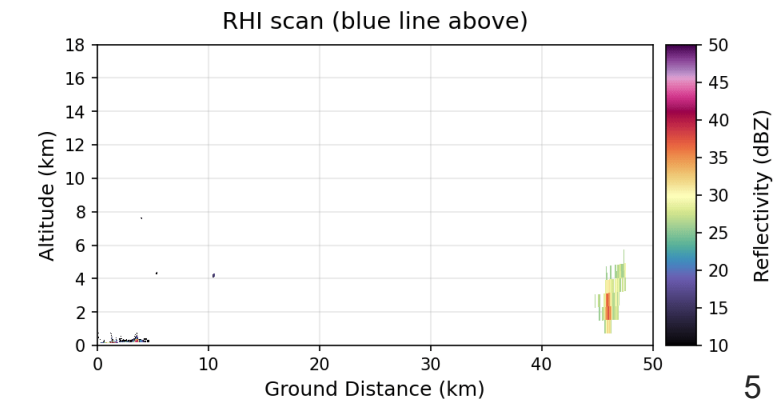
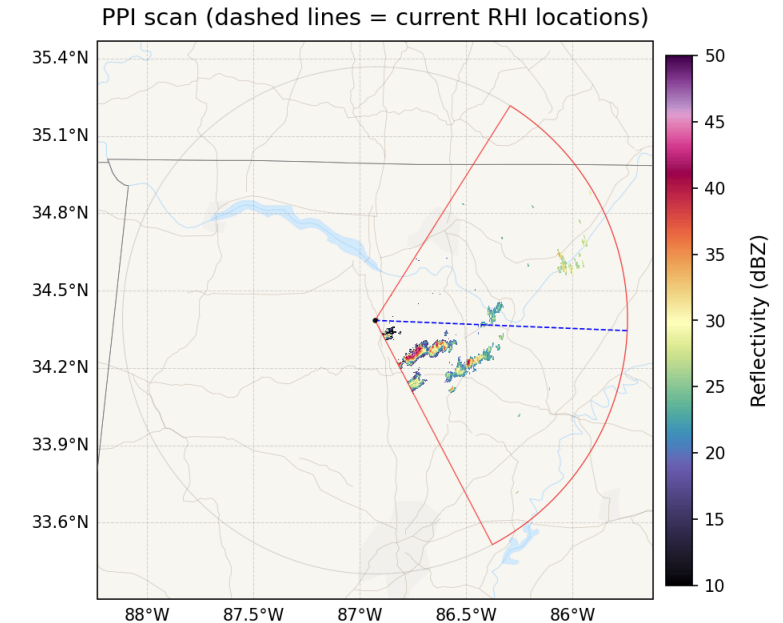
Parameter	Value
Frequency Range	13.75 to 14.5 GHz (Ku beam) 10.7 to 12.5 GHz (X beam)
Typical Operating Frequencies	14.25 GHz (Ku beam) 10.95 GHz (X beam)
Peak Transmit Power	100W (up to 50% duty)
Electronic Scan Volume	± 60° Azimuth and Elevation
Antenna Gain / 3 dB Beamwidth	Ku beam: Up to 34 dBi / 2° X beam: Up to 34 dBi / 2.2° degree
Polarization	Software-defined, arbitrary linear or circular
Sensitivity	Noise equivalent reflectivity = 5 dBZ @ 10 km (250 m range resolution)
PRF Ranges	10 Hz to 25 kHz
Pulse Widths	0.1 us to 100 us, LFM, CW, or arbitrary waveform pulses
Power Consumption	~ 500 W @ 24-36 VDC input power (max)
Weight	~38 kg (not including tower)
Temperature Range	-40 °C to +70 °C (operating) -40 °C to +85 °C (storage)

ROARS: Ground-based Surveillance & Science Applications

- Long-term deployment at DOE ARM BNF mobile observatory
- Close collaboration with Stony Brook Univ / BNL / Kollias group
- Single-face, X-band (10.9 GHz) ROARS mounted on 30-foot tower
- Real-time level 2 (reflectivity/Doppler) outputs and both manual/automated software control for adaptive sampling
- Many simultaneously accessible radar dwell/CPI modes of operation (e.g., adaptive sampling):
 - Long pulse / short pulse parameters
 - Number of pulses
 - Digital receiver processing configuration
 - Pulse repetition interval(s) & optional stagger

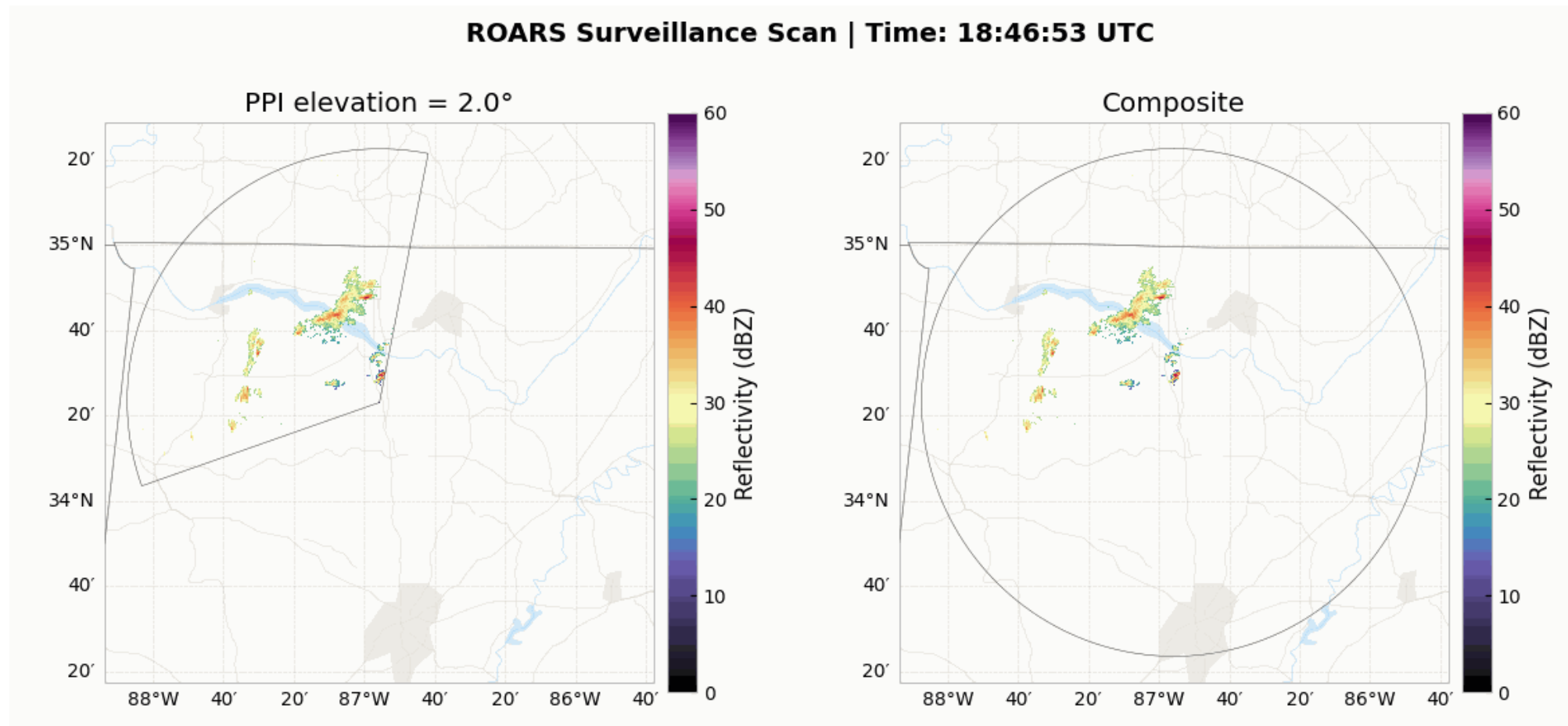


**ROARS X-band Radar Weather Surveillance
Huntsville, AL
2025-08-01 19:29:34 UTC**



Surveillance → Storm Identification/Prioritization → Tracking

- Surveillance mode consists of configurable PPI set (120° azimuth wedge) execute at each of 3 azimuth rotator positions
 - PPI execution time for 1° azimuth spacing (2x oversampling) ~10 seconds
- Full surveillance scan composite reflectivity map used to characterize convective environment:
 - Clustering using binary opening/closing and connected component labeling
 - Convective ranking using a heuristic combination of peak and peak-to-mean contrast in reflectivity – filter on initial target range and cluster size bounds

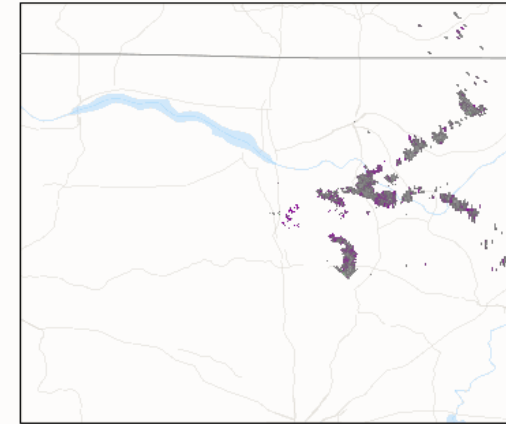
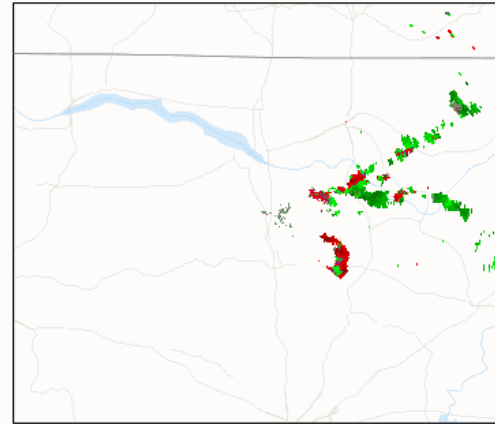
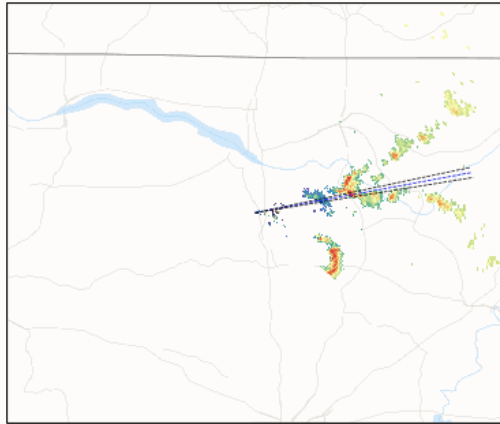


Storm Tracking & High Spatiotemporal Resolution RHI

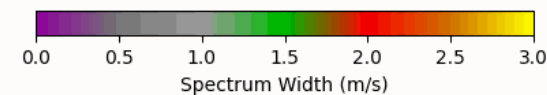
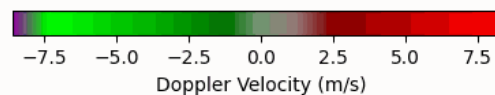
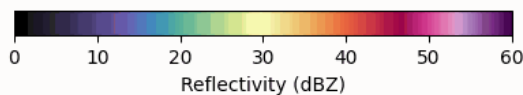
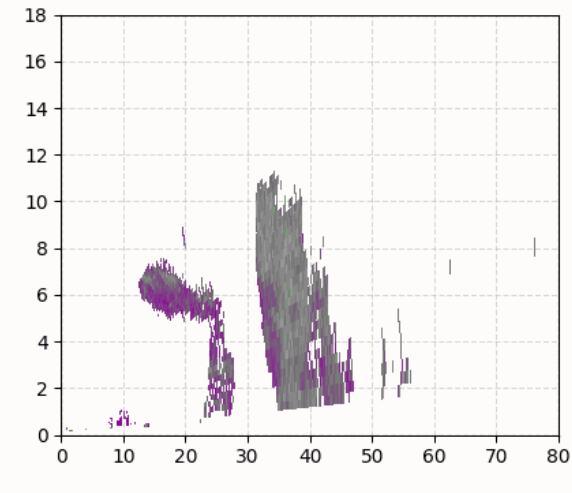
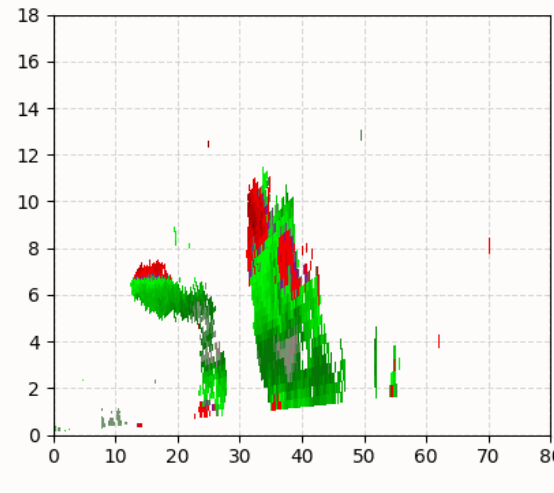
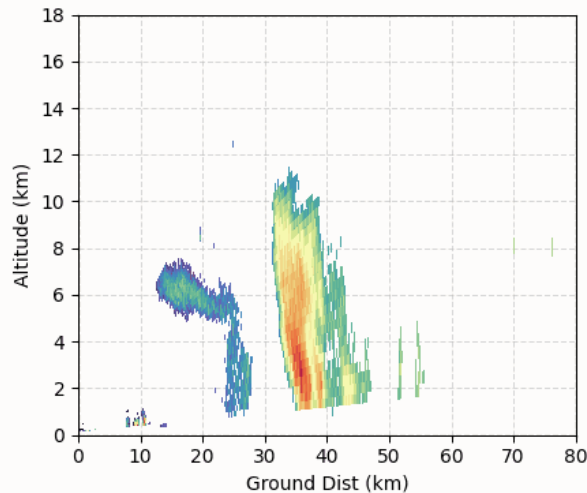
Sampling: 9/24/2025 Case Study

ROARS Tracking Scan | Time: 21:25:52 UTC

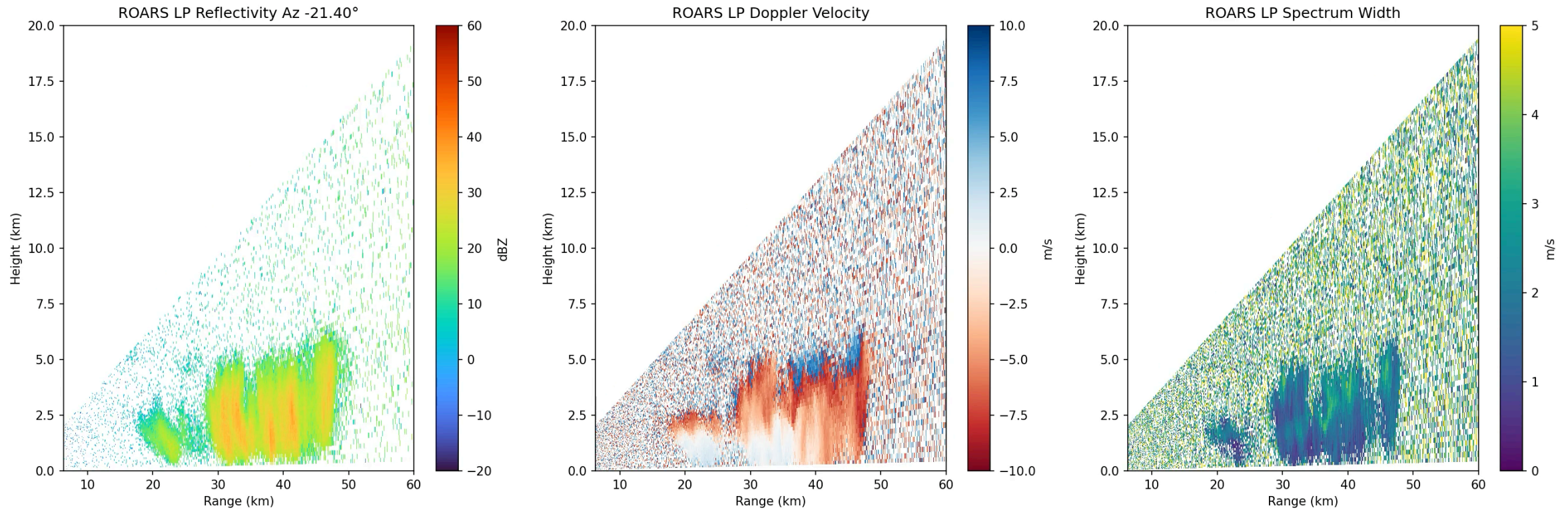
Tracker maintaining lock on point of highest reflectivity within highest priority storm feature/cluster



RHIs configured with max elevation corresponding to 20 km altitude at target location and configurable number of elevation steps (i.e., oversampled)



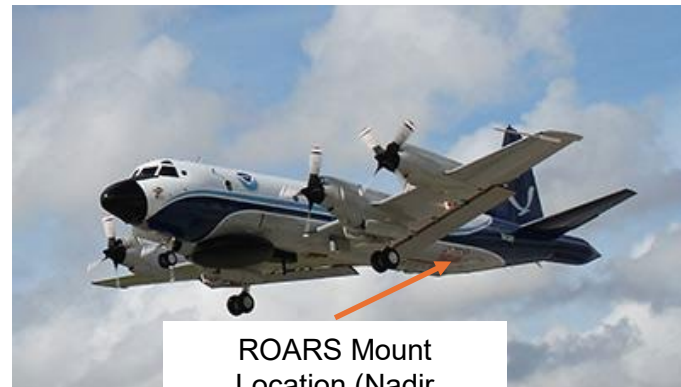
MAAS Tracker Integration: 11/20/2025 Testing



Animation courtesy of Katherine McKeown (Kollias group)

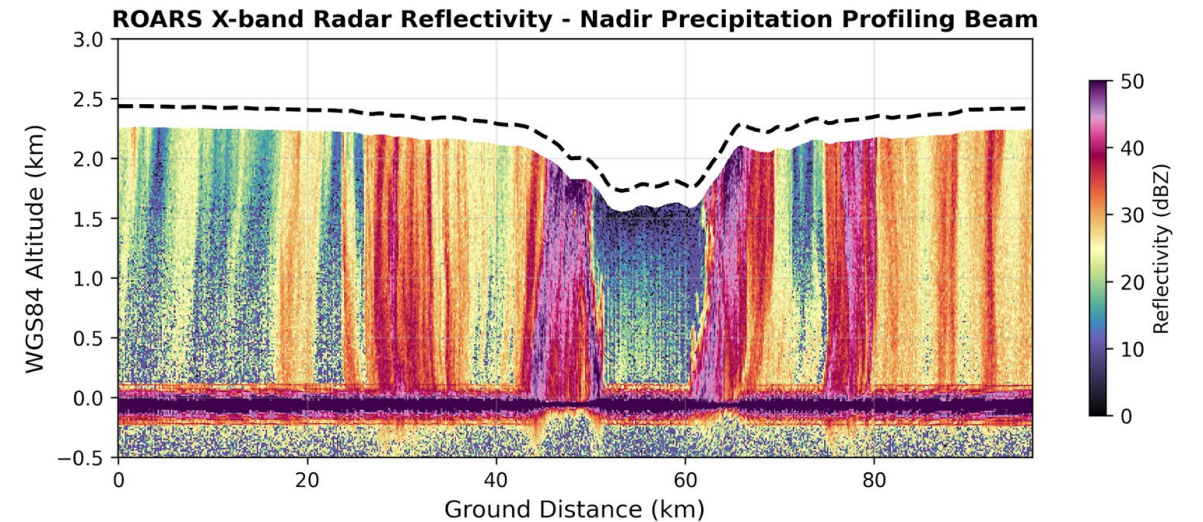
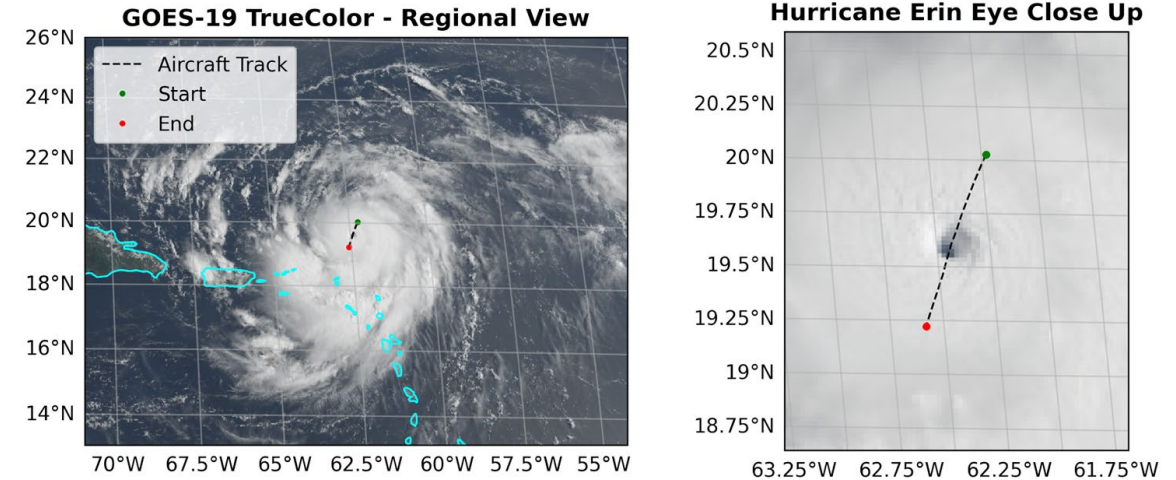
Airborne ROARS: NOAA WP-3D Hurricane Hunters

- Currently deployed on both NOAA WP-3D aircraft (N42RF and N43RF)
 - Altimeter, OSVW scatterometer, and precipitation radar (all-in-one)
 - Deployed throughout 2025 hurricane season for initial testing, calibration, and science algorithm development
 - Targeting provision of near-real-time wind, wave, and precipitation products in upcoming 2026 hurricane season



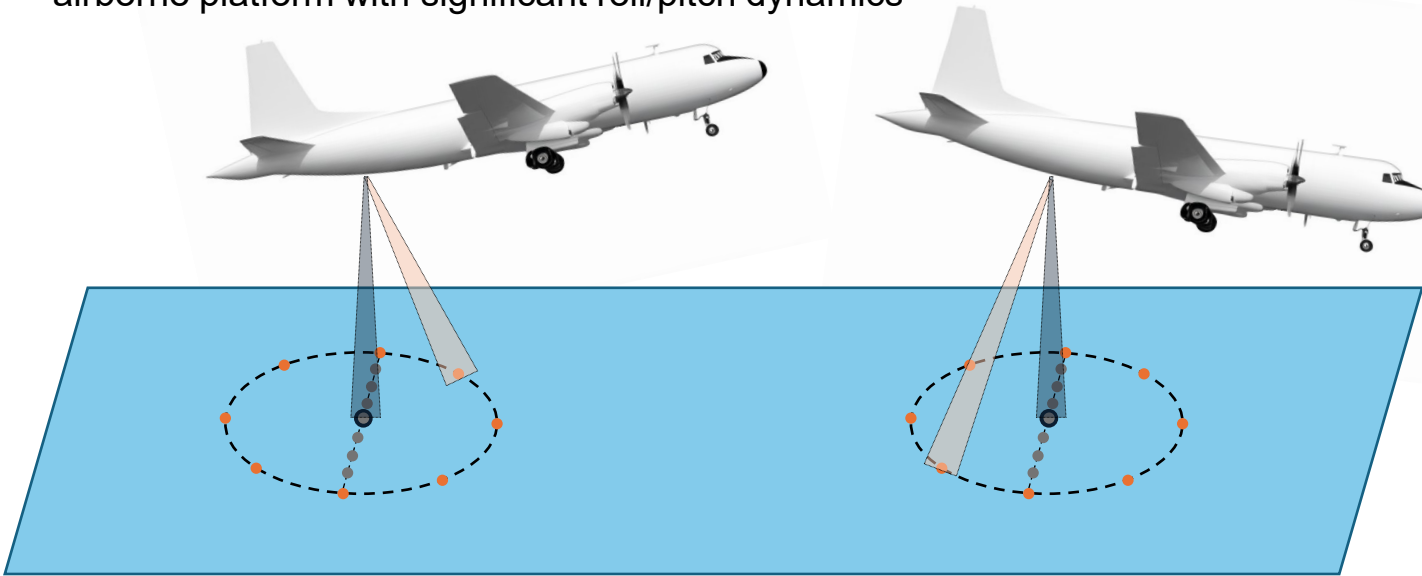
ROARS Mount Location (Nadir pointed)

Hurricane Erin Aircraft (NOAA WP-3D N42RF) Eyewall Penetration August 16, 2025, 13:21 to 13:33 UTC



Airborne ROARS CONOPS & Specifications

- ROARS operated simultaneously as a sea surface altimeter, an ocean surface vector wind scatterometer, and a Doppler precipitation radar (all-in-one)
- Illustration below of ROARS electronic beam stabilization to remove aircraft attitude variation (compensating for pitch and roll – yaw currently ignored to keep beams aligned with aircraft heading)
- Greatly simplifies interpretation of Doppler, scatterometry, and altimetry data on an airborne platform with significant roll/pitch dynamics



- Conical scan precipitation/scatterometer beams for ocean surface vector winds and precipitation Doppler winds
- Cross-track precipitation/scatterometer beams for improved near-surface sampling (clutter) and viewing geometry diversity (not depicted)
- Nadir-pointing sea surface altimetry beam for significant wave height

Precipitation/Scatterometer Mode

Parameter	Value
Pulse LFM bandwidth	0 MHz (short) / 5 MHz (long)
Pulse length	200 ns (short) / 10 μ s (long)
PRI	80 μ s
Pulses per dwell	344
Along-track sampling	125 m
Polarization	VV
Reference Sensitivity	-10/-2 dBZ at 1 km range for 150/30 m range resolution
Unambiguous velocity	67 m/s

Altimeter Mode

Parameter	Value
Pulse LFM bandwidth	240 MHz
Pulse length	10 μ s
PRI	120 μ s
Pulses per dwell	200
Along-track sampling	62.5 m
Expected significant wave height error	0.1-0.2 m

Airborne ROARS: Electronic Beam Stabilization Assessment

- Control loop attempts to keep beams “frame stable” in a local-vertical, local-horizontal (LVLH) frame
- Three independent sources of error to consider to assess stabilization fidelity:
 1. Control loop latency – i.e., time between attitude estimation used for beam steering and actual radar measurement ($\sim 30 \text{ ms} + \text{CPI} / 2$)
 2. Inertial navigation system (INS) filter estimate variance (i.e., random/systematic uncertainty in roll/pitch/yaw)
 3. Rigid body misalignment between the INS unit mounting and the antenna coordinate system (static)

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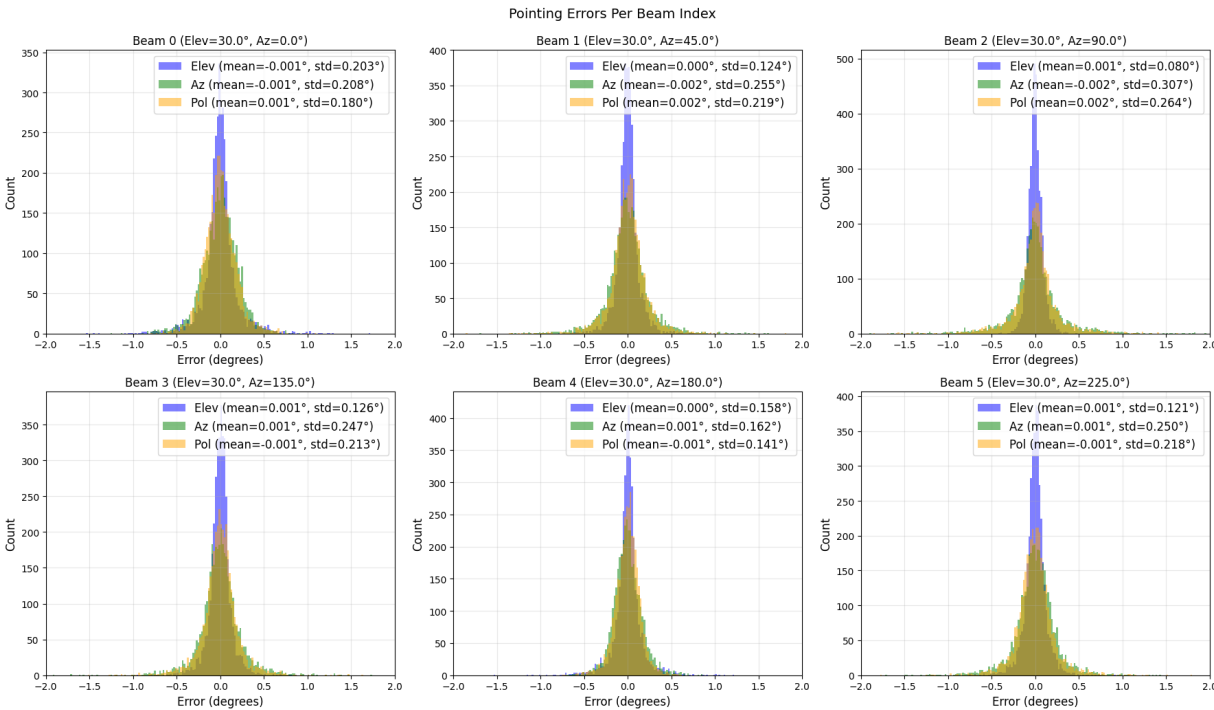
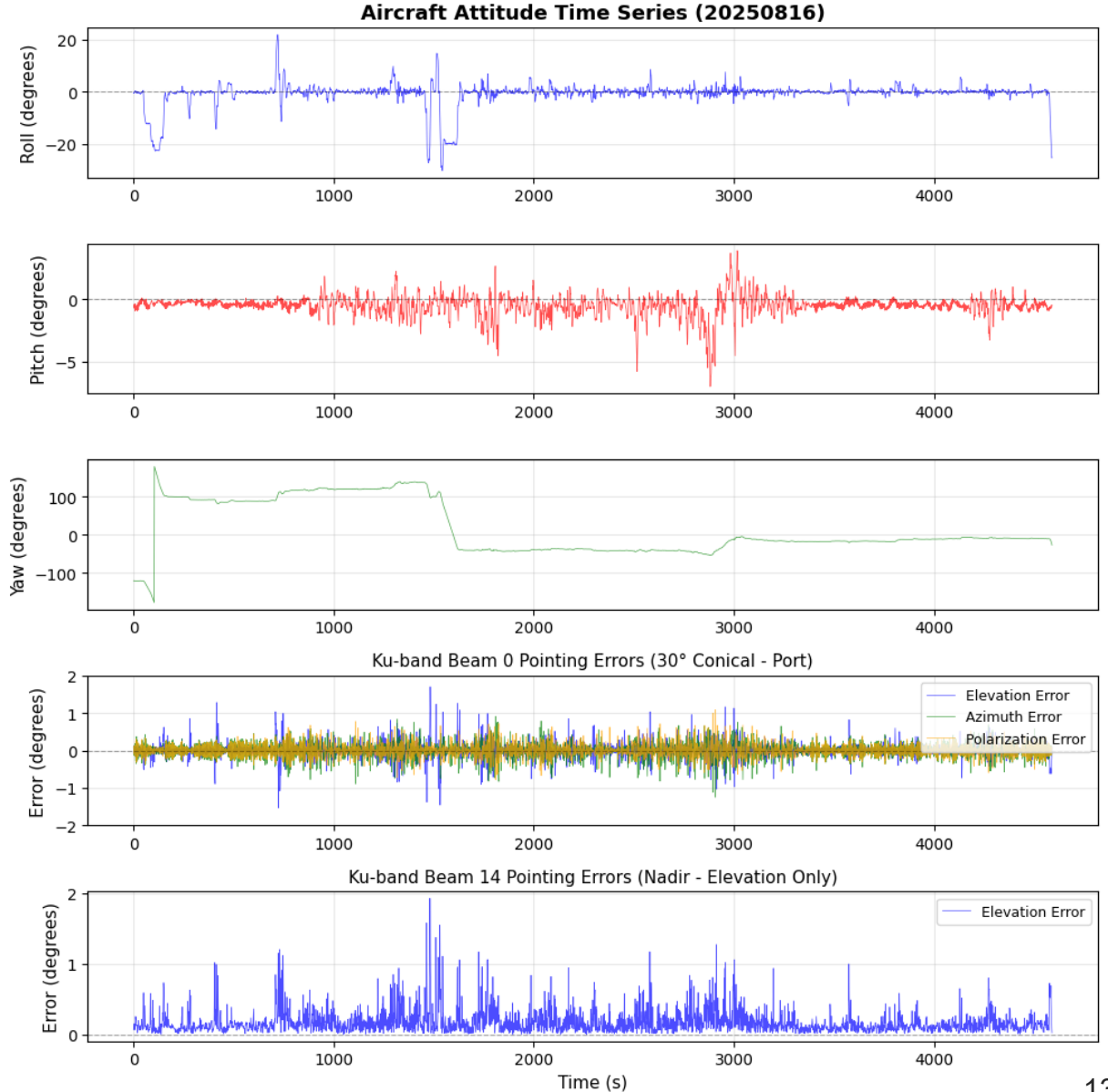
Can be estimated using high-rate INS data, comparing attitude at time of steering command and radar CPI mid-point

Combined impact can be estimated on a scan-by-scan basis from ocean surface scattering measurements themselves:

- *Surface Doppler shift sensitive to pitch/yaw*
- *Surface range measurement sensitive to pitch/roll*

Airborne ROARS: Electronic Beam Stabilization Assessment

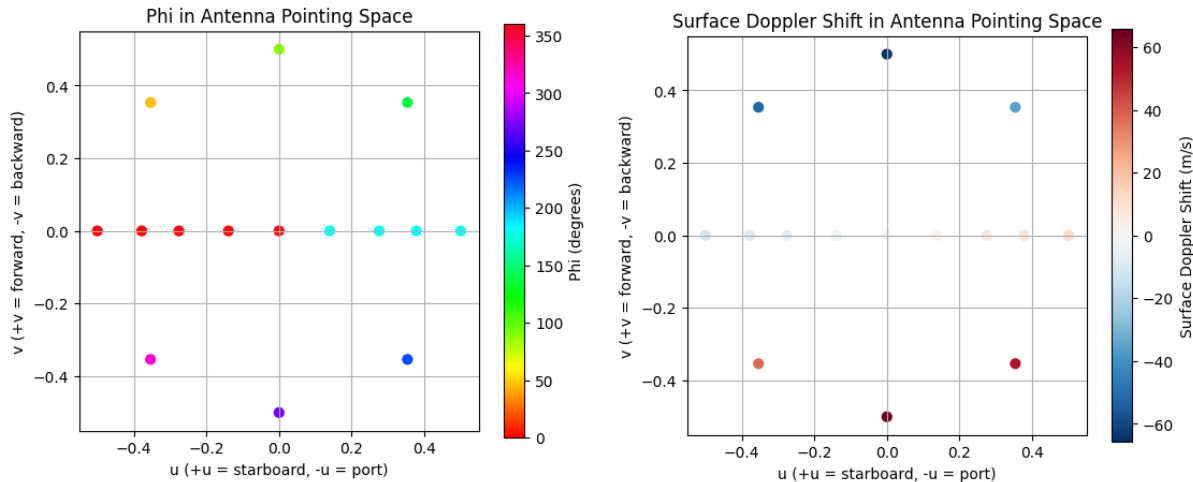
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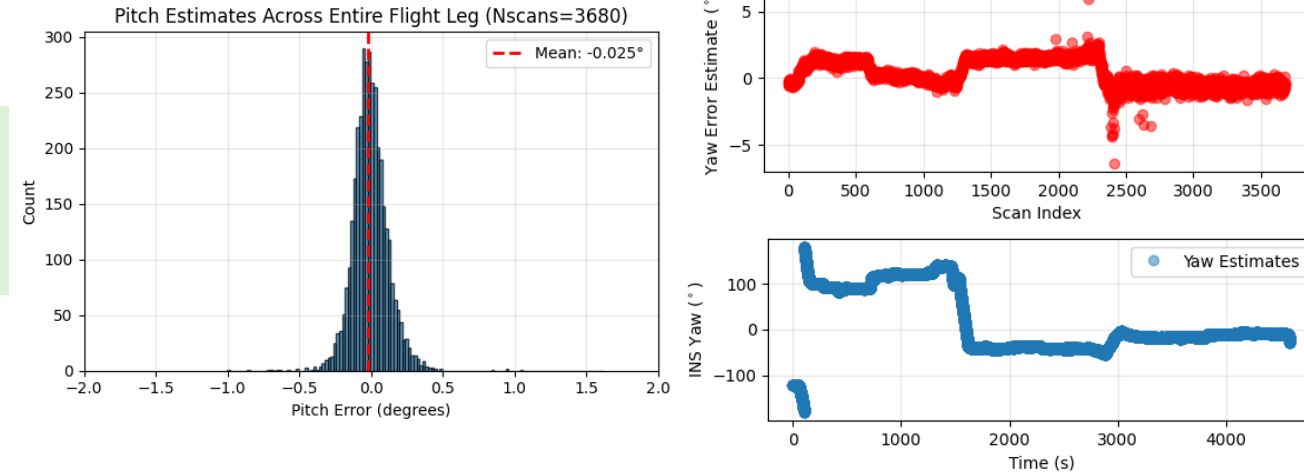
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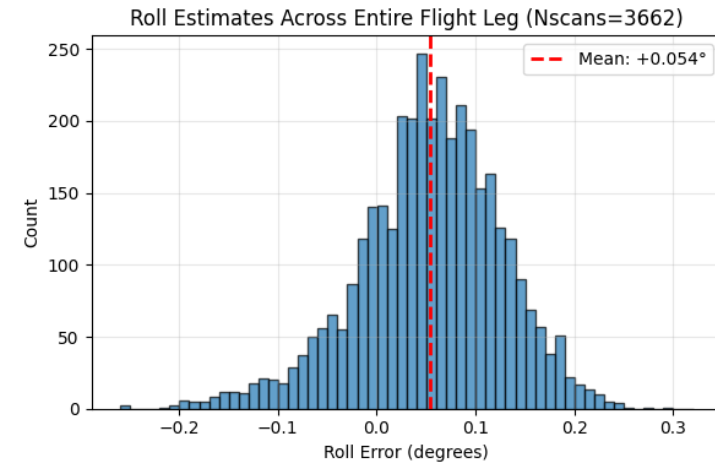
16-beam scan configuration and observed surface Doppler velocity



Solve for pitch and yaw errors as a linear least squares problem (predicted vs. observed surface Doppler across scan)

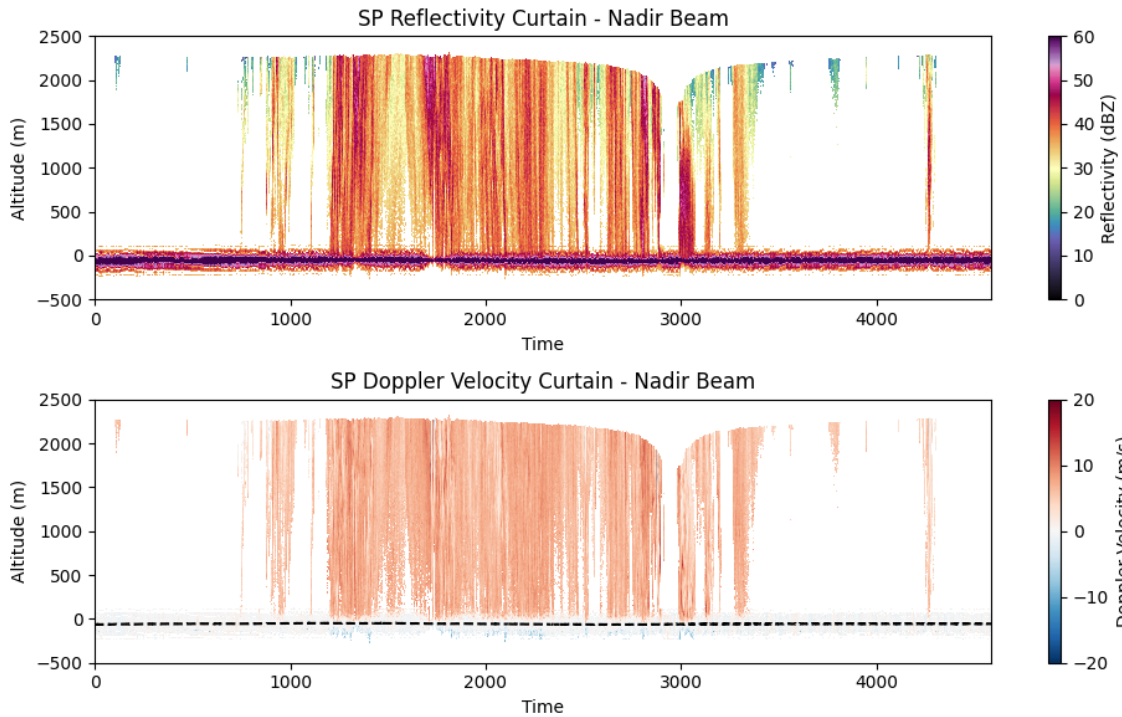


Solve for roll error using ratio of observed range to surface across scan (also LLS)

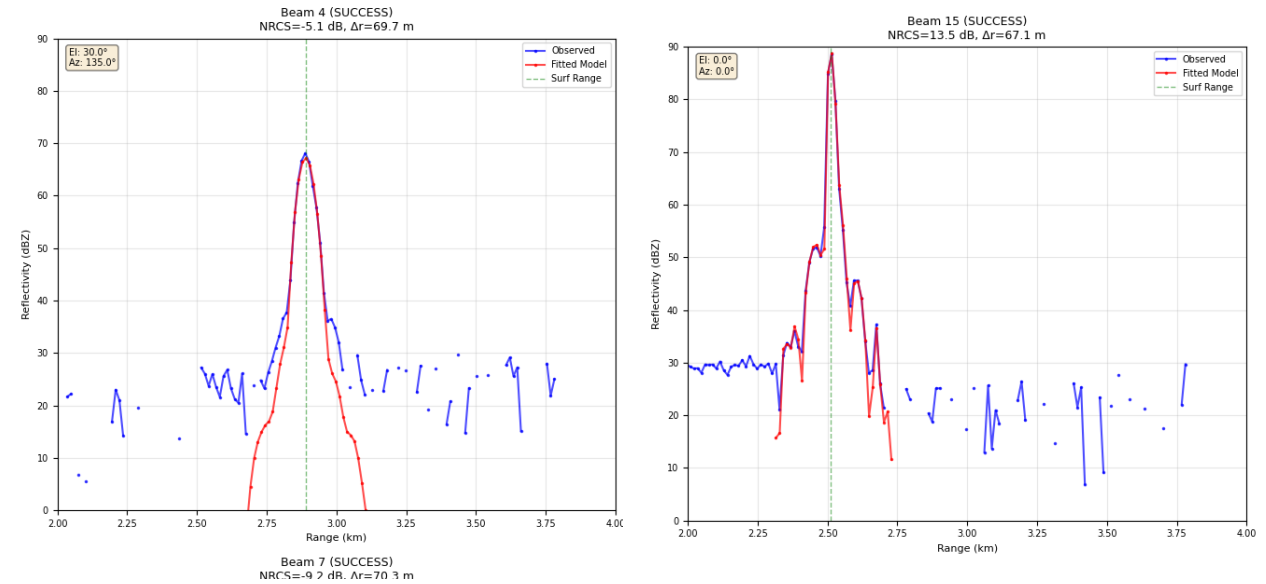


Airborne ROARS Data Products: Precipitation and Surface

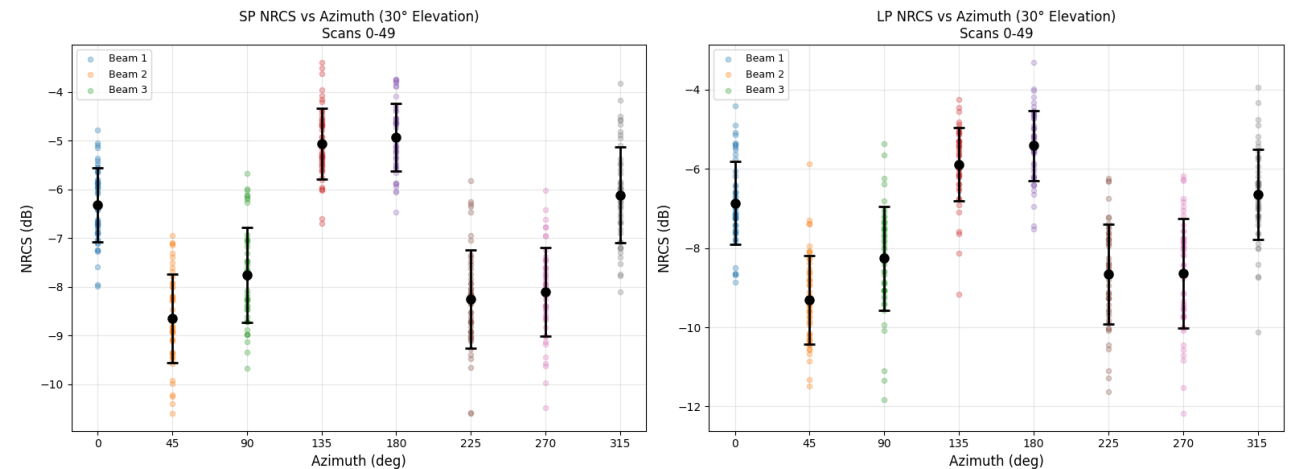
- Calibrated level 1 product includes observed (attenuated) reflectivity, aliased Doppler velocity, raw IQ for near surface gates for spectral processing, position/attitude information, and detailed surface characterization
- Level 1 surface module includes forward modeling of surface reflectivity response given detailed simulated antenna beam pattern, fits to observed surface, and multiple NRCS/surface range estimates



Forward modeled surface response fit to observation

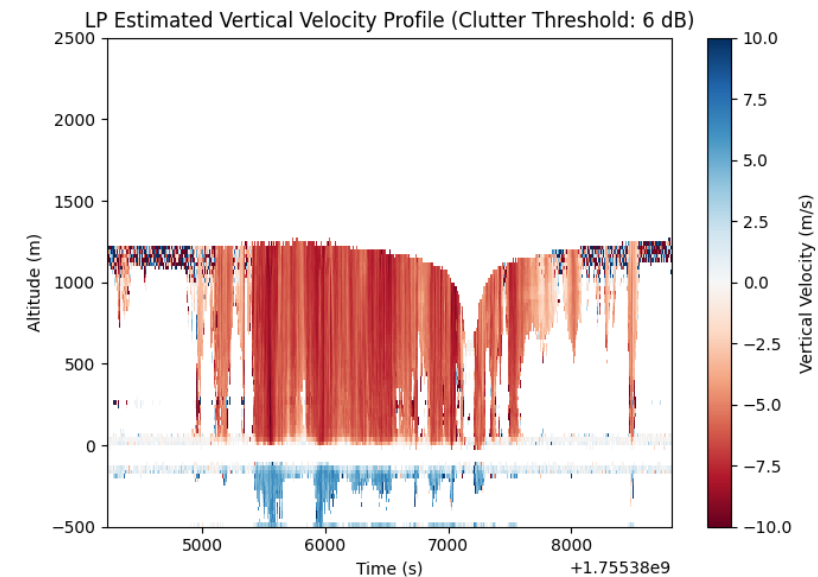
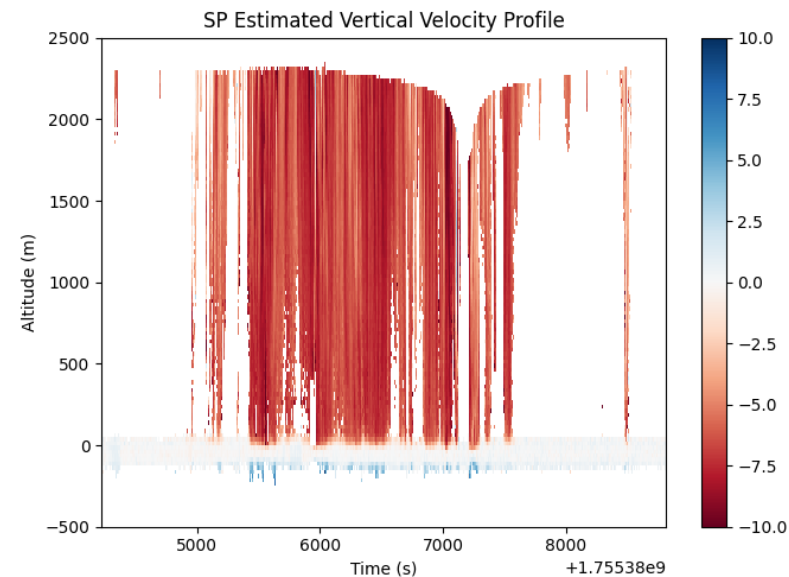
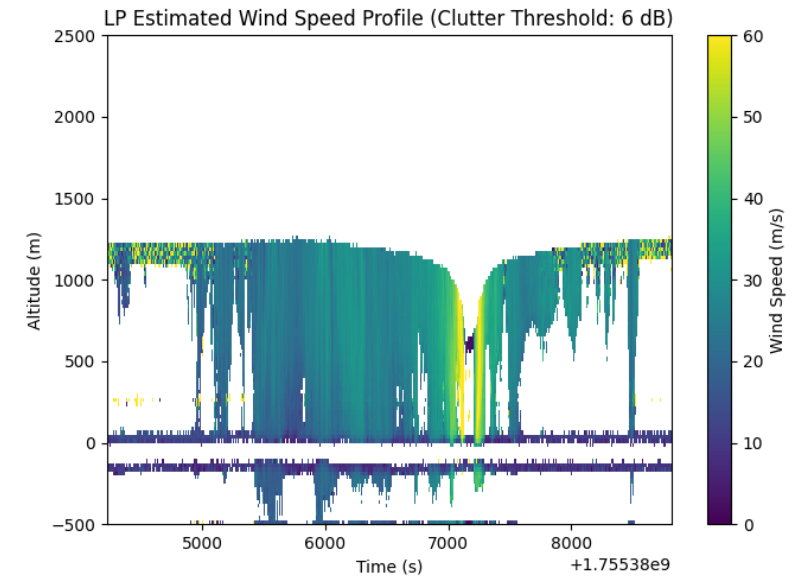
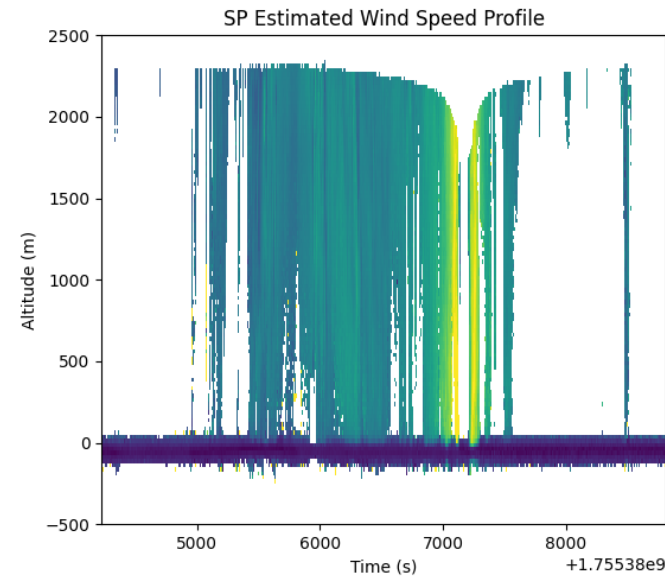


Observation of NRCS azimuth modulation for 30° conical scan



Airborne ROARS Data Products: Doppler Wind Retrievals

- Showing Ku-band data from Hurricane Erin observations on 8/16/2025
- Aircraft platform Doppler removed and velocity folded back into Nyquist domain
- 3D vector wind retrieval performed on constant WGS84 altitude grid (25 m)
- Long pulse data masked for signal-to-clutter ratio of > 6 dB (uses the forward modeled surface backscatter profile)

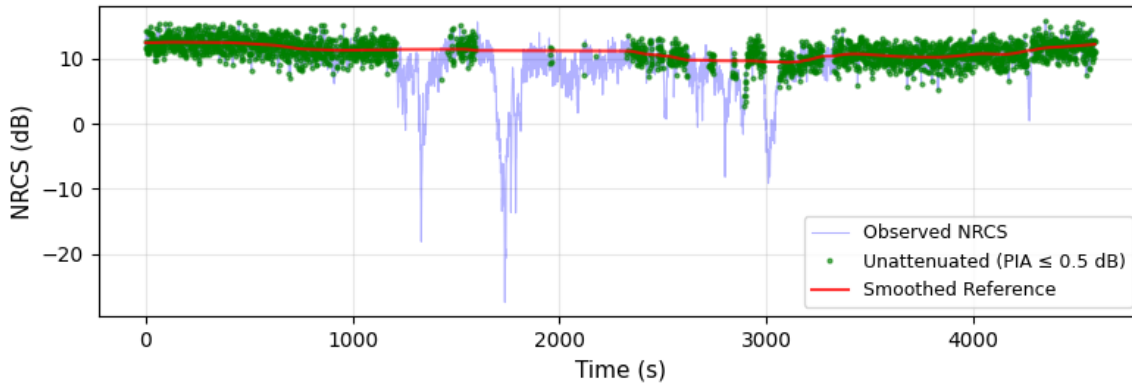


PIA Estimation & OSVW Retrievals (PRELIMINARY)

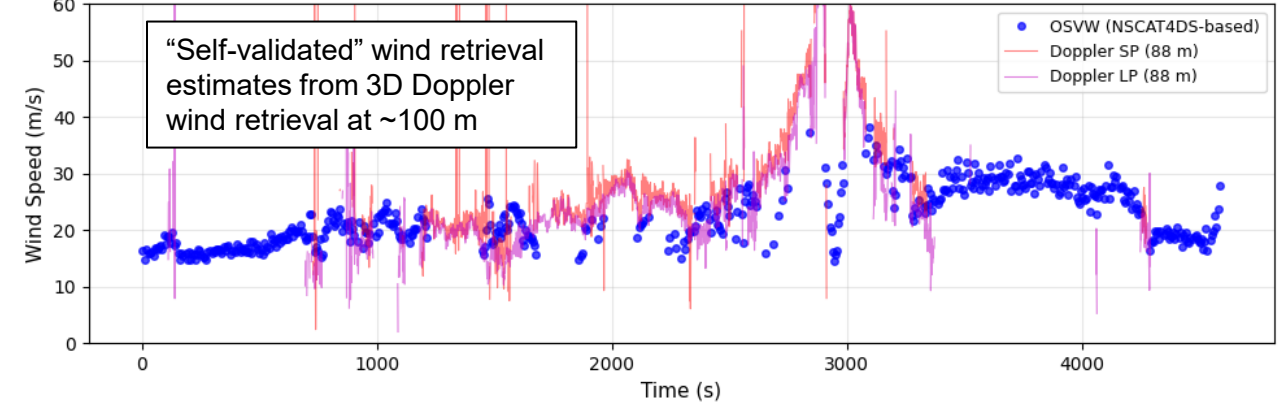
- Utilize nadir beam for PIA analysis because of high NRCS
- First-pass PIA estimation using k -Z relation and Hirschfeld-Bordan
- Threshold on first-pass PIA to derive smoothed unattenuated NRCS and therefore PIA measurement (surface reference technique)

- Use measured PIA to flag scans before OSVW retrieval (potential for PIA-corrected retrievals) using 30° conical scan beams
- Initial tests using NSCAT4DS geophysical model function
- Two-stage retrieval – (1) estimate 10-meter wind speed with average NRCS; (2) retrieve wind direction with NLS GMF fit (susceptible to 180 deg ambiguity)

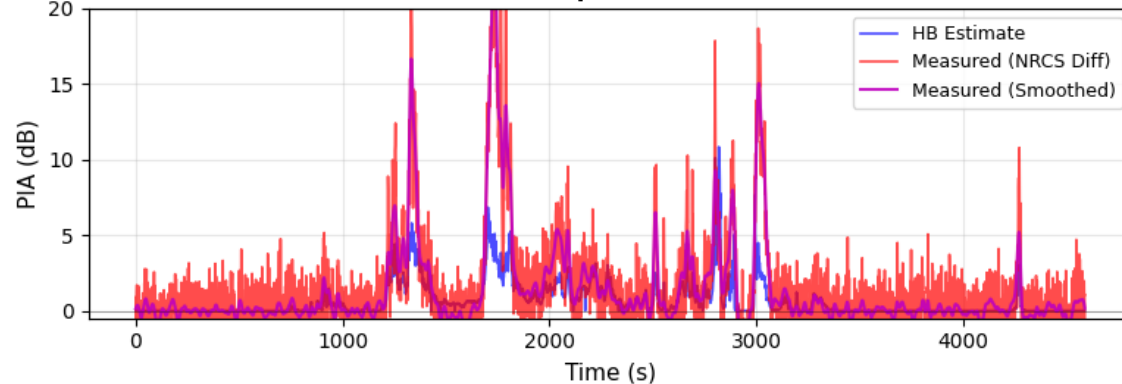
Nadir Beam Surface NRCS: Observed vs. Smoothed Reference



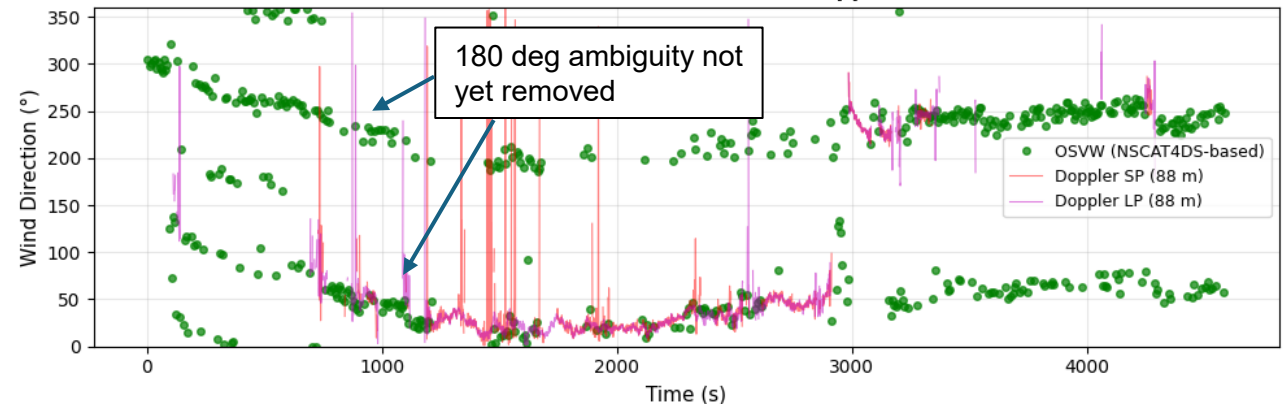
Retrieved Wind Speed (OSVW vs Doppler at 88 m)



Nadir Beam PIA Comparison: HB vs. Measured



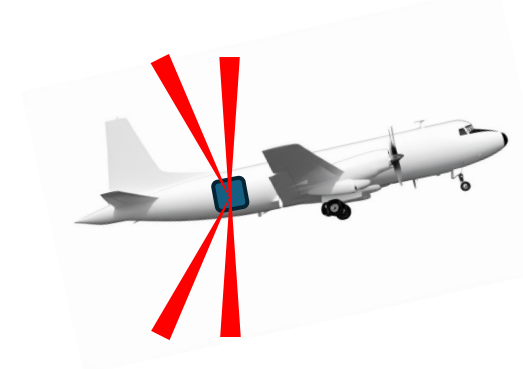
Retrieved Wind Direction (OSVW vs Doppler at 88 m)



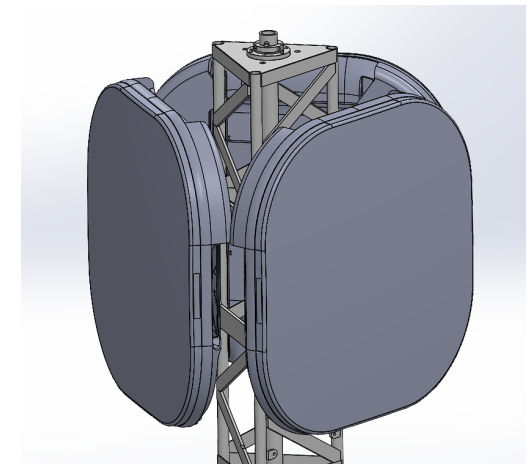
Summary and Outlook

- ROARS is the first atmospheric radar based on metamaterials antenna technology, and proves viability of low-cost, X/Ku-band electronically scannable radar for a wide range of weather surveillance and science applications
- Control loop for frame-stable ground/airborne electronic beam steering validated with detailed error quantification from airborne observations of the surface
- Demonstrated automated storm identification and tracking capability during DOE ARM BNF summer 2025 season – exciting plans for severe storm dynamics studies in Spring/Summer 2026
- Airborne ROARS:
 - Preliminary retrievals of Doppler wind profiles and OSVW
 - Provision of near-real-time winds, waves, and precipitation for NOAA 2026 hurricane season
 - Plan to try out new scan strategies for optimized wind retrieval
- Future simultaneous dual-pol X-band metamaterials system
- Three-face ROARS for comprehensive/instantaneous 3D volume coverage with no rotator assembly

ROARS-based solution for improved TDR-like (Tail Doppler Radar) measurements leveraging proven e-beam stabilization



Three-face weather surveillance ROARS for increased coverage rates and adaptive storm tracking capabilities

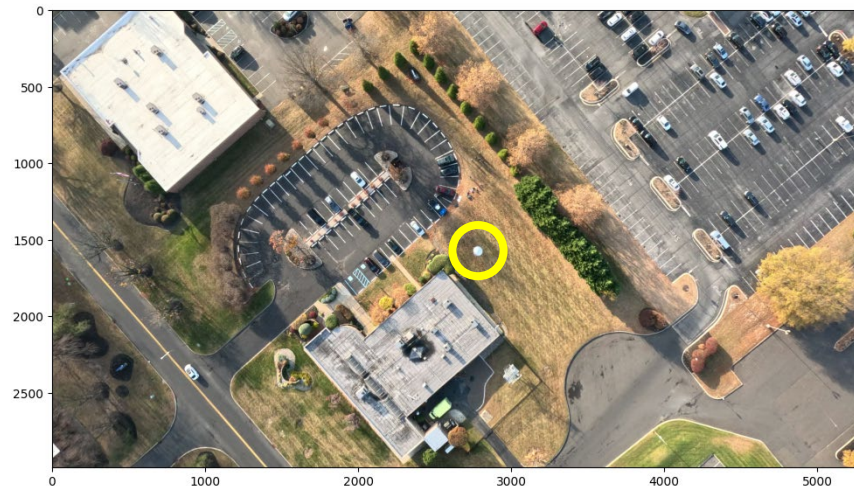


A Drone-Based Method for Calibrated Pattern Measurements

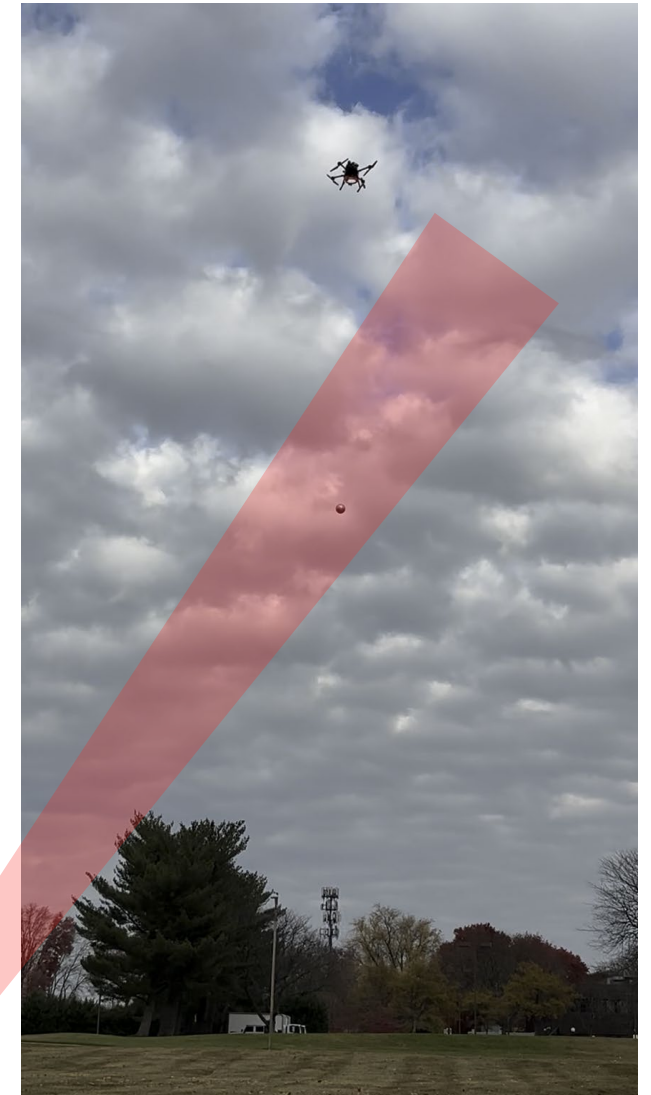
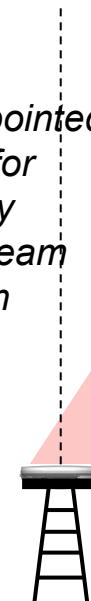
- Utilize high-sphericity aluminum target (10" sphere from Century Metal Spinning)
- Suspend sphere using low-dielectric, thin tether 10-20 meters beneath drone flying at ~400 ft AGL
- Given radar orientation and e-steered beam angle, generate drone flight path that performs raster scan over expected main lobe position
- Use drone position+attitude and mounted context camera (GoPro) to derive GPS-time-tagged absolute sphere position
- Correlate with GPS-time-tagged radar measurements with sphere location to derive 2D calibrated beam pattern



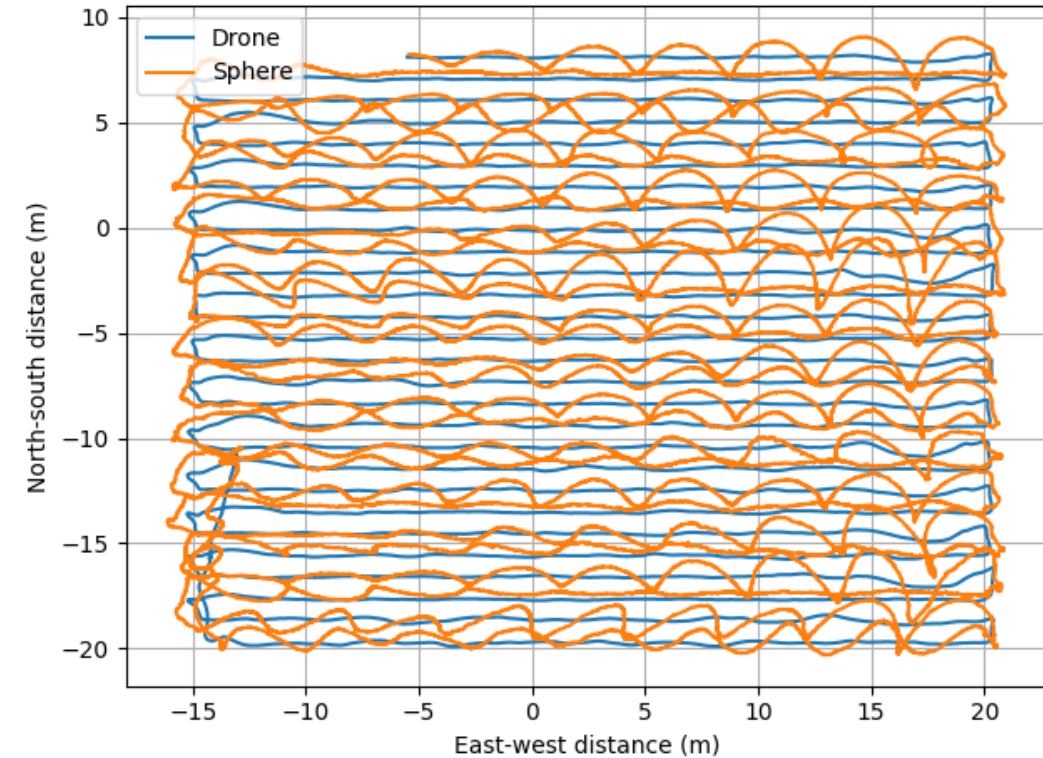
Image of sphere from drone context camera



ROARS pointed at zenith for electrically steered beam calibration



Calibration Sphere Tracking and Geolocation



Sphere position vector in North-East-Down navigation (“n”) coordinate system:

$$[\mathbf{x}_s]_n = [\mathbf{x}_d]_n + R_n^d R_d^g [\mathbf{x}_s]_g$$

Drone position vector in navigation coord sys

Transformation from drone to navigation coord sys (uses drone pitch, roll, yaw)

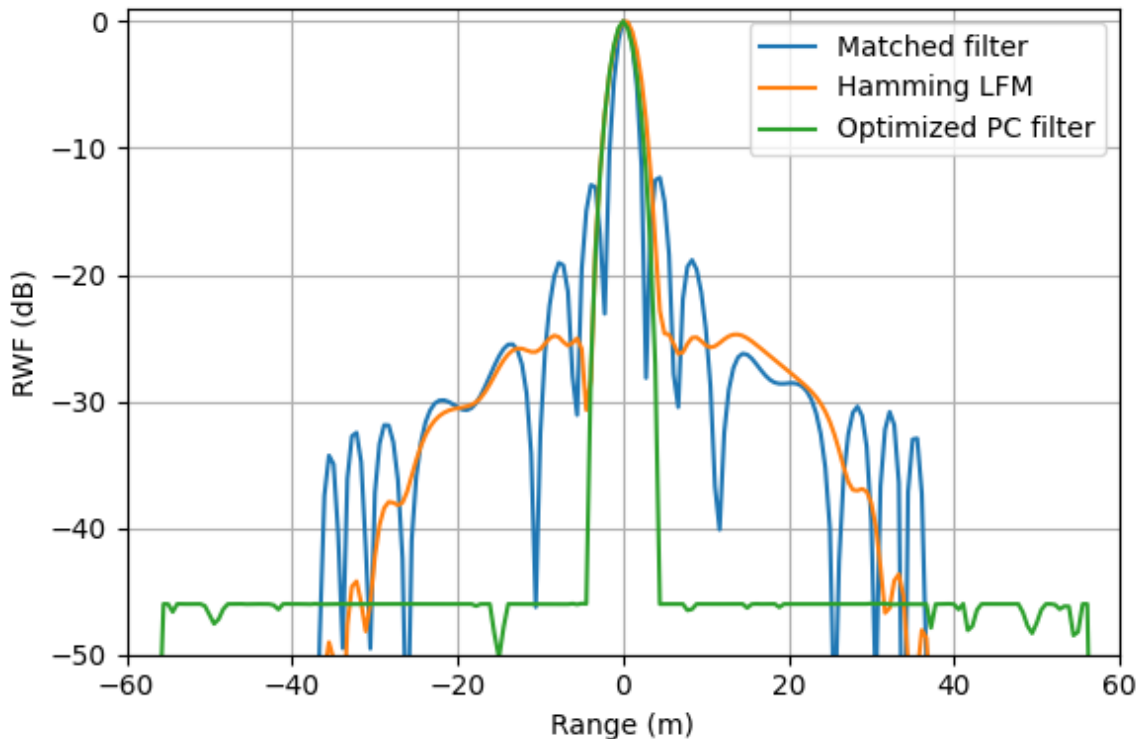
Sphere position in the GoPro (“g”) camera-centered coord sys (uses tracked pixel position and known tether length)

Transformation from GoPro to drone (“d”) coord sys

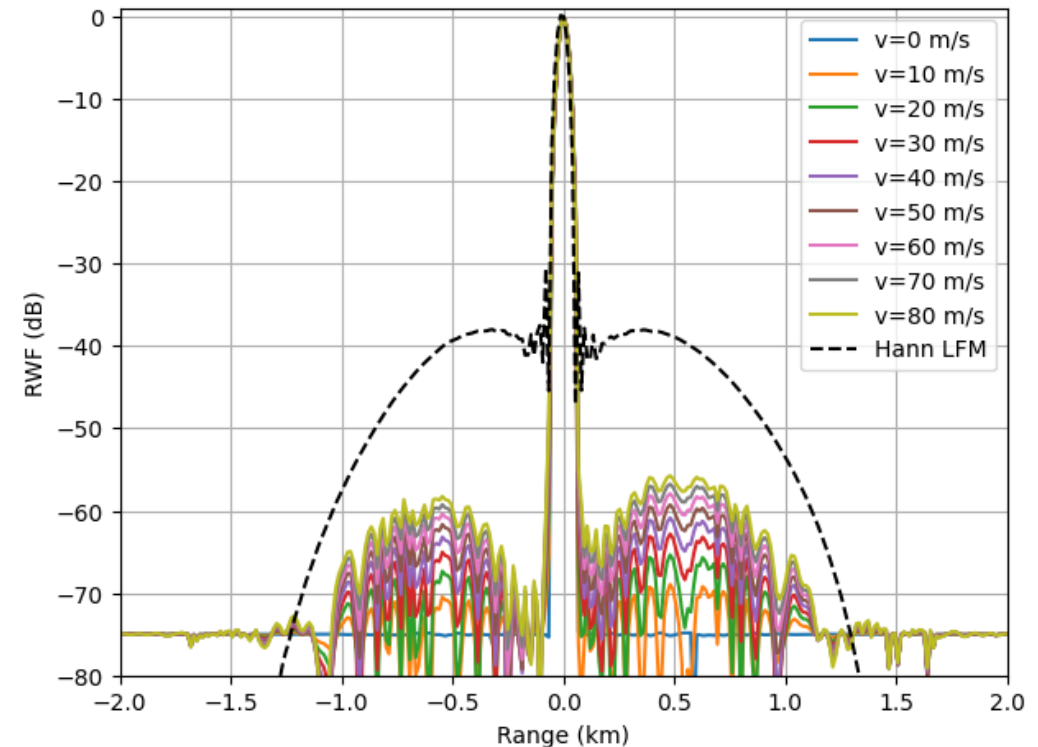
Pulse Compression Filter Optimization

- Calibrate using short (250 ns) 60 MHz LFM pulse to provide accurate cal at target frequency
- Challenge: range sidelobe contamination from drone backscatter in the sphere range bin (separation ~4-8 bins)
- Designed mismatched filter for LFM pulse that sacrifices some Doppler sensitivity for greatly reduced range side lobes using a convex optimization method

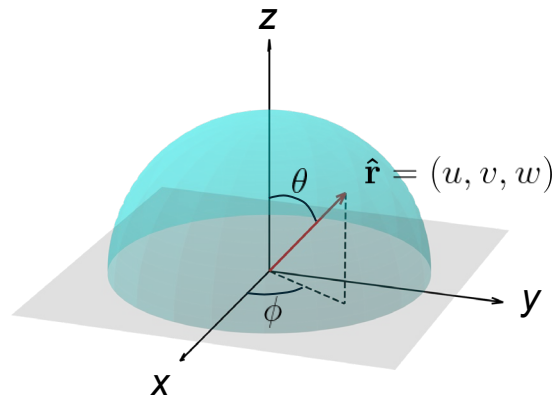
Optimized using 250 ns measured drone calibration waveform



Optimized using 10 μ s measured weather surveillance waveform



Calibrated Beam Pattern and Sensitivity Assessment



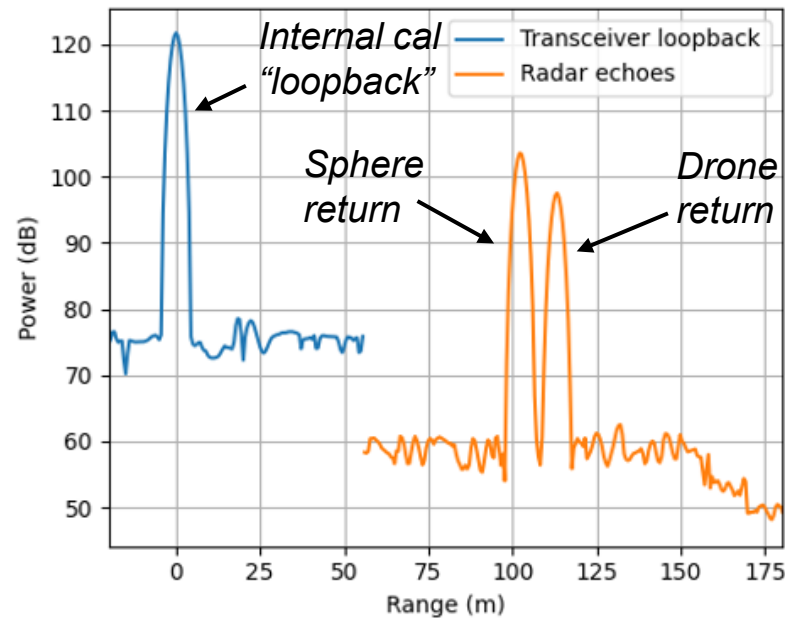
$$u = \sin(\theta) \cos(\phi)$$

$$v = \sin(\theta) \sin(\phi)$$

- Measured calibration sphere signal SNR related to key weather radar equation parameters:

$$\text{Sensitivity: } \text{SNR}_{\text{peak}} = \frac{P_{tx} \lambda^2 G_a^2 \sigma_s \tau}{(4\pi)^3 r_s^4 k_B T_{\text{sys}} L_w}$$

- This method *directly* measures the 2D beam shape and there for integrated volume, which is the only remaining unknown in the radar reflectivity calibration equation.
- Execute tests for ~10 electronic steering angles within 120° FOV to calibrate across scan



Geolocated beam pattern measurement expressed in the native u/v coordinate system of the antenna array

