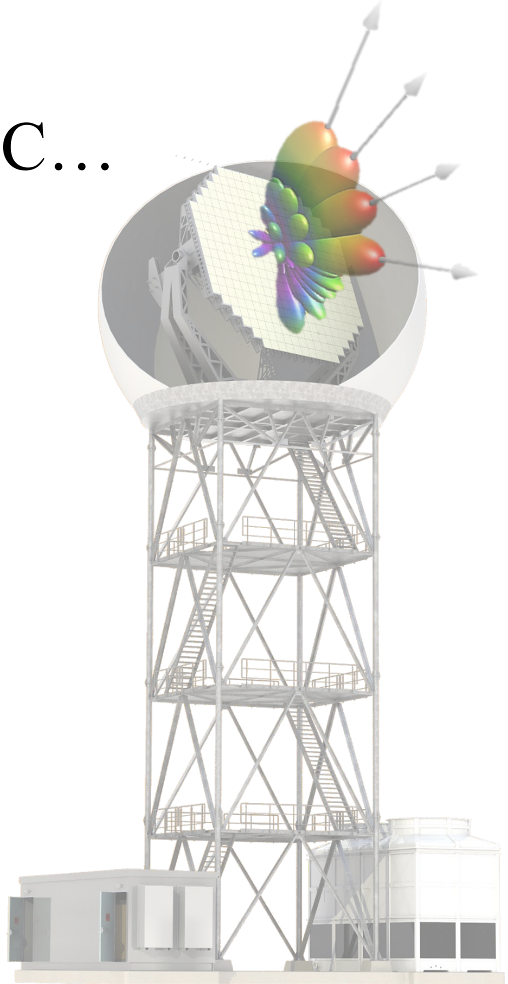
Advancements in PAR and Bistatic Radar Hardware and Capabilities

David Schvartzman, Robert Palmer
and many collaborators from the ARRC, OU, NSSL, NWC…

OU – **A**dvanced **R**adar **R**esearch **C**enter (**ARRC**)
OU – **S**chool **o**f **M**eteorology (**SoM**)
OU – School of **E**lectrical and **C**omputer **E**ngineering (**ECE**)

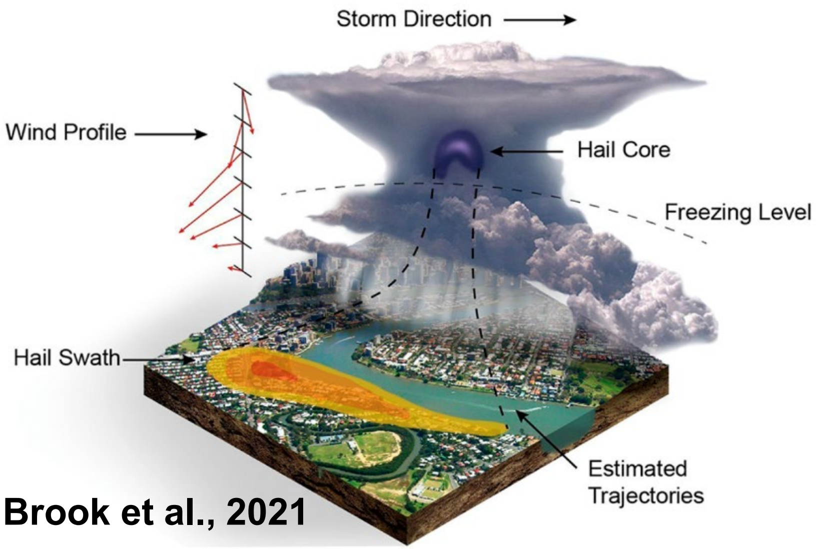
NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

NSF NCAR
RADAR TECHNOLOGY
community workshop

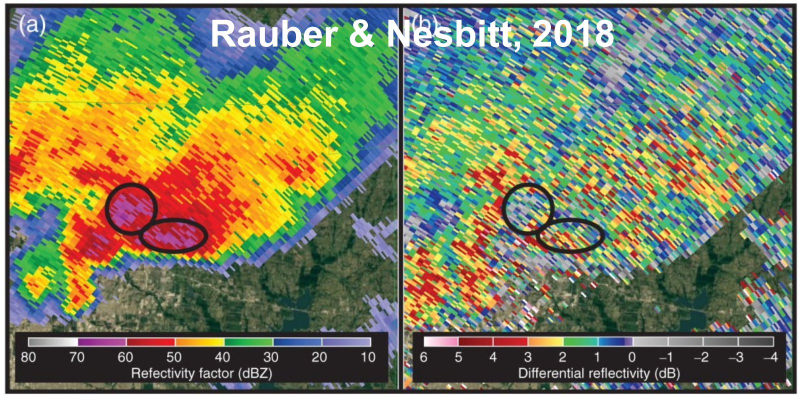


Weather Radar Development Decisions

How Science Drives Technical Decisions



Brook et al., 2021



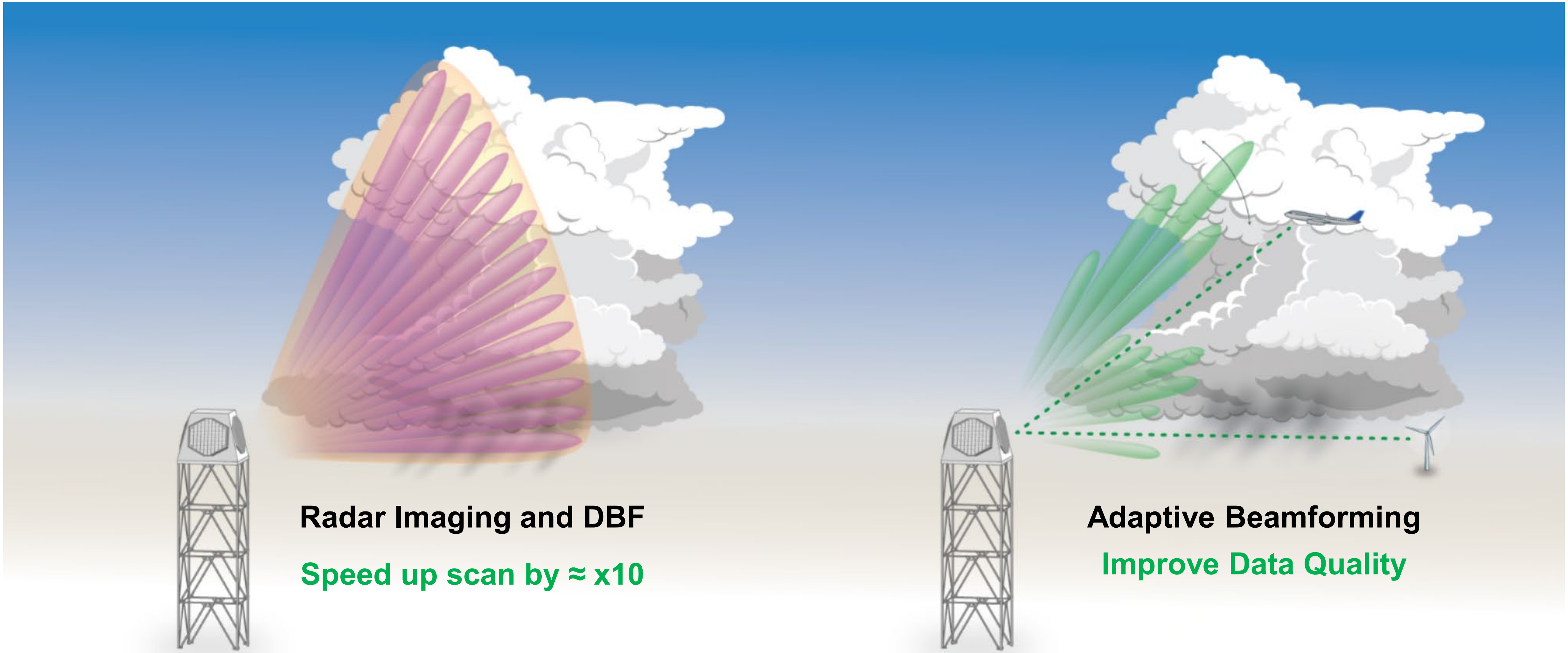
Rauber & Nesbitt, 2018

- **What is the observable scatterer (e.g., rain, snow, cloud particles, turbulent eddies) and the desired observation range?**
  - ➢ **Scattering, attenuation, sensitivity (wavelength, transmit power, antenna gain)**
- **Is the observable scatterer geometrically complex?**
  - ➢ **Polarimetry**
- **Within the observation range, what are the spatial scales of interest?**
  - ➢ **Spatial resolution (bandwidth, antenna size)**
  - ➢ **Fine/adaptive angular sampling (mechanical vs phased array)**
- **Are the atmospheric processes rapidly evolving?**
  - ➢ **Temporal resolution (mechanical vs phased array)**

Many atmospheric observational needs naturally lead to a polarimetric phased array radar

- Robert Palmer et al., A Primer on Phased Array Radar Technology for the Atmospheric Sciences, Bulletin of the American Meteorological Society, Oct 2022.
- Pavlos Kollias et al., Science Applications of Phased Array Radars, Bulletin of the American Meteorological Society, Oct 2022.

Potential of Phased Array Radar (PAR) for Polarimetric Weather Observations



Radar Imaging and DBF

Speed up scan by ≈ x10

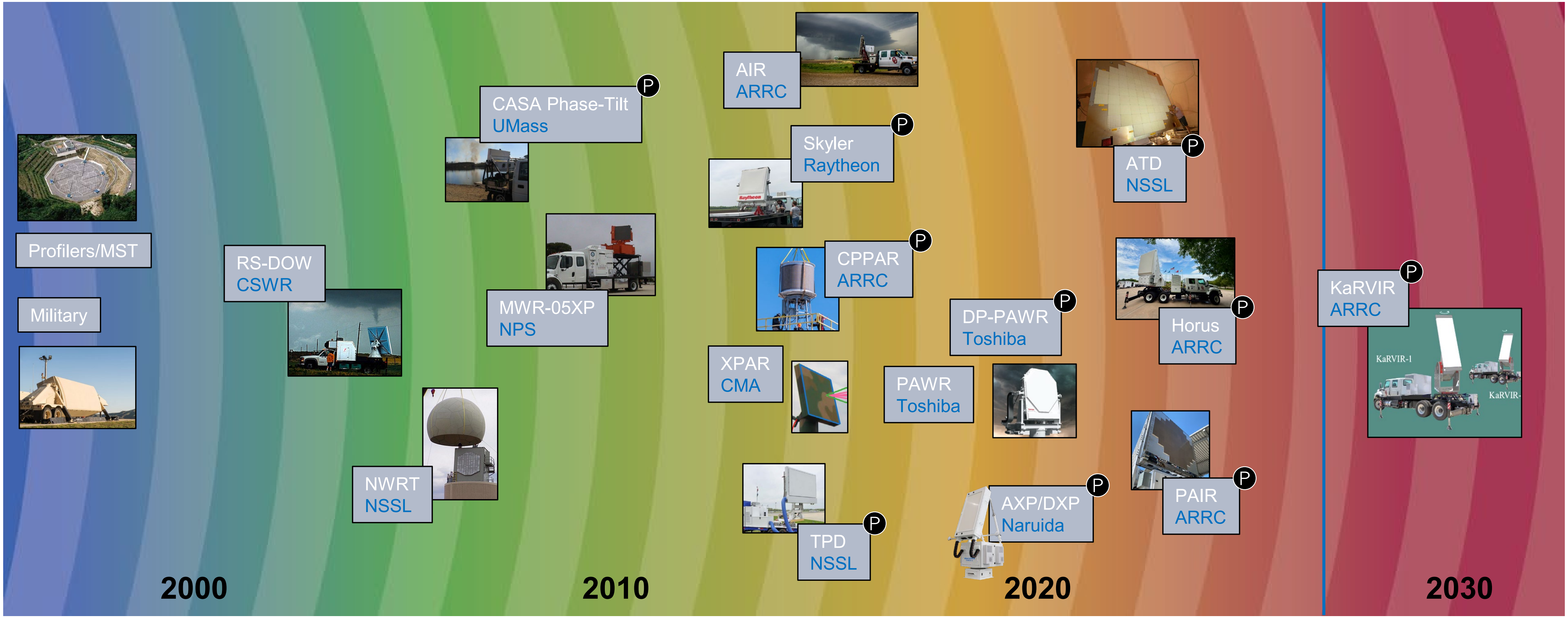
Adaptive Beamforming

Improve Data Quality

R. D. Palmer and D. Schvartzman, "Emerging Trends in Radar: Phased Arrays for Weather Observations," in IEEE Aerospace and Electronic Systems Magazine, vol. 40, no. 6, pp. 60-64, June 2025, doi: https://doi-org.ezproxy.lib.ou.edu/10.1109/MAES.2024.3524937

Phased Array Radar R&D History

Ground-Based Atmospheric Radar



Profilers/MST

Military

RS-DOW
CSWR

NWRT
NSSL

CASA Phase-Tilt
UMass P

MWR-05XP
NPS

AIR
ARRC

Skyler
Raytheon P

CPPAR
ARRC P

XPAR
CMA

TPD
NSSL P

PAWR
Toshiba

DP-PAWR
Toshiba P

AXP/DXP
Naruida P

ATD
NSSL P

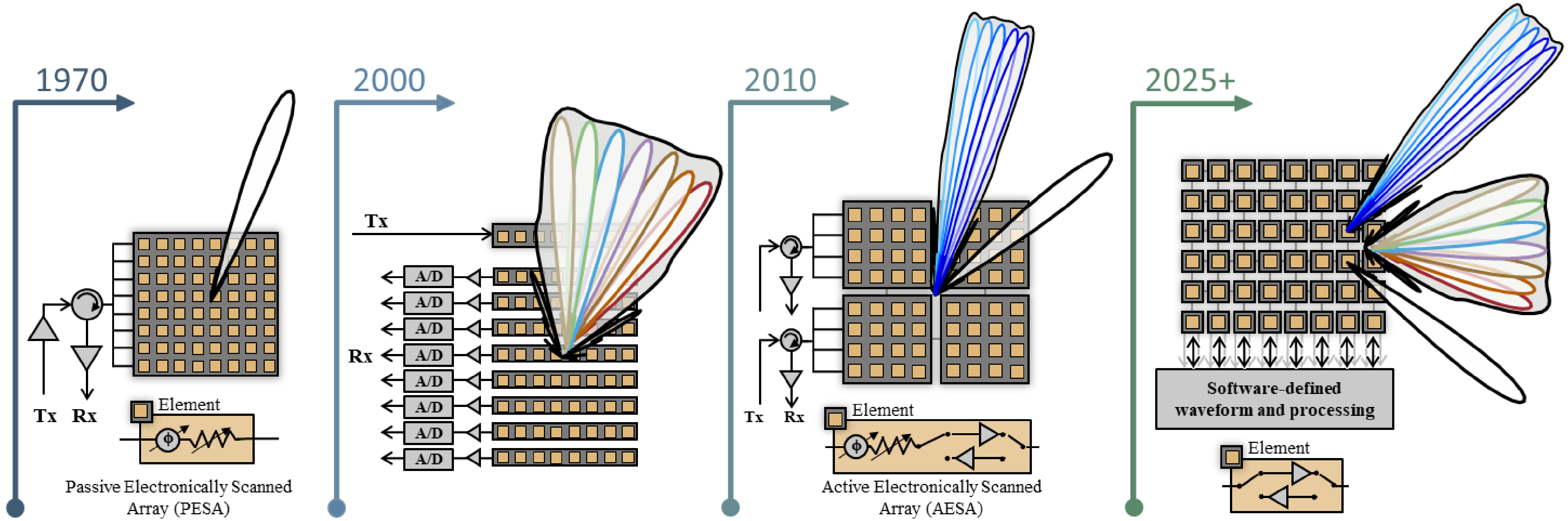
Horus
ARRC P

PAIR
ARRC P

KaRVIR
ARRC P

The trend is for more advanced capabilities and polarimetry

Phased Array Radar Architectures



INCREASING CAPABILITIES FOR SCIENCE APPLICATIONS

ANALOG BEAMFORMER

- Focusing
- Limited Adaptive Scanning

FIXED IMAGING

- Imaging

SUBARRAY BEAMFORMER

- Imaging
- Focusing
- Adaptive Scanning

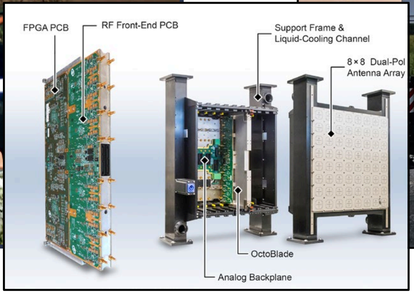
ALL DIGITAL BEAMFORMER

- Imaging
- Focusing
- Flexible Adaptive Scanning
- Reconfigurable

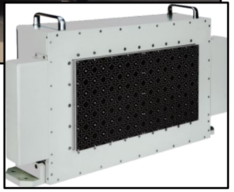
Robert Palmer et al., A Primer on Phased Array Radar Technology for the Atmospheric Sciences, Bulletin of the American Meteorological Society, Oct 2022.

Two Horus and One PAIR


January 2024




August 2024



Horus-NOAA

- S-band: 2.7 – 3.1 GHz
- Fully digital, dual-polarized
- First weather measurements **June 2022**
- Potential for large-scale versions
- 13 panels (832 elements), “diamond shape” operational (as of August 2023)

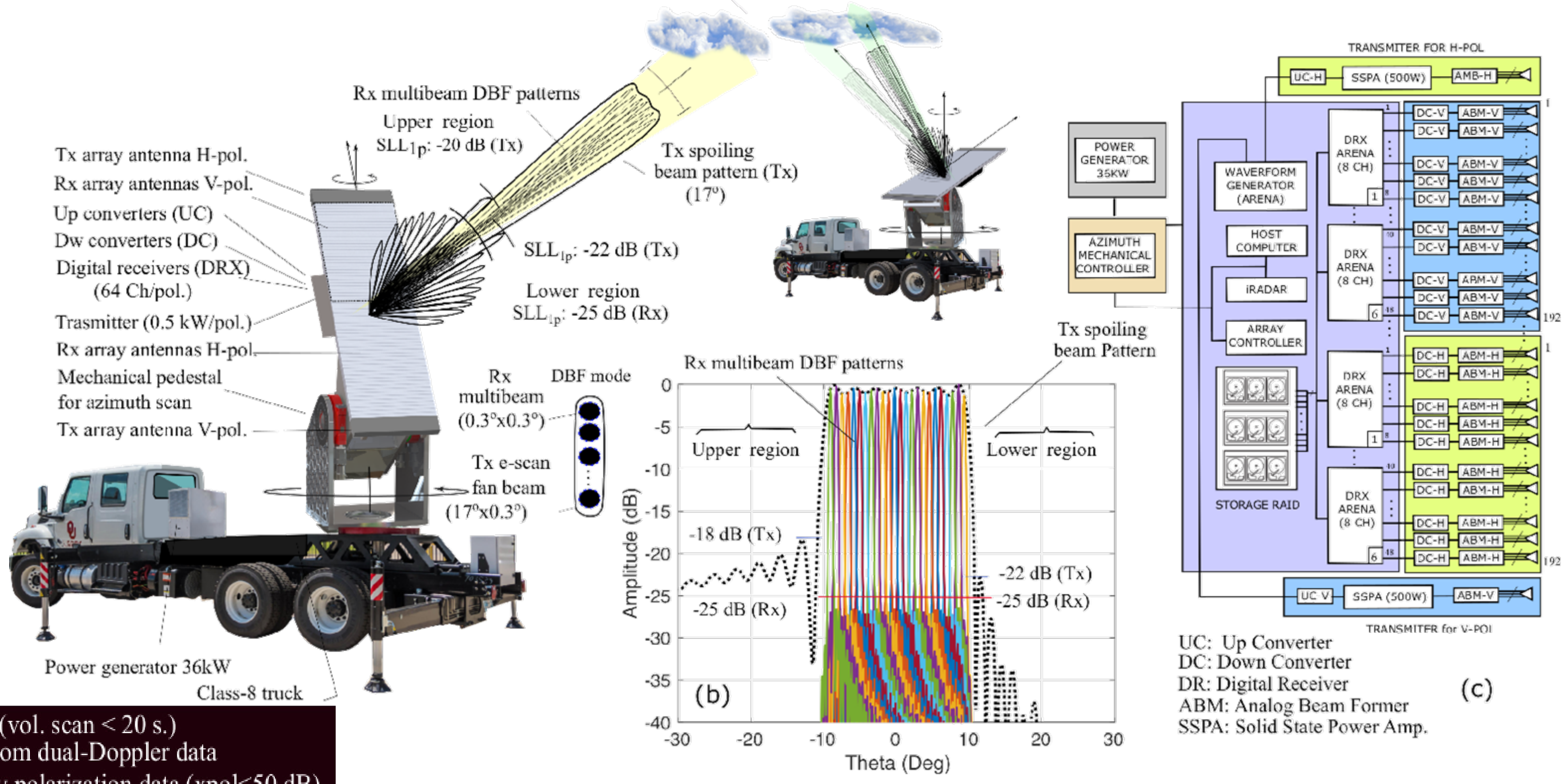
Horus-D

- S-band: 3.0 – 3.5 GHz
- Fully digital, dual-polarized
- First outdoor measurements collected in **August 2025**
- Potential for large-scale versions
- 13 panels (832 elements), “diamond shape” operational (soon to be expanded to 25 panels)

PAIR

- C-band: 5.3 – 5.5 GHz
- Dual-polarized
- 40 channels per polarization in elevation
  - Digital beamforming on Tx and Rx
- Analog-combined in azimuth (mechanically steered)
- 4864 dual-polarized elements

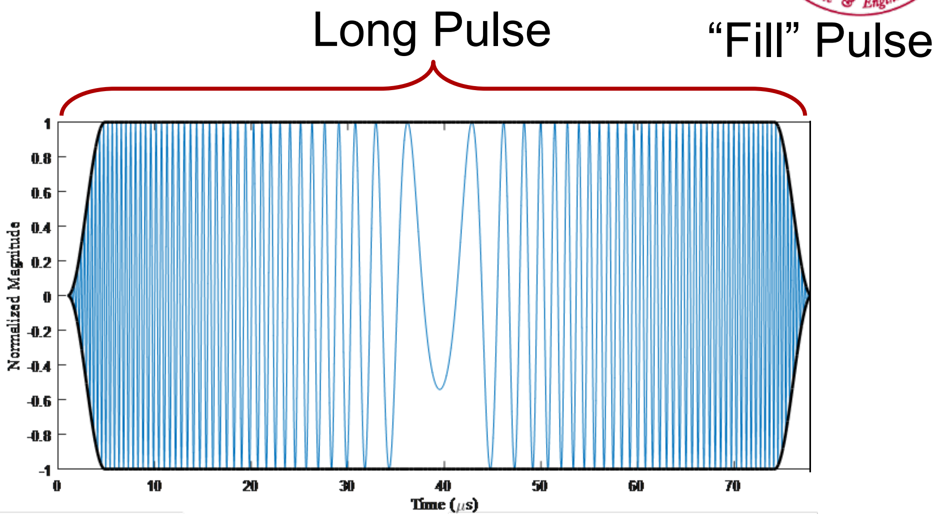
The Upcoming, NSF-Funded, Ka-band Rapid-Scanning Volume Imaging Radar

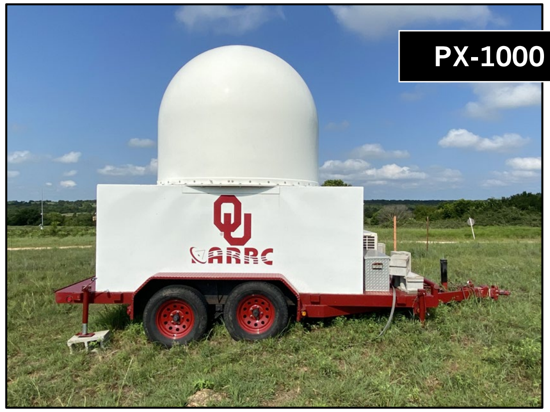


Rapid-scan (vol. scan < 20 s.)
3D winds from dual-Doppler data
High-quality polarization data (xpol<50 dB)
Vertically continuous data (Imaging radar)
High radar sensitivity (-26 dBz @ 5km)
High spatial resolution (~26 m @ 5 km)

Solid State Radars

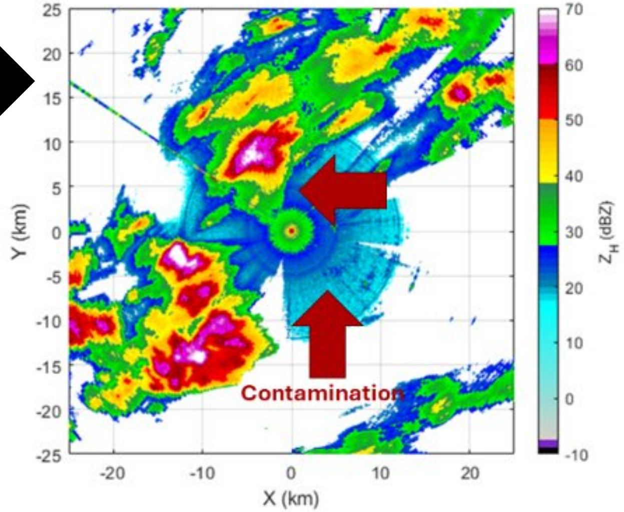
- Traditionally, SSPA radars used a **long pulse + short “fill”** pulse to cover the long-pulse blind range.
- This **added bandwidth/processing complexity** and introduced artifacts in the recovered products.
- With PPC, the **fill pulse is no longer needed**, since the blind-range recovery is achieved from the long pulse.



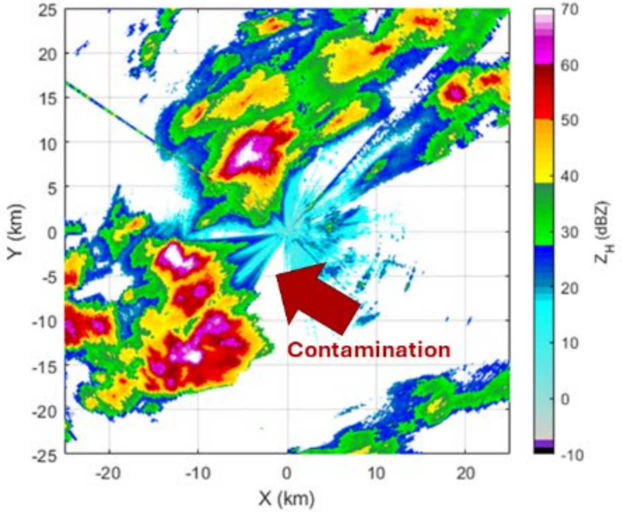


PX-1000

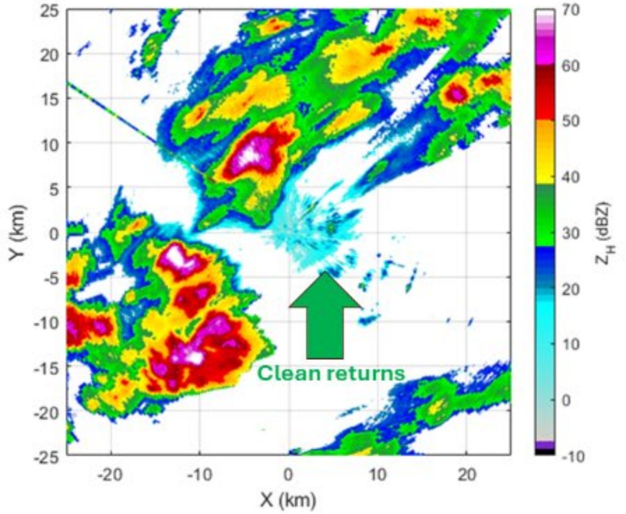
LPC - Reflectivity



PPC - Reflectivity



PPC+ - Reflectivity



Salazar et al., “Progressive Pulse Compression: A Novel Technique for Blind Range Recovery for Solid-State Radars,” in AMS JTECH 2021.

Salazar et al., "Improvements in the Compression Filter and Calibration Factor of the Progressive Pulse Compression Technique," in IEEE TGRS, 2024.

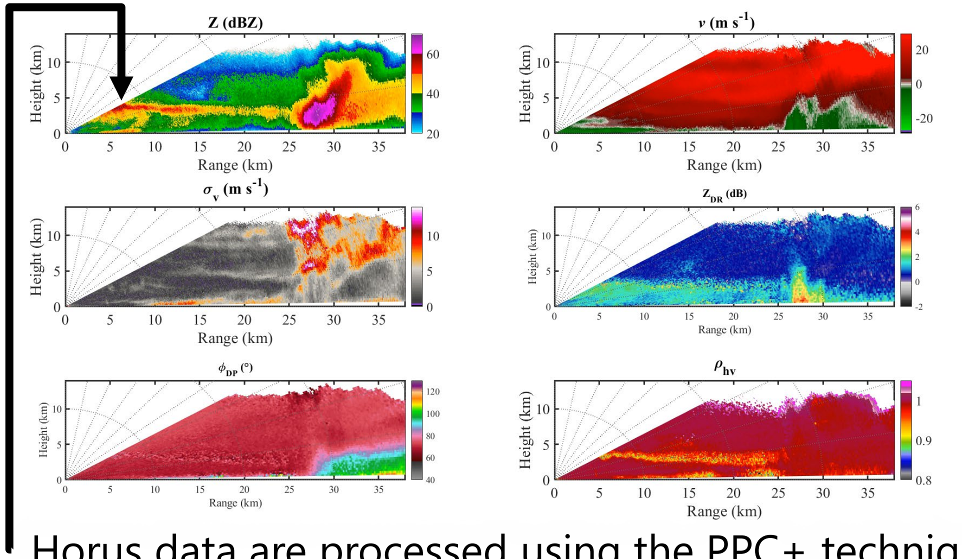
The Scalable Horus Radar is Operational

High-Quality Polarimetric Weather Measurements

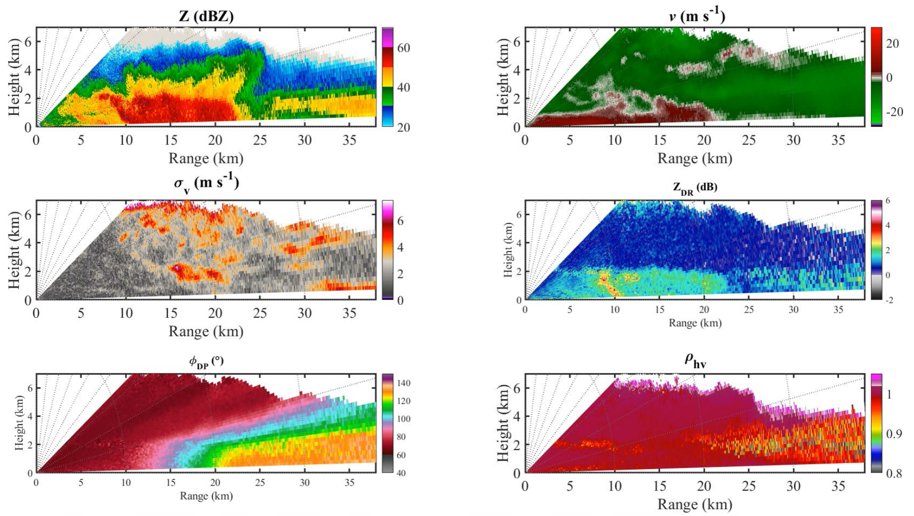
Designed to be ***scalable****, upgradable, maintainable and real-time operation*

Horus calibration in the NF Scanner

Scan 1 – 10/04/2023

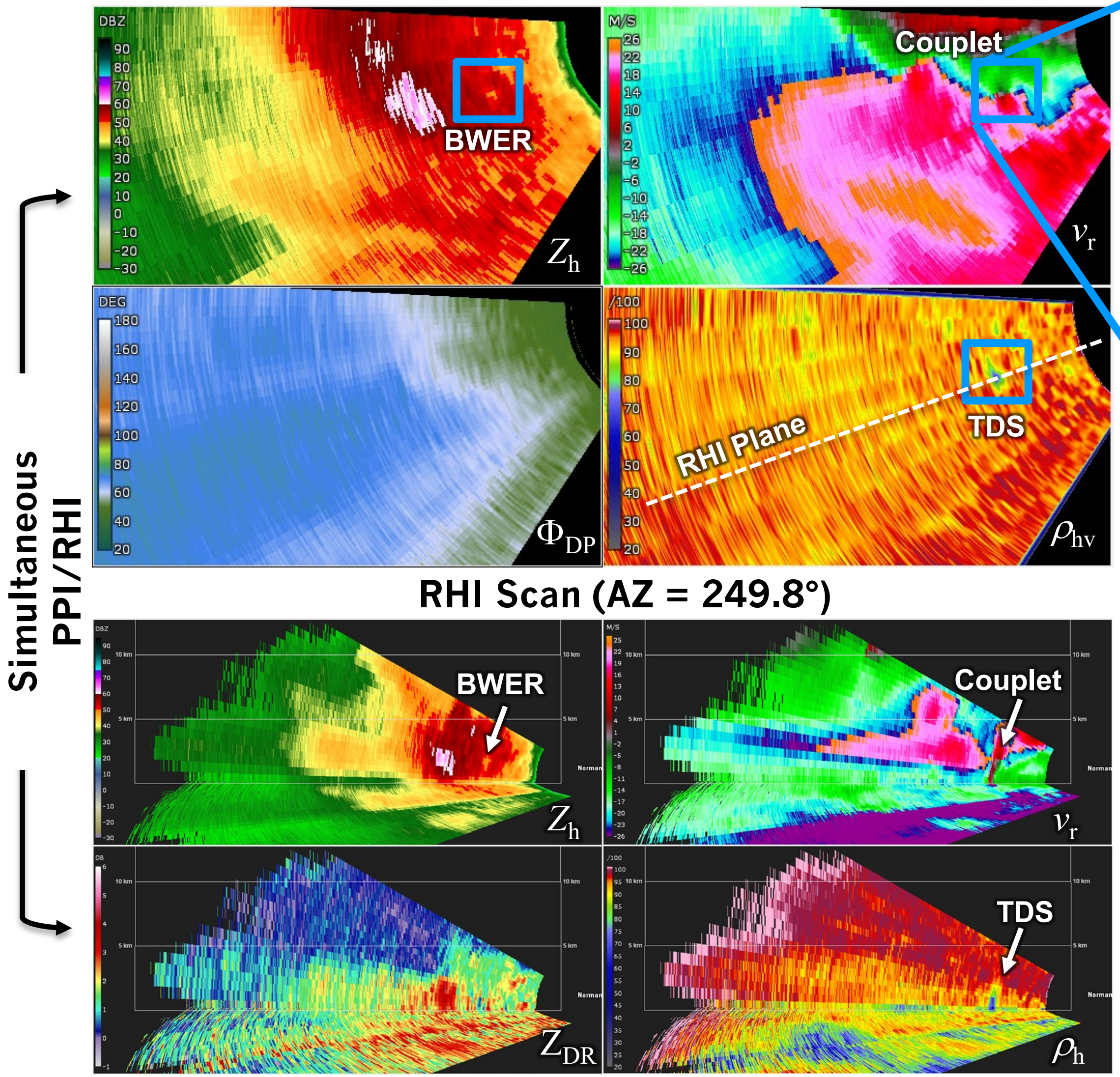


Scan 2 – 10/04/2023



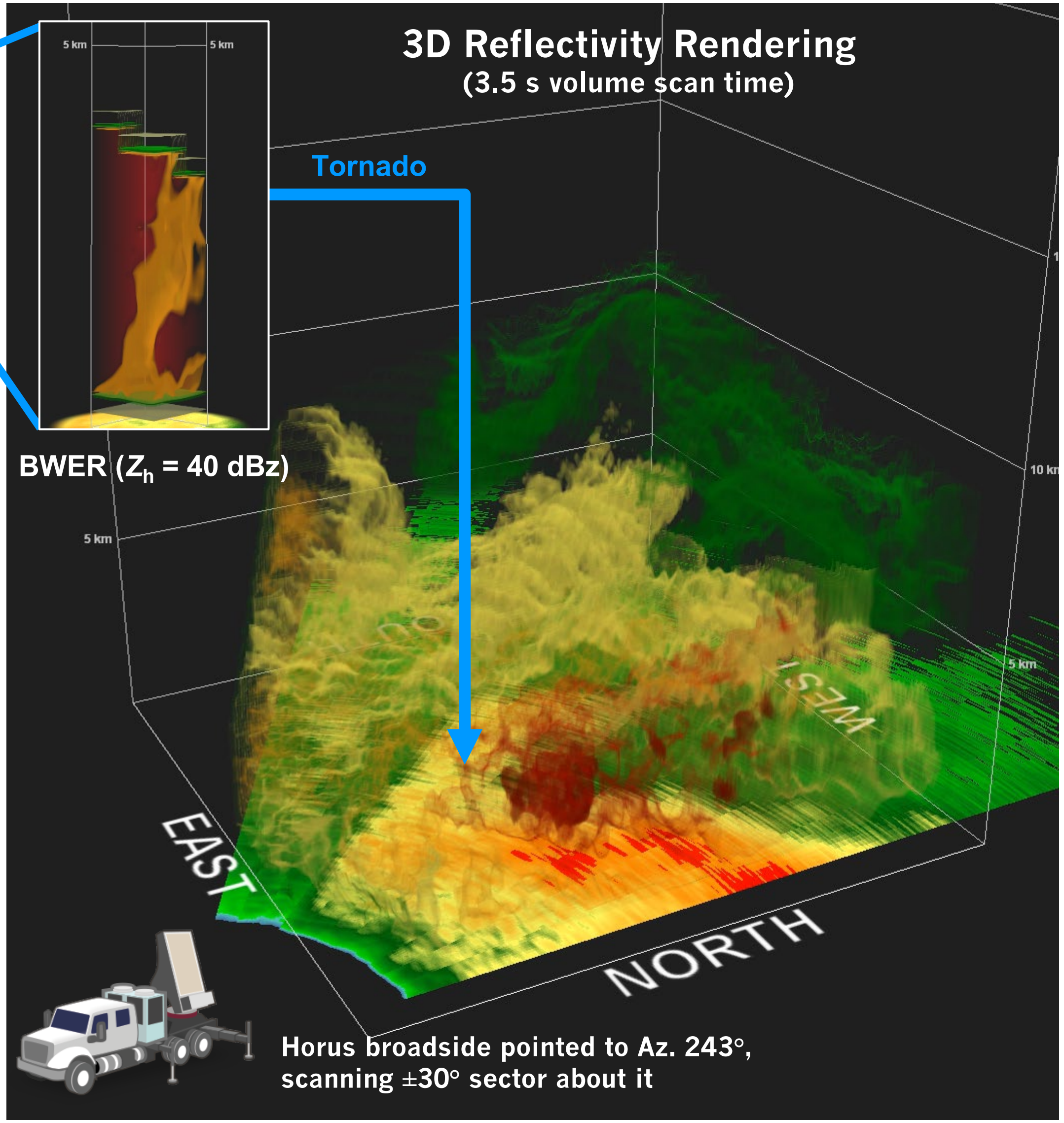
Horus data are processed using the PPC+ technique to mitigate the transmit pulse blind range

Unique Observations Enabled by Horus



PPI Scan (EL = 6.8°)

RHI Scan (AZ = 249.8°)



3D Reflectivity Rendering
(3.5 s volume scan time)

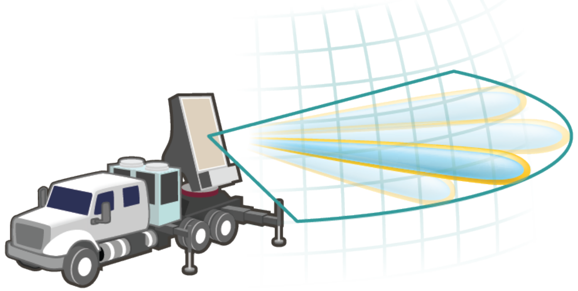
Horus broadside pointed to Az. 243°, scanning ±30° sector about it

R. D. Palmer et al., 2023, "*Horus—A Fully Digital Polarimetric Phased Array Radar for Next-Generation Weather Observations,*" in IEEE Transactions on Radar Systems

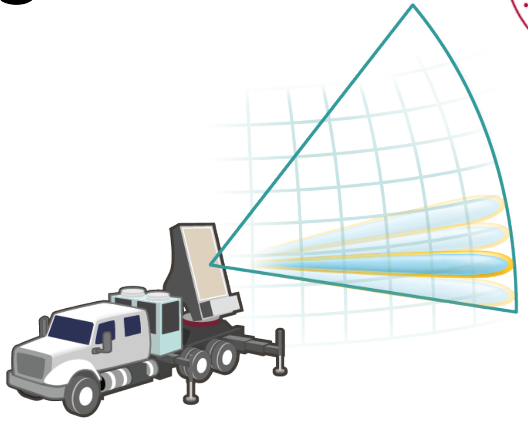
Operational Scan Modes

SPECIFICATIONS OF THE HORUS RADAR

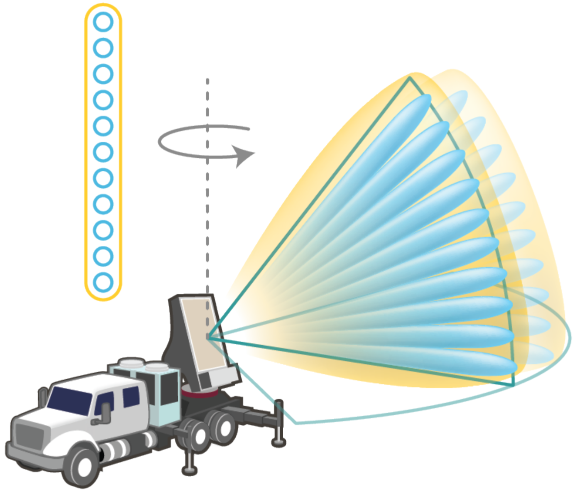
Frequency	2.7–3.1 GHz
Polarization	ATSR/STSR/RHCP/LHCP
Tx Waveform	Arbitrary Waveform Generator
Tx Peak Power (single element)	10 W/polarization
Max Tx Pulse Width	100 μs @ 10% duty cycle
Max Tx Bandwidth	100 MHz
Element Spacing	0.5 λ @ 2.951 GHz
Number of Panels	25 (1600 elements)
Max Electronic Scan Angle	$\pm 45°$ az, $\pm 45°$ el
Aperture Size	2.03×2.03 m^2
Tx/Rx Beamwidth Broadside	2.58° (no taper)
Detectability (1 pulse)	9.9 dBZ @ 50 km



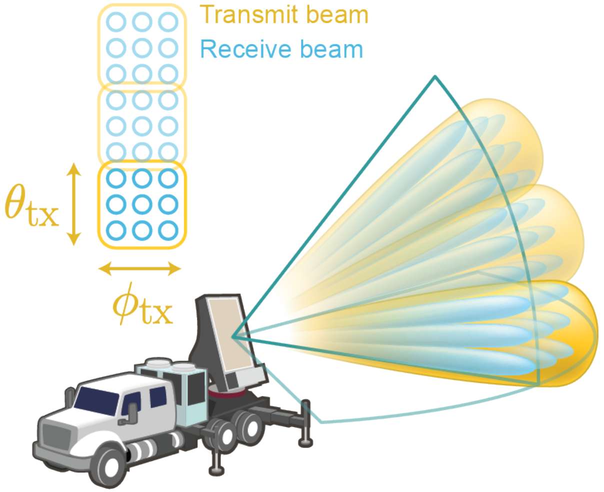
Traditional PPI



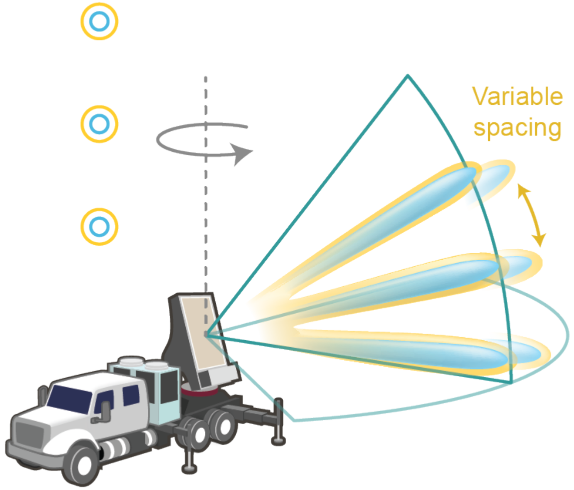
Traditional RHI



One-Dimensional Imaging



Two-Dimensional Imaging



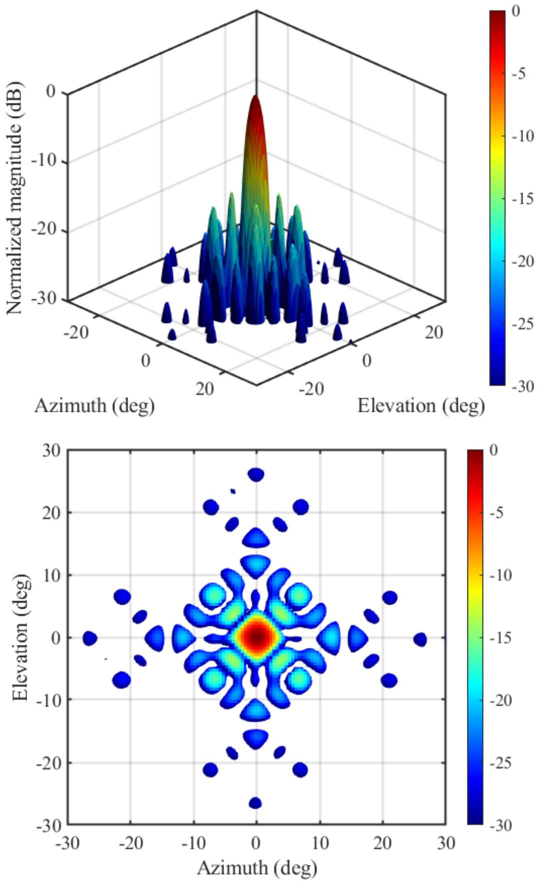
Multiple Simultaneous Pencil Beams

Schvartzman, D., and Coauthors, 2026: *Advanced Weather Surveillance Capabilities of the Fully Digital Horus Phased Array Radar*. Bull. Amer. Meteor. Soc., 107, E59–E78, https://doi.org/10.1175/BAMS-D-24-0296.1.

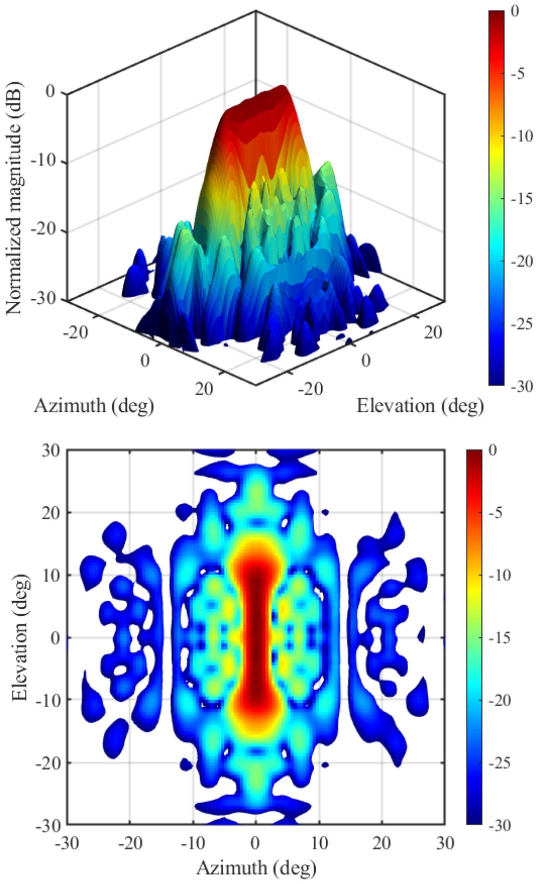
Synthesized & Measured Patterns

- After chamber re-calibration, we **synthesized and measured** different types of beams.
- These include pencil beams, 1D spoiled beams, trident beams, and 2D spoiled beams

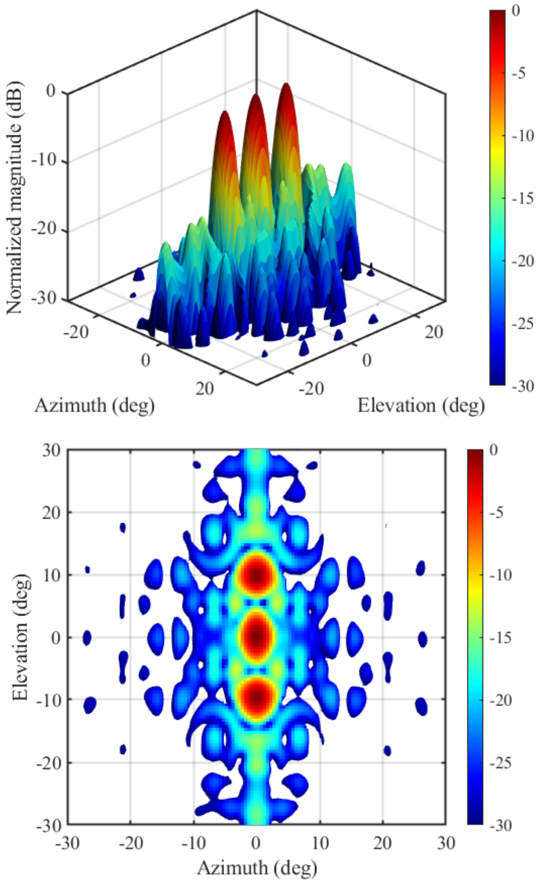
Pencil Beam



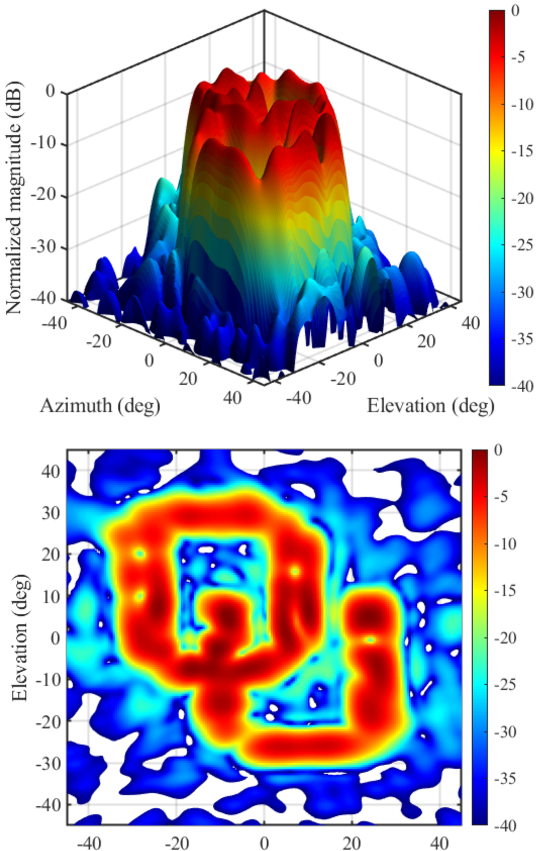
1D Spoiled – 6X



Trident Beam



OU Beam

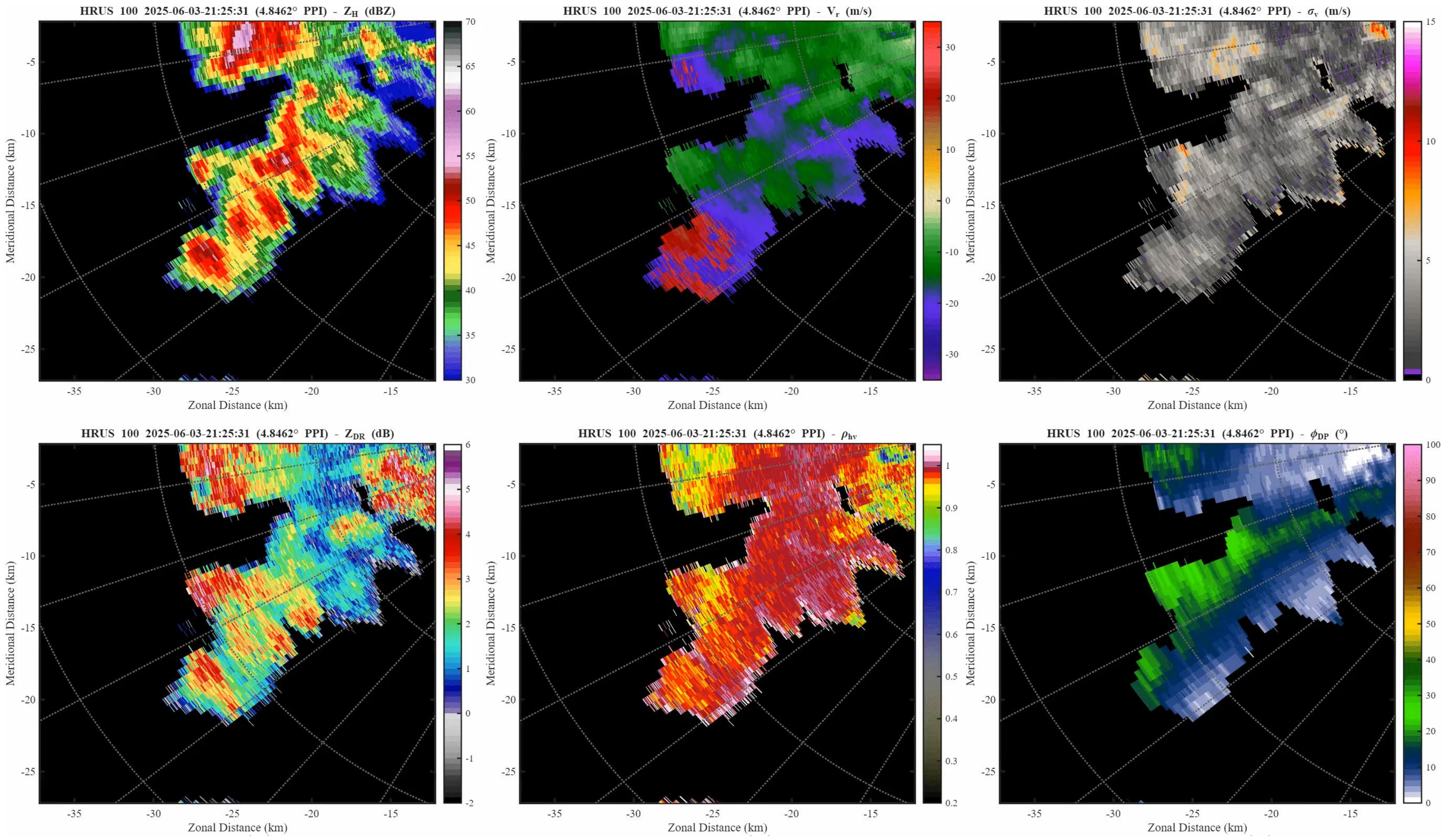


One-Dimensional Imaging

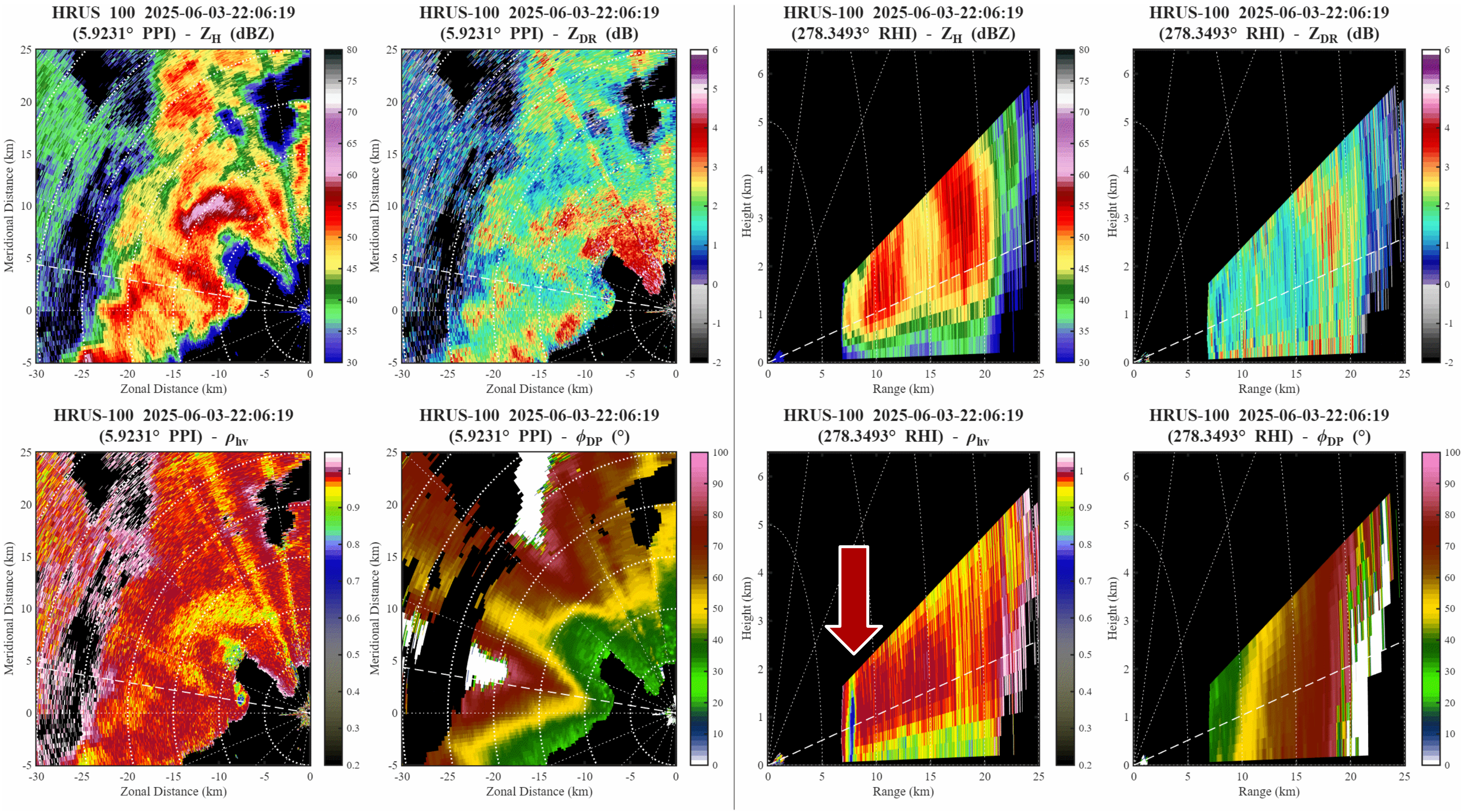
- We deployed Horus on 3 June 2025, and collected data during a **severe weather outbreak**
- Observations include **an EF-1 tornado** that started in Newcastle and moved to SW Norman

Scan Information:

- **Tx:** 14° spoiled beam
- **Rx:** 13° beams (EL 0° -13°)
- **Ts:** 1 ms
- **Antenna Rot.:** 15 °/s
- **M**: 64 samples/°
- **Volume time:** 24 s.

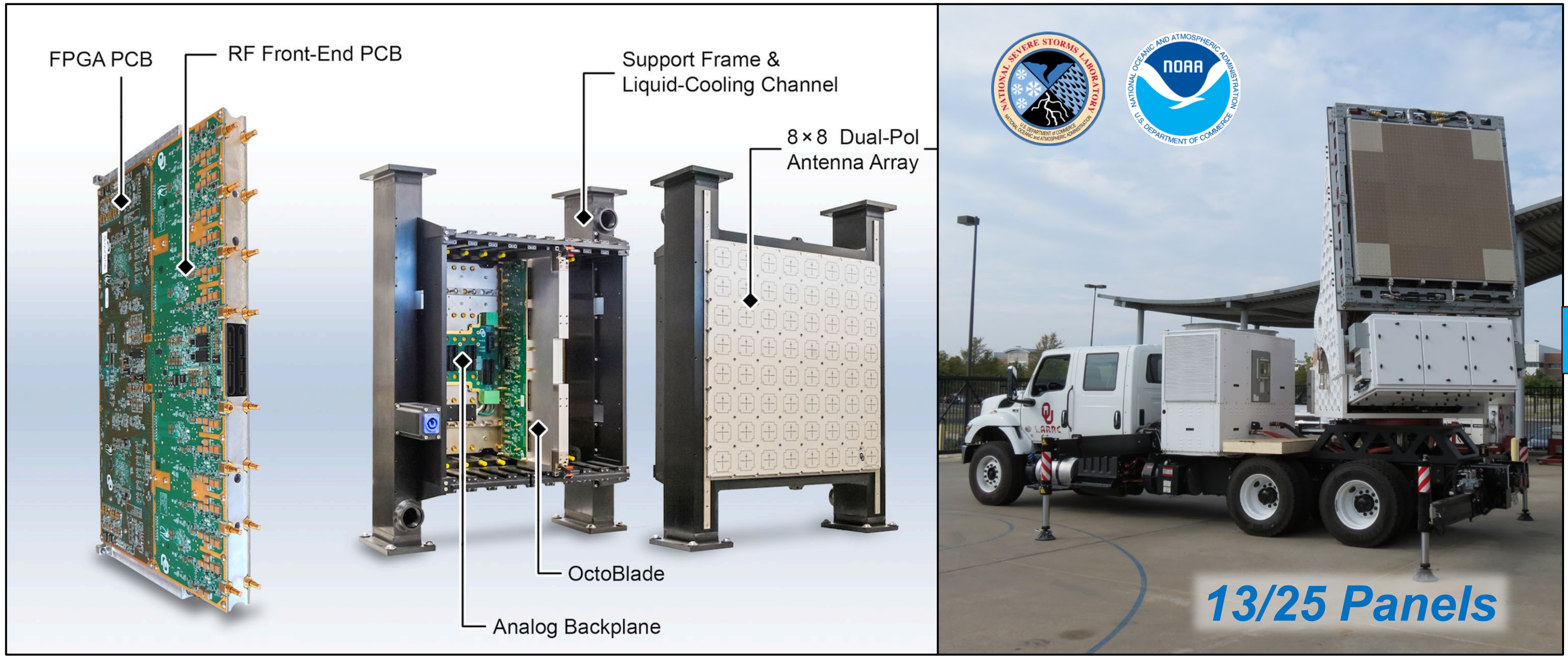


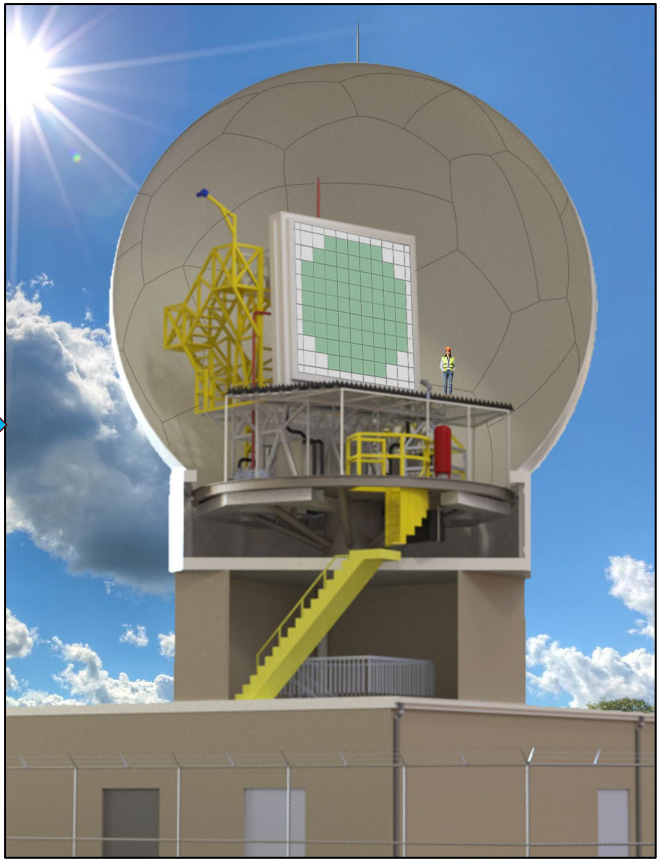
One-Dimensional Imaging



Exploiting the Scalability of Horus

Need for Higher Angular Resolution



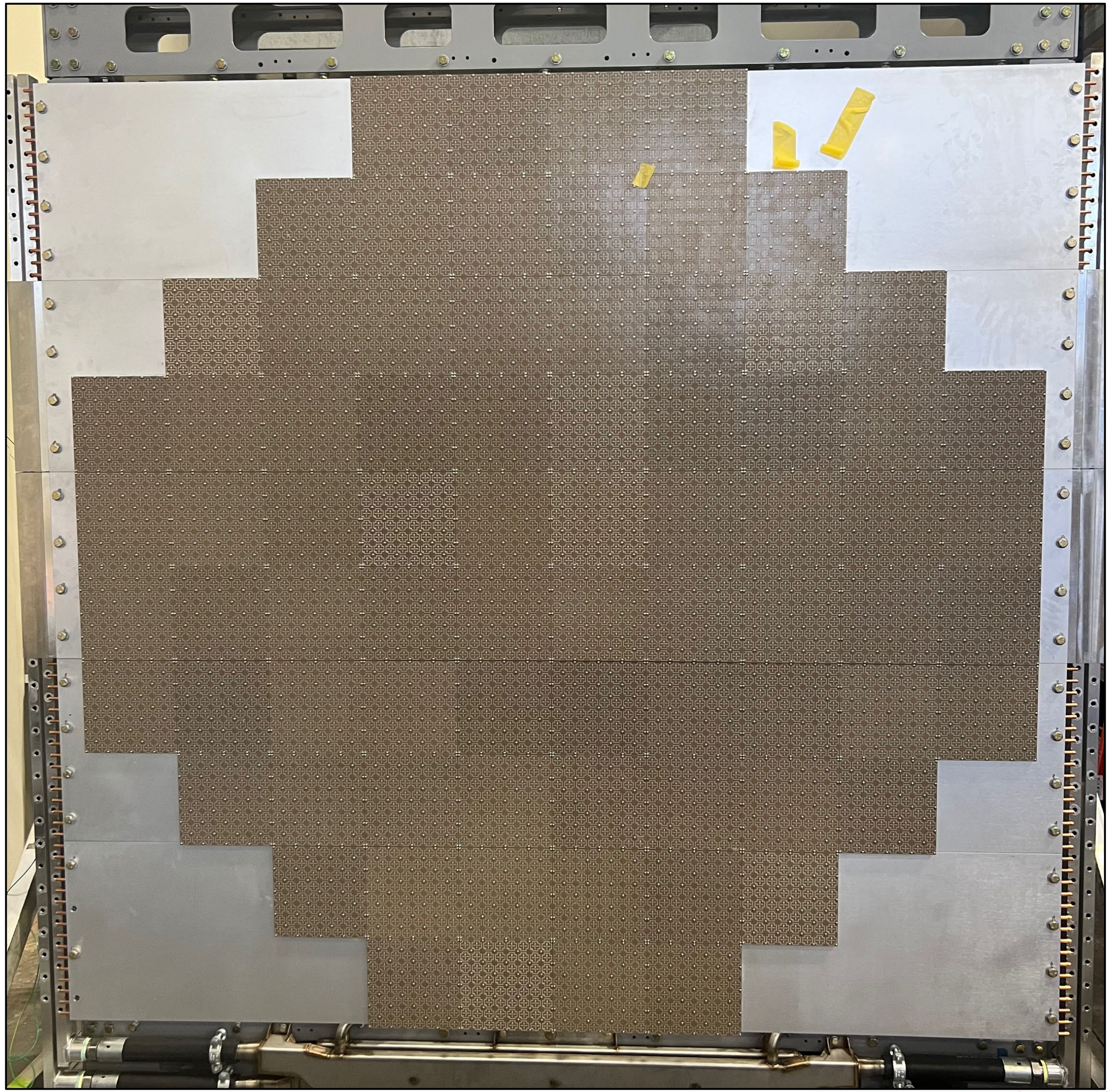


Scalability of Horus based on “building block” panels

Polarimetric Atmospheric Imaging Radar (PAIR)

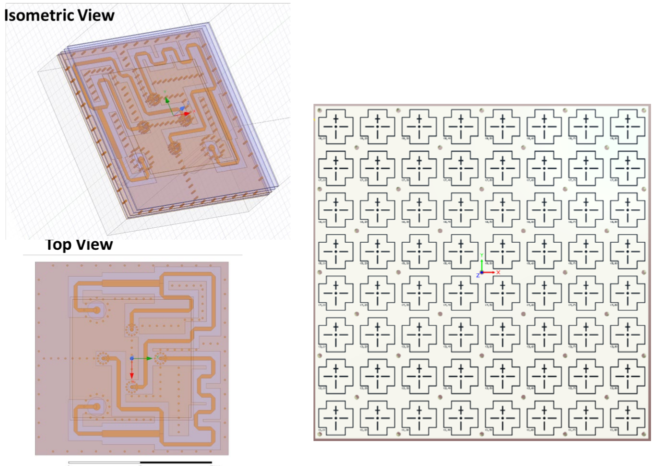
Mobile, with Rapid-Updates, and High Angular Resolution

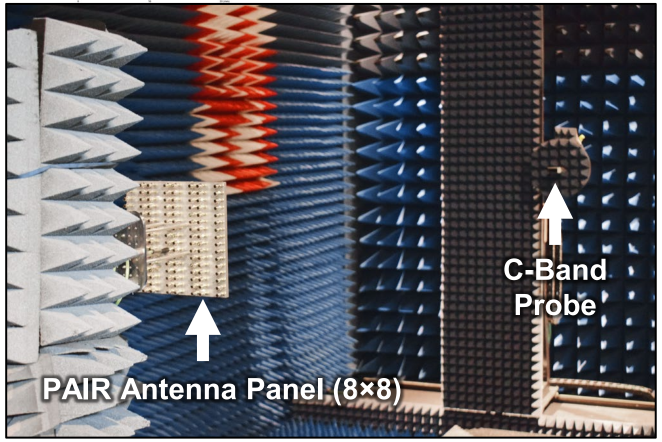
- Mobile, **C-band**, **Polarimetric** Imaging radar
- Digital beamforming and e-scan in EL for ultra-high update time, 360ºx20º in **6-10 s**
- Broadside **beamwidth of 1.5°** with pencil beam
- High sensitivity, **-2.9 dBZ @ 10 km**

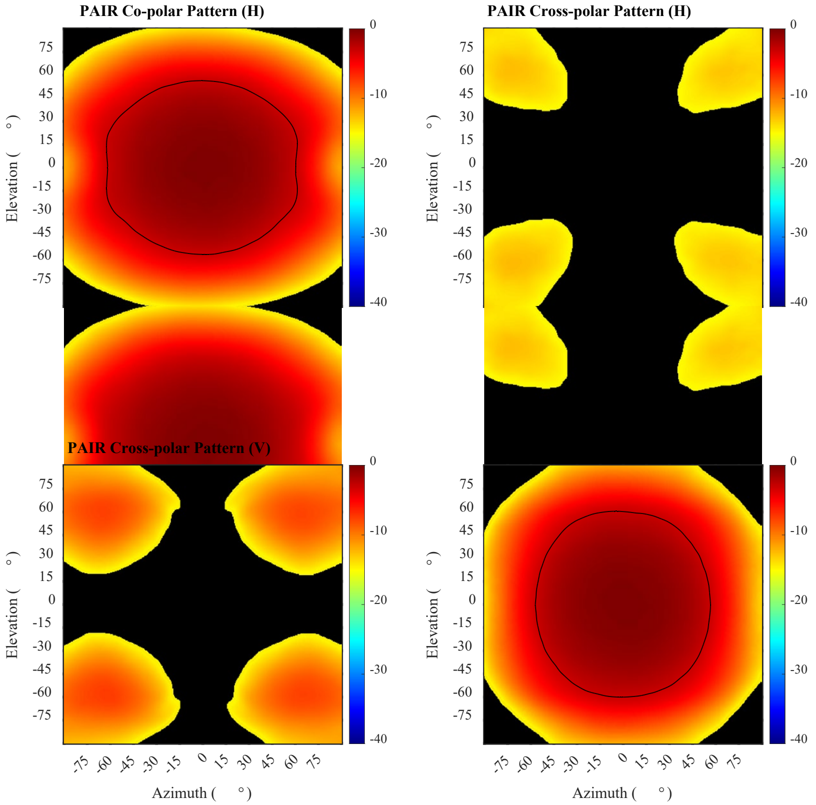


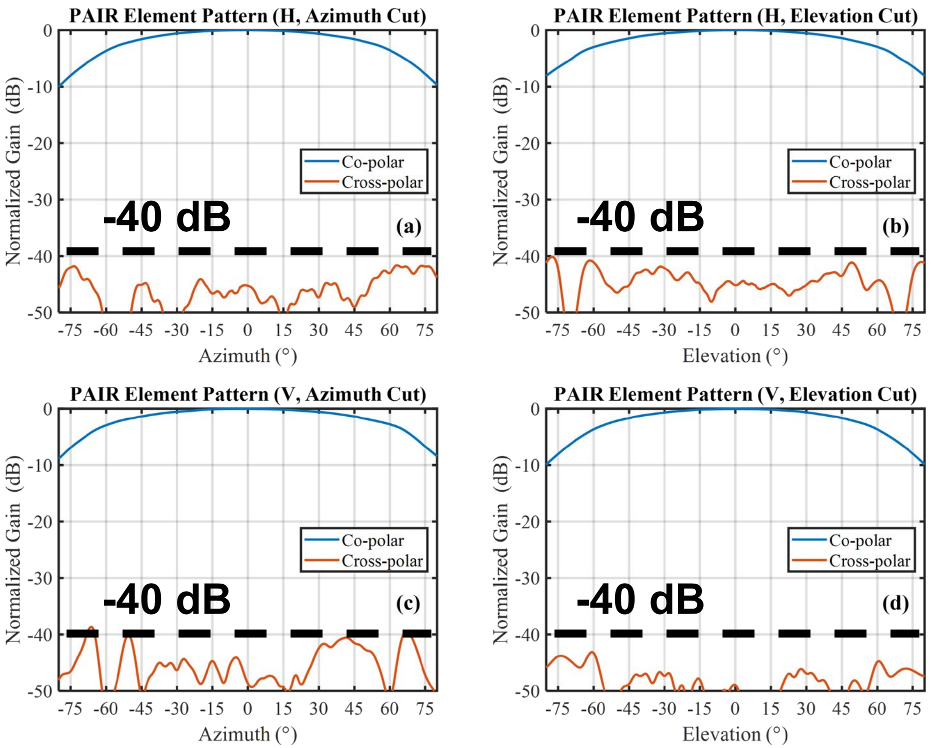
PAIR Element Patterns

- The PAIR antenna element patterns were characterized in the ARRC's anechoic chamber using the spherical far-field scan mode, from one panel (64 H + 64 V)
- Measurements agreed with simulations, and showed **cross-polarization levels < -40 dB** (single element) in the principal planes









PAIR Status

Radar Truck Integration

Support infrastructure and mobile radar platform integration complete.

Array Calibration

Analog array calibration and development of field-deployable self-calibration routine.

Starting August 2026

System Operational

Field-deployable in support of science goals with engineering assistance.

Radar Truck → **Array** → **Calibration** → **Field Testing** → **Operational**

2025

Array Integration

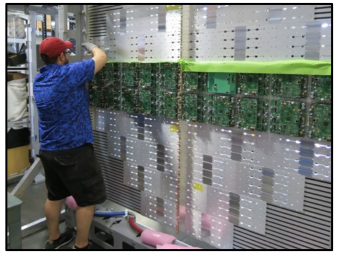
Analog array electronics mechanically integrated and software controllable.

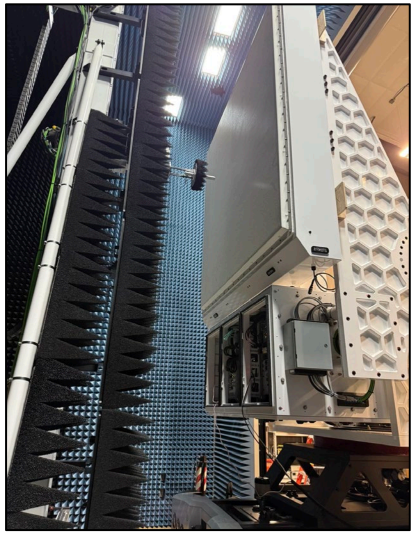
2026

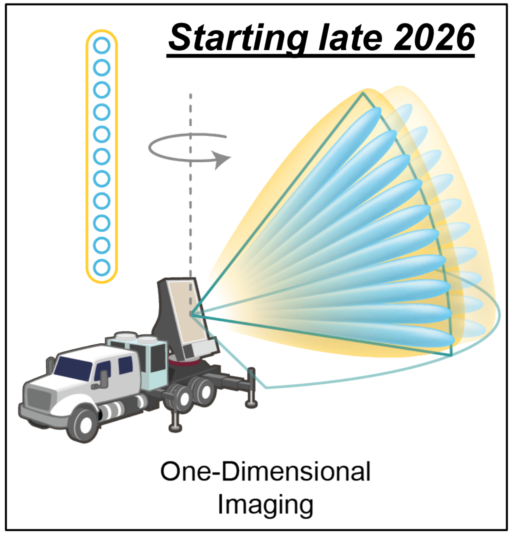
Field Testing and Integration

Robust system sequencing, develop and test weather scan strategy.

2027

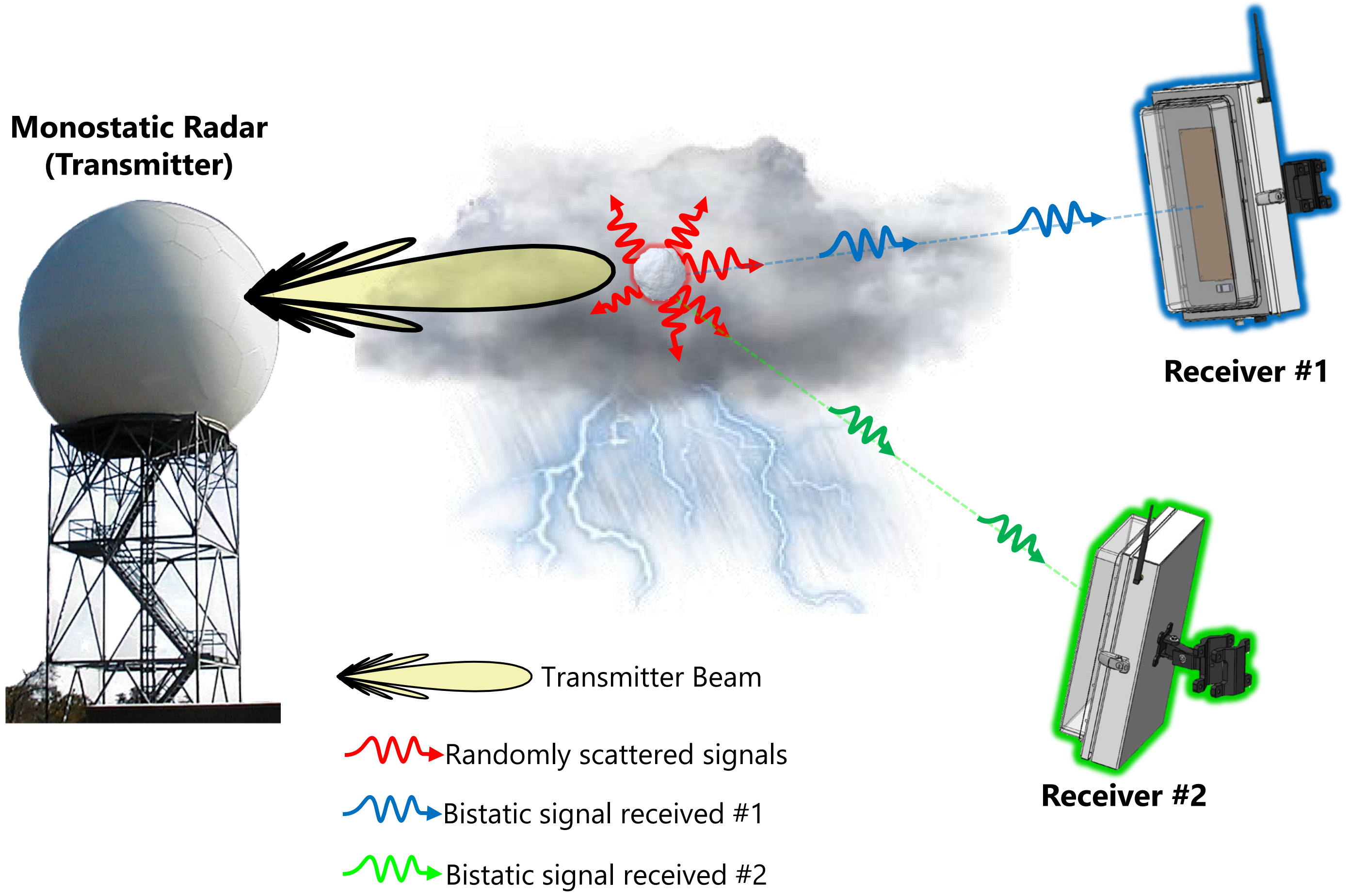


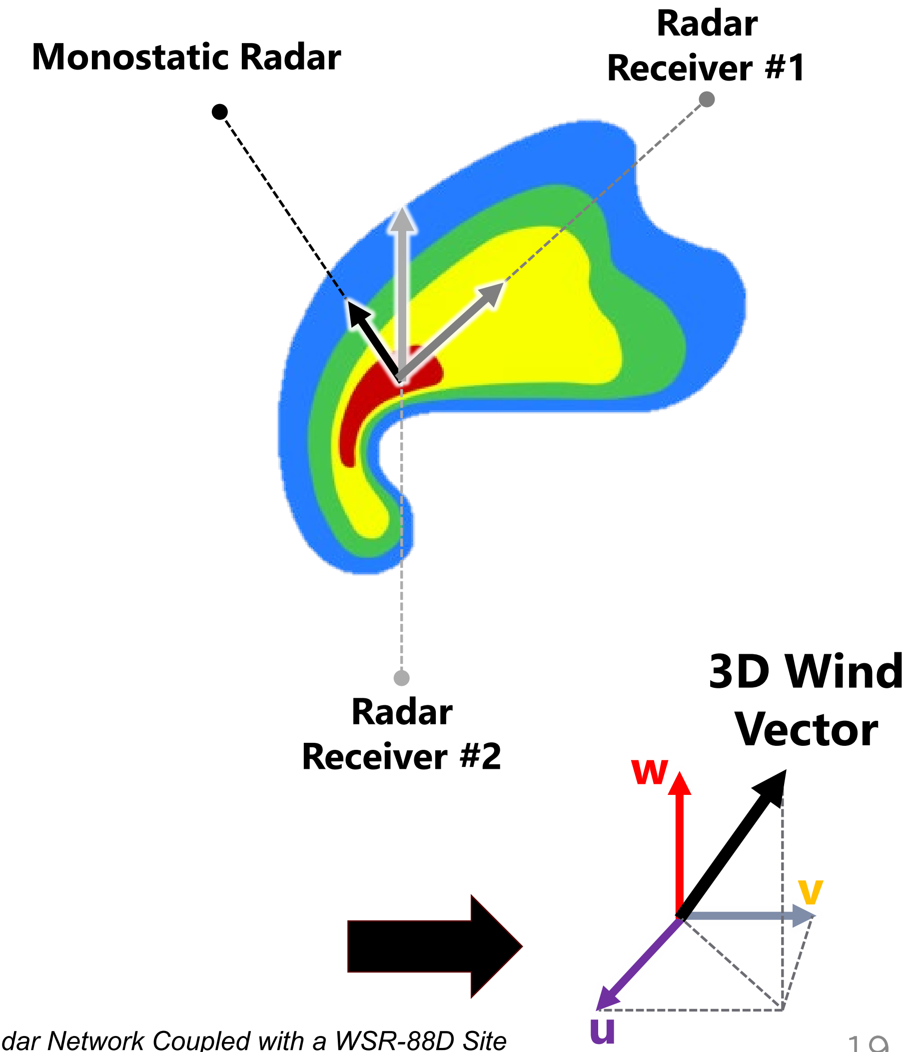



Starting late 2026

One-Dimensional Imaging

MULTISTATIC RADARS

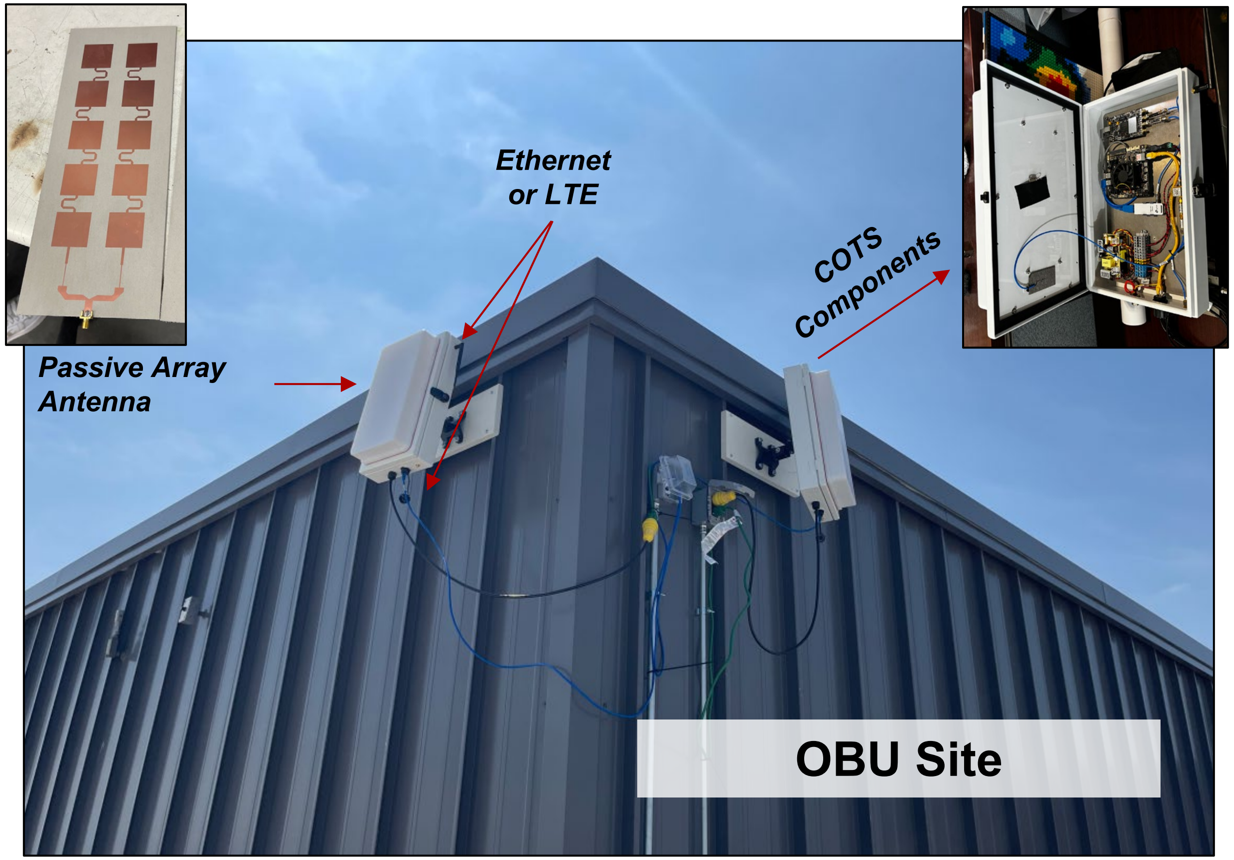


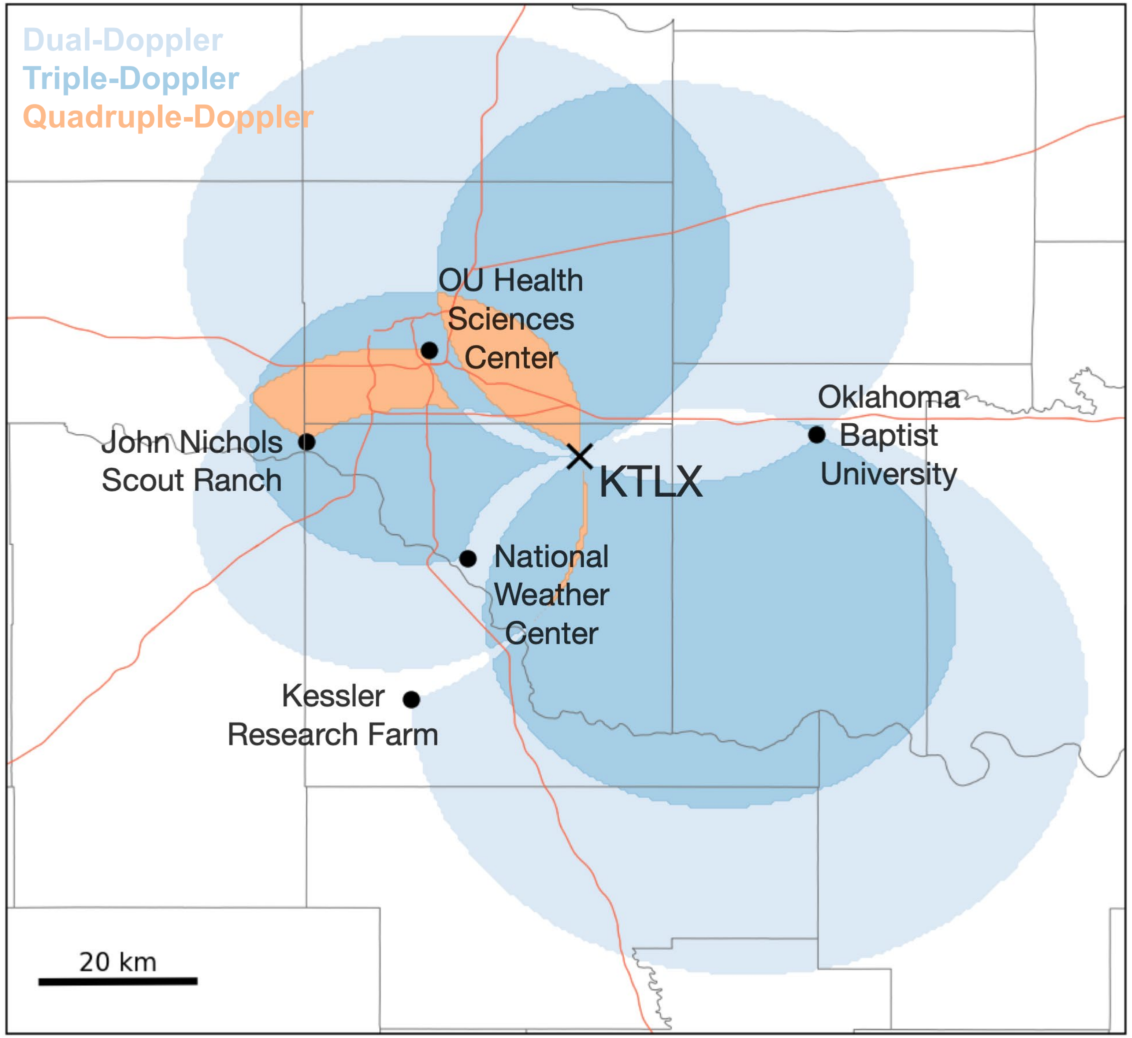


Emmerson et al., AMS Radar 2025: *Three-Dimensional Wind Retrievals in Convective Storms from a Multistatic Radar Network Coupled with a WSR-88D Site*

The KTLX Multistatic Radar Network

A six-receiver network has been operating with the KTLX WSR-88D site in Central Oklahoma since summer of 2024

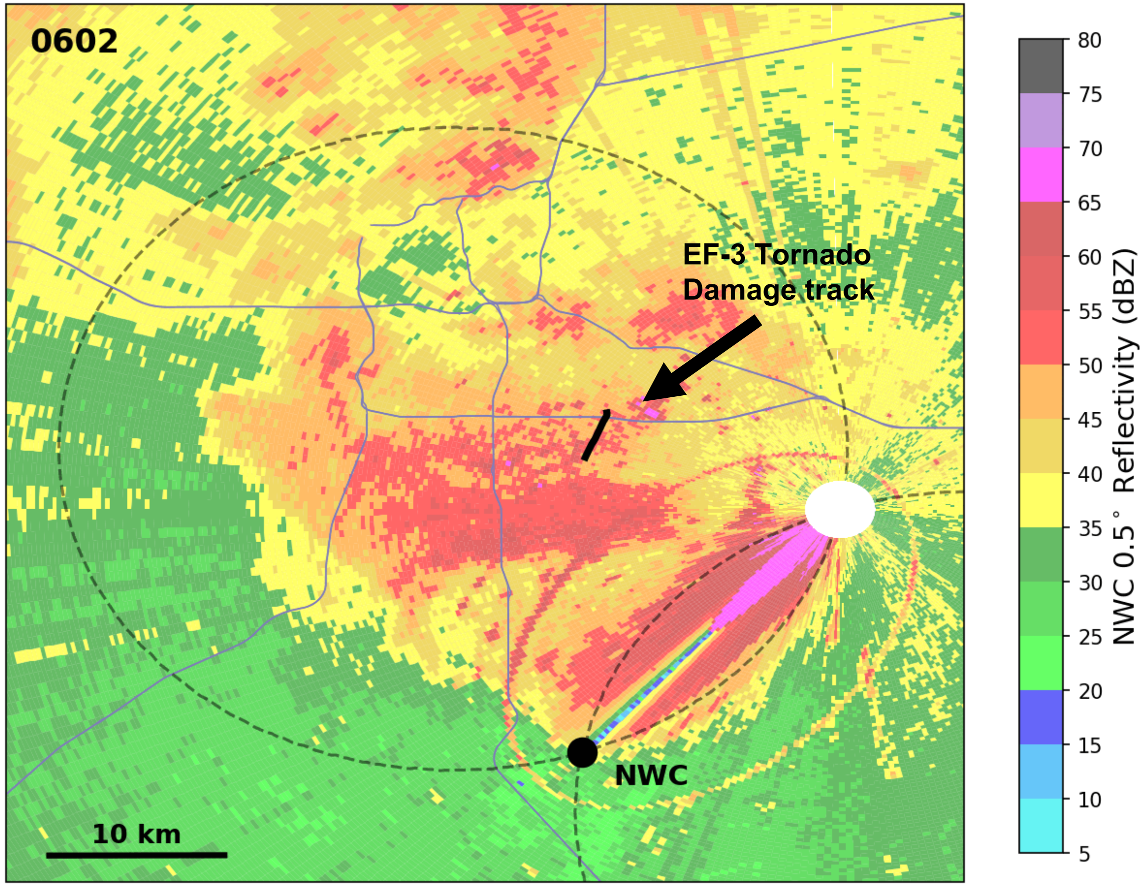




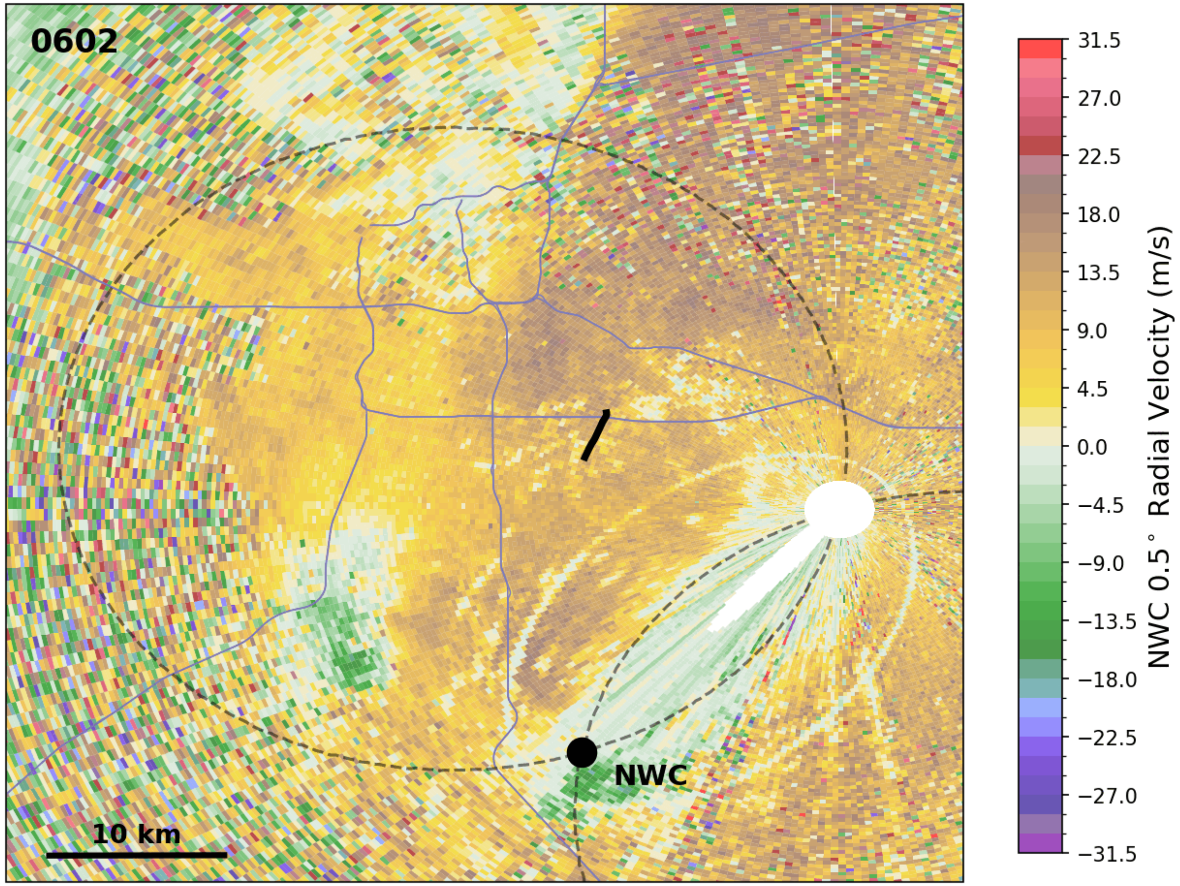
Emmerson et al., Retrieval and Quantitative Evaluation of Three-Dimensional Winds in Severe Convection with Multistatic Radar. *JTECH* https://doi.org/10.1175/JTECH-D-24-0155.1.

What do the Raw Multistatic Observations Look Like?

NWC 0.5 deg. Reflectivity

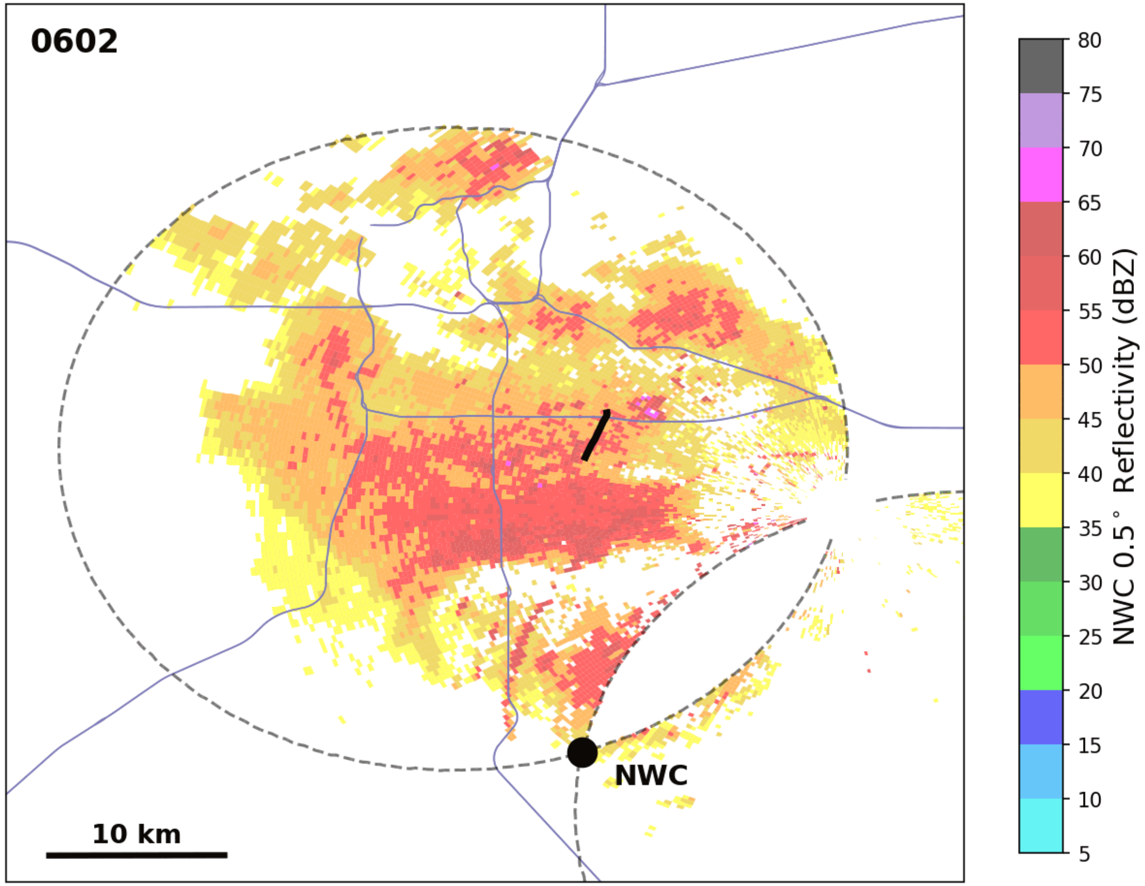


NWC 0.5 deg. Radial Velocity

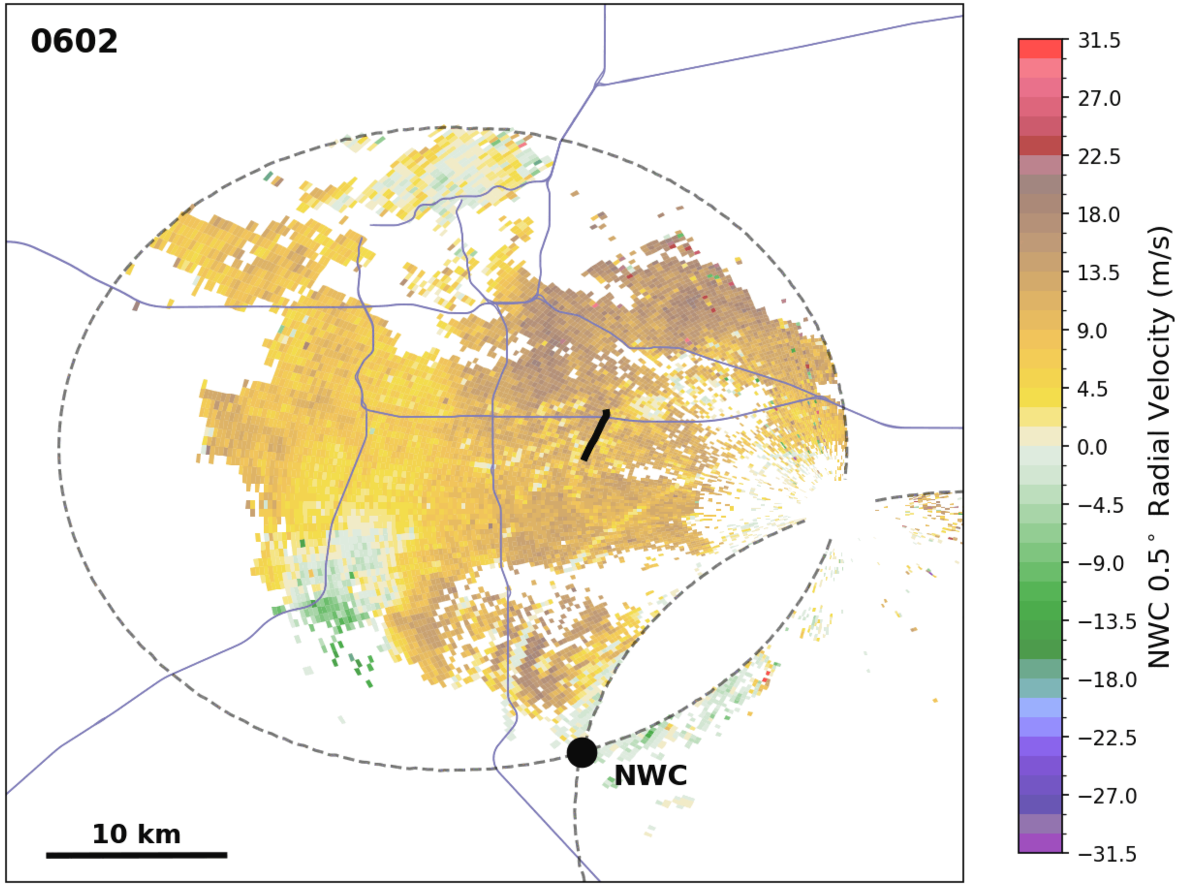


Skinner et al., AMS Annual 2024: *Development of Real-Time, Multistatic Radar Networks for Severe Weather Prediction.*

Basic Quality Control can Mitigate Limitations in Multistatic Observations



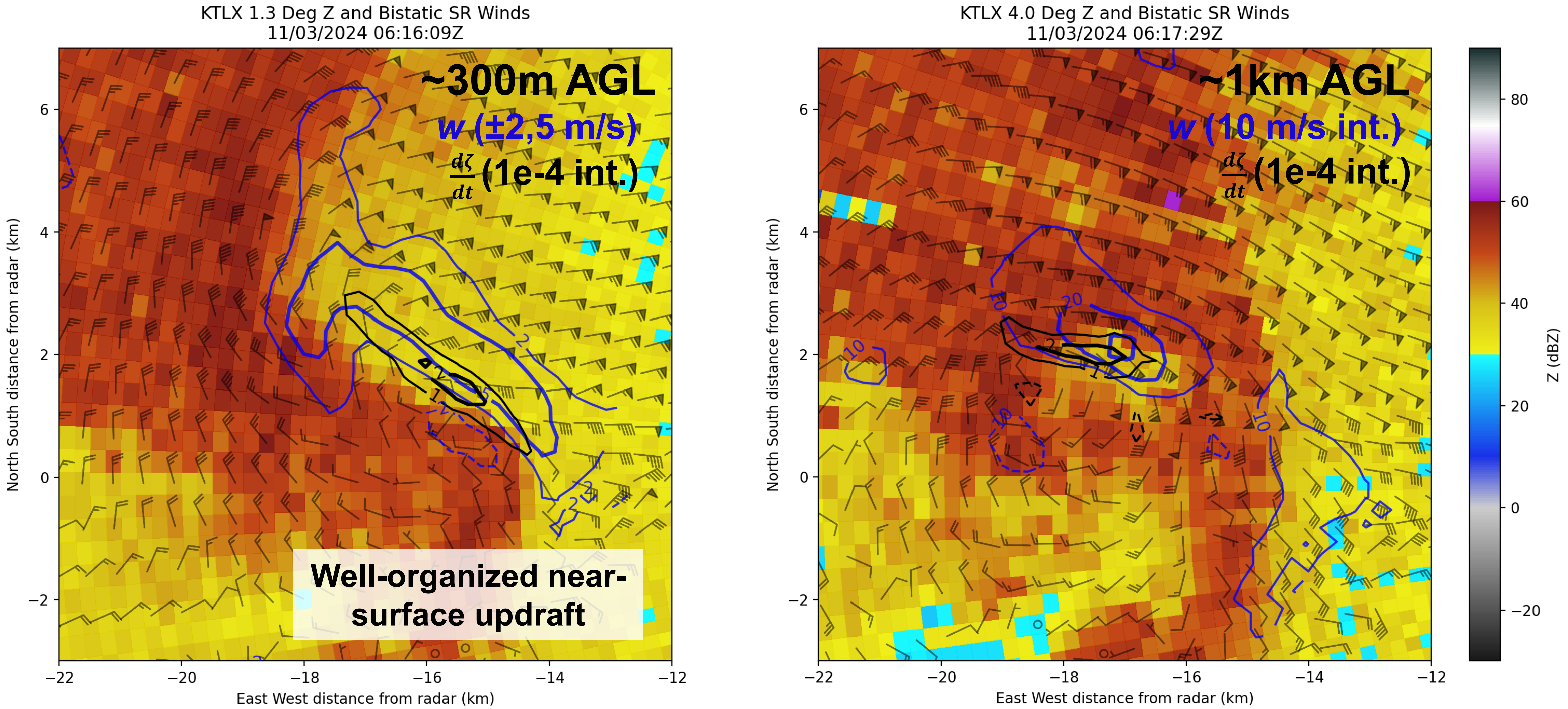
NWC 0.5 deg. Reflectivity



NWC 0.5 deg. Radial Velocity

Observations removed where either transmitter reflectivity is < 35 dBZ and where a < 30 deg beam crossing angle is present

SE OKC Tornado (T-4 min)



KTLX 1.3 Deg Z and Bistatic SR Winds
11/03/2024 06:16:09Z

~300m AGL

w (±2,5 m/s)

$\frac{d\zeta}{dt}$ (1e-4 int.)

Well-organized near-surface updraft

KTLX 4.0 Deg Z and Bistatic SR Winds
11/03/2024 06:17:29Z

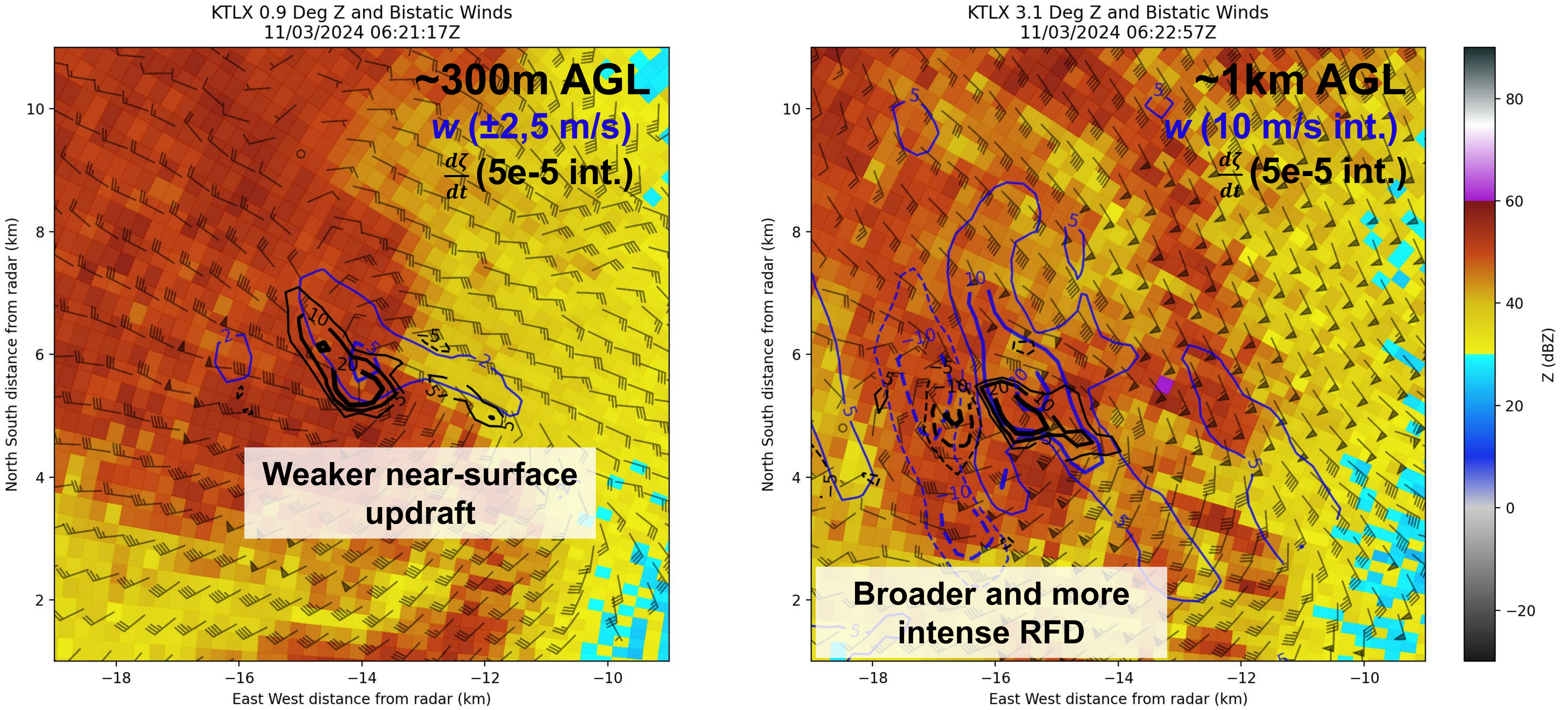
~1km AGL

w (10 m/s int.)

$\frac{d\zeta}{dt}$ (1e-4 int.)

Emmerson et al., AMS Radar 2025: *Three-Dimensional Wind Retrievals in Convective Storms from a Multistatic Radar Network Coupled with a WSR-88D Site*

SE OKC Tornado (T+1 min)



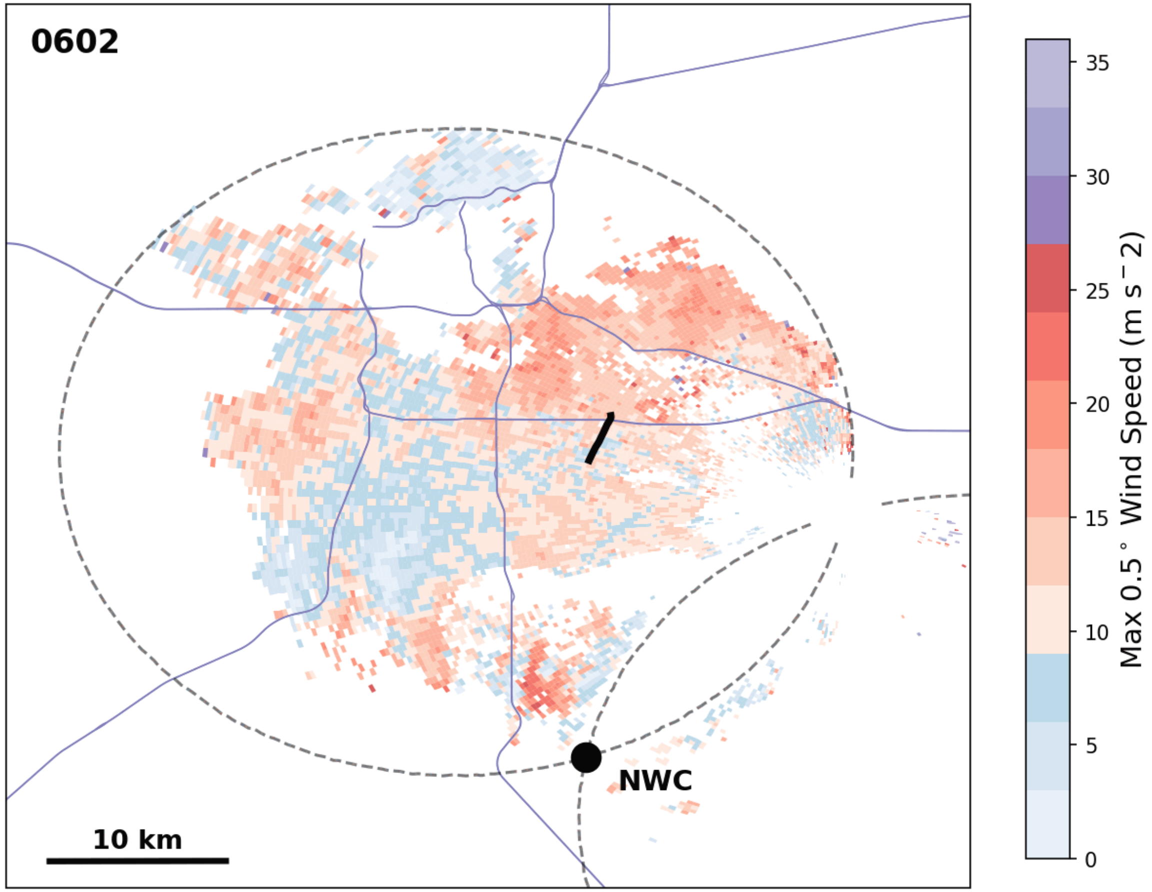
Weaker near-surface updraft

Broader and more intense RFD

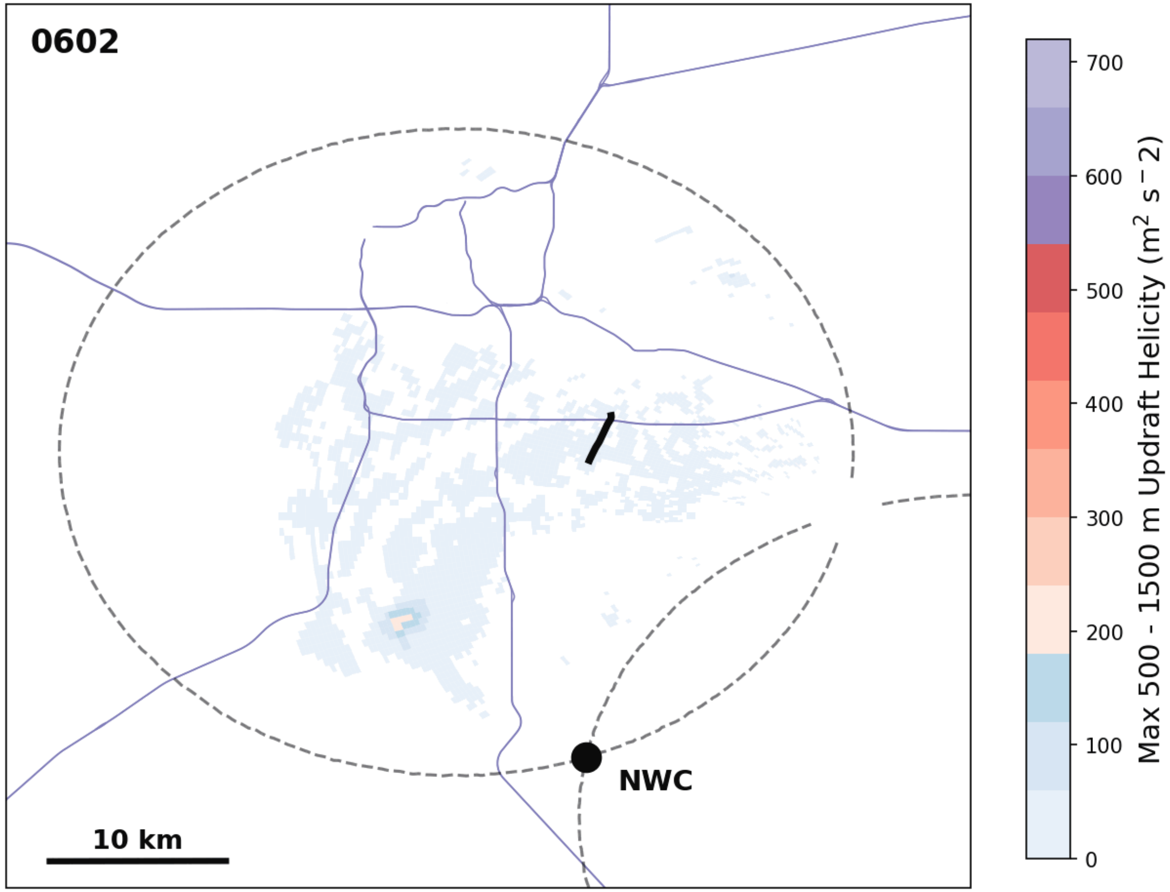
Emmerson et al., AMS Radar 2025: *Three-Dimensional Wind Retrievals in Convective Storms from a Multistatic Radar Network Coupled with a WSR-88D Site*

Retrieved Properties may be Aggregated in Time to Produce Swaths

Accumulated Max 0.5 deg Wind Speed



Accumulated Max 500-1500 m Updraft Helicity



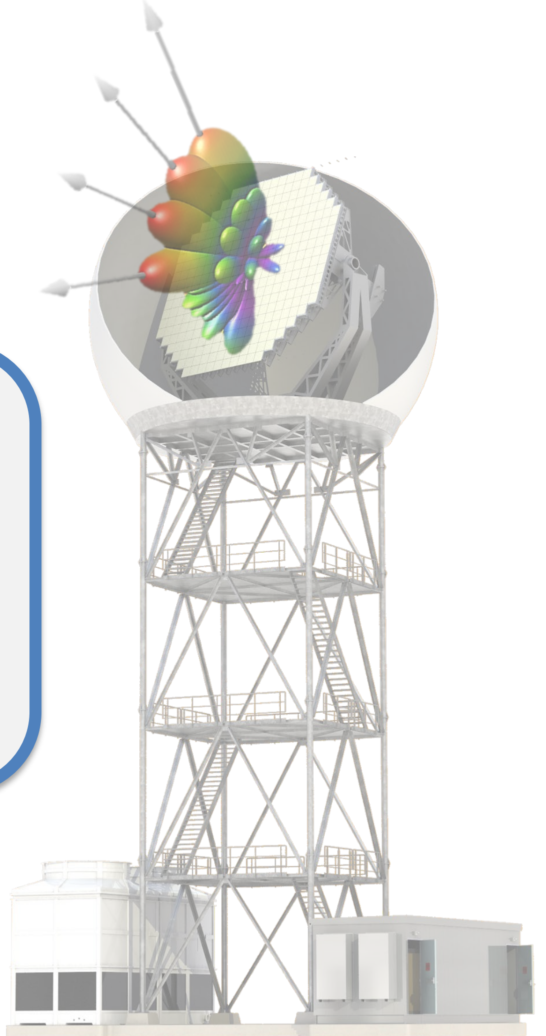
Skinner et al., AMS Annual 2024: *Development of Real-Time, Multistatic Radar Networks for Severe Weather Prediction.*

Takeaways

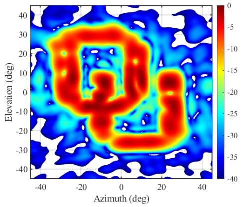
- **PAR enables faster updates, flexible scanning, and better sampling** of rapidly evolving storms; **multistatic networks are low cost** and add **critical 3D wind retrievals** to enhance weather observations.

- The **ARRC is open to collaborating** to advance radar technology for weather surveillance, and transition for future weather radar systems.

PAR technology has matured to the point that it can ***credibly support the next generation of weather radar observations****, with capabilities that go beyond conventional radar systems*



Thank You!



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