

Advanced Weather Surveillance Capabilities of the Fully Digital Horus Phased Array Radar

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ABSTRACT: The fully digital Horus polarimetric phased array radar (PAR) represents a transformative leap for weather observation, offering unprecedented flexibility in scanning strategies, and enhanced data quality. Developed by members of the Advanced Radar Research Center (ARRC) at the University of Oklahoma, Horus leverages a fully digital S-band architecture to implement advanced scanning, including one- and two-dimensional beam spoiling and simultaneous transmission of multiple beams. These capabilities enable rapid scan reconfiguration to capture evolving atmospheric conditions, optimizing trade-offs between spatial resolution, temporal resolution, and data quality. While spatial resolution is constrained by the physical antenna aperture, Horus achieves unprecedented improvements in temporal resolution and scanning agility compared to traditional radars. Operational since late 2022, Horus has demonstrated high-temporal-resolution observations of severe convective storms and efficient surveillance of stratiform precipitation, providing critical data for better understanding storm evolution. Its fully digital design supports flexible scanning strategies for high-fidelity measurements of impactful weather. In this article, we present Horus observations with these advanced scanning modes of a severe weather event in Oklahoma in 2024 where multiple tornadoes occurred. These observations showcase Horus' ability to capture storm evolution with high temporal resolution across diverse beamforming configurations. The ability to seamlessly switch between scanning modes makes Horus well suited for tracking rapidly evolving storm features and studying fine-scale precipitation structures. The scanning techniques demonstrated with Horus highlight the potential of fully digital phased array radar technology to advance weather observations, improve storm monitoring, and enhance warning decision-making in future radar networks.

SIGNIFICANCE STATEMENT: The Horus radar opens a new era in weather observations, leveraging a fully digital phased array design to achieve high-temporal-resolution and flexible scanning strategies. By employing sophisticated beamforming techniques, Horus improves observation of severe weather events such as tornadoes and hailstorms while also providing efficient surveillance of widespread precipitation. During a severe weather outbreak in Oklahoma in 2024, Horus demonstrated its ability to capture storm evolution with high temporal resolution, marking a key step toward future radar monitoring of weather. These advances in radar technology promise critical improvements in atmospheric science, severe weather monitoring, and public safety by enabling faster and more accurate storm tracking, ultimately supporting better forecast and warnings.

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1. Introduction

Accurate and timely weather observations are critical for understanding storm dynamics and microphysics, particularly during severe convective storms, hail, and tornadoes. The Weather Surveillance Radar-1988 Doppler (WSR-88D) network has provided invaluable weather data for decades. However, its mechanically scanned, single-beam design limits temporal resolution and adaptability, making it difficult to capture rapidly evolving weather systems in real time (Zrnic et al. 2007; Weber et al. 2007).

Advances in phased array radar (PAR) technology have improved meteorological observations by steering beams electronically, enabling rapid updates and adaptive scan strategies that respond to evolving weather (Torres and Schwartzman 2020; Palmer et al. 2022; Kollias et al. 2022). A key architectural choice is where signals are digitized: at the element level or after analog combining within subarrays. Palmer et al. (2022) summarize these PAR architectures and identify fully digital systems—with element-level digitization, enabling the most advanced PAR architecture to date: a software-defined radar. In a fully digital PAR, both polarization signals from every antenna element are digitized and combined across the full aperture; this permits precise beam shaping and agile control (e.g., simultaneous multi-beam transmission, wide spoiling with controlled sidelobes) without grating lobes and other constraints inherent to subarray designs (Fulton et al. 2016; Weber et al. 2021). By contrast, partially digital (subarray) PARs group elements and combine their signals before digitization or digitize by rows/panels; this reduces the number of channels and cost and can be effective for surveillance (Stailey and Hondl 2016; Schwartzman et al. 2021a; Alford et al. 2024), but it restricts beam control, can introduce grating lobes, and limits spoiled-beamwidths and sidelobe nulling (Palmer and Schwartzman 2025). Element-level access in fully digital systems also enables in situ mutual coupling calibration, critical to meet strict dual-polarization requirements (Fulton and Chappell 2010; Herndon et al. 2024; Segales et al. 2025).

Developed by the University of Oklahoma's Advanced Radar Research Center (ARRC), the fully digital "Horus" radar overcomes these constraints by digitizing received signals at each antenna element and polarization channel (Palmer et al. 2023). This element-level data acquisition supports flexible digital beamforming across the full aperture, enabling advanced scanning techniques—such as one-dimensional (1D) and two-dimensional (2D) beam spoiling, multiple simultaneous transmit beams in nearly arbitrary directions, or adaptive nulling. These capabilities are unattainable with conventional or subarray PARs, particularly for improving temporal resolution and scan agility (Schwartzman et al. 2024). While subarray PARs can support some of these modes, they face restrictions (e.g., limited spoiled beamwidths, grating lobes).

Horus can dynamically adapt its scans to optimize spatial sampling, temporal resolution, and data quality. Figure 1 shows the Horus fully digital S-band polarimetric phased array radar on its mobile platform at the National Weather Center. Horus can adapt its scanning

strategy to match the weather conditions. In convective storms, it employs high-temporal-resolution scans with multiple simultaneous beams, enhancing storm cell tracking while mitigating sidelobe contamination, which is critical to observing tornadoes and hail cores. For widespread stratiform precipitation, where reflectivity gradients are weak, broader beam spoiling increases spatial coverage with minimal impact on data quality. Compared with a vertically spoiled beam, multiple

simultaneous pencil beams preserve much of the array gain, maintain narrow beamwidths, and keep two-way sidelobe levels low—advantages particularly important at low elevation angles where sharp reflectivity gradients and strong ground clutter are common. Spoiled beams, in contrast, have deliberately broader main lobes, reduced antenna gains, and increased sidelobe levels but illuminate a deeper slice of the atmosphere at once. Therefore, many elevation angles can be sampled per rotation, and full-volume scan times are shorter. In practice, this motivates a hybrid approach in Horus: multiple simultaneous pencil beams at the lowest scans to maximize resolution, sensitivity, and polarimetric data quality and more aggressively spoiled beams aloft, where reflectivity gradients are weaker, to ultimately achieve rapid volumetric coverage. This adaptability contrasts with traditional systems, which must compromise between coverage, resolution, and quality due to fixed scanning strategies (Weber et al. 2017; Torres and Schwartzman 2020).

High-temporal-resolution PAR observations are valuable beyond severe convective cores (Bodine and Griffin 2024). They aid studies of convective initiation along boundaries (e.g., drylines, outflow, and sea-breeze fronts). They resolve rapidly evolving boundary layer phenomena like bores and gravity waves (Kollias et al. 2022). They also improve characterization of wind hazards (microbursts/downbursts) and mesoscale organization (e.g., rear-inflow jets). Finally, in stratiform and winter regimes, they enable detailed analyses of melting-layer/brightband evolution, snowband kinematics, and orographic precipitation.

Fully digital PARs like Horus enable rapid volumetric scanning, with demonstrated update times as low as 3.52 s for volumes covering 60° in azimuth by 30° in elevation and 15–20 s for full 360° azimuth scans over the same elevation span. This is crucial for tracking complex storms with evolving cells, where timely data enhance severe weather surveillance and warnings (Kurdzo et al. 2017; Bodine and Griffin 2024). Operators can modify the scanning modes, optimizing observations for specific meteorological conditions—an advantage over conventional radars limited by mechanical scanning and fixed antenna patterns (Schwartzman 2020).

Subarray architectures offer a cost-effective alternative by digitizing only portions of the array—typically vertical rows or horizontal subpanels. Although this reduces hardware complexity, it comes at the expense of flexibility. In particular, these systems are more susceptible to unwanted radiation peaks known as grating lobes, which can introduce signal contamination and limit scan agility. This trade-off underscores the value of element-level



FIG. 1. The Horus fully digital S-band polarimetric PAR on its mobile platform deployed at the National Weather Center (Norman, Oklahoma).

digitization, which eliminates grating lobe issues and enables full spatial control over the transmitted and received beams. Traditional radars, including WSR-88D, struggle with ground clutter from moving targets like wind turbines (Isom et al. 2009; Hood et al. 2010). Subarray PARs can also reduce interference from terrain and wind turbines by making the radar less sensitive in those directions, but their control is coarser than in fully digital, element-level arrays, so suppression is typically less deep and less flexible (Palmer et al. 2008; Curtis et al. 2016; Schwartzman 2023).

Horus overcomes these challenges with flexible scan design, ensuring high-quality data for meteorological analysis and storm modeling. In brief, the requirements that motivate a fully digital PAR are (i) subminute volumetric updates (e.g., ≤ 60 s for 360° coverage and $\sim 3\text{--}5$ s for 90° sectors); (ii) improved dual-polarization data quality via low sidelobes, stable calibration, and adaptive interference suppression; and (iii) special observing modes that concentrate sampling in regions of interest while maintaining situational awareness. Horus achieves these through element-level digitization and full-aperture digital beamforming (Fulton et al. 2016; Weber et al. 2021; Palmer et al. 2022; Palmer and Schwartzman 2025).

This study highlights Horus's real-world capabilities since its deployment in late 2022, bridging the gap between fully digital PAR theory and practice. The rest of this article is organized as follows: Section 2 describes Horus's advanced scanning techniques and trade-offs, section 3 details the experimental setup and observations, and section 4 discusses broader implications for future radar systems and operational weather surveillance. We provide definitions of phased-array-specific terminology in the appendix.

2. Horus scan modes

This section describes the traditional and advanced scanning modes implemented on Horus, including multiple simultaneous beams and imaging techniques enabled by its fully digital architecture. Figure 2 summarizes these strategies. Traditional modes include conical scans [plan position indicator (PPI)], where the beam is electronically steered in azimuth at a constant elevation, and range–height indicator (RHI) scans, where the beam is steered in

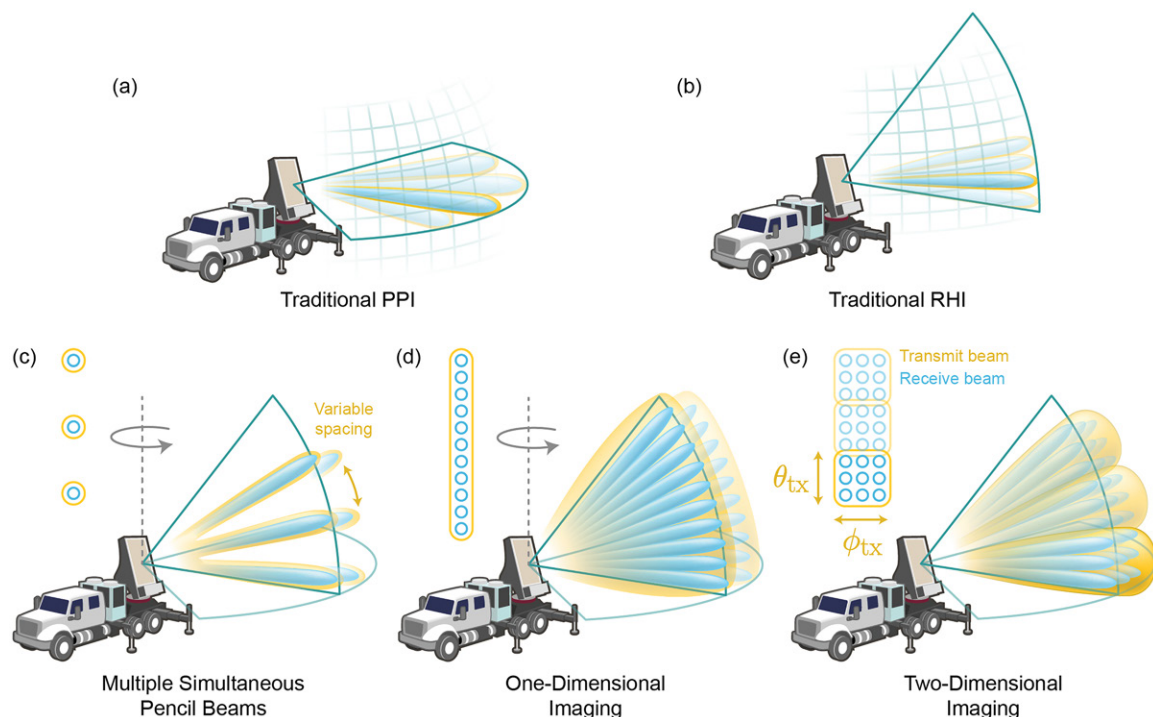


FIG. 2. Traditional and advanced scan strategies implemented in Horus.

elevation. Advanced modes include (i) simultaneous transmission of multiple beams in different directions, (ii) one-dimensional imaging (“spoiling”) where the transmit beam is broadened in elevation while mechanically rotating in azimuth, and (iii) two-dimensional imaging where the beam is broadened in both azimuth and elevation to provide wide-area coverage with digitally formed receive beams. A full overview of the Horus system architecture and performance specifications is in Palmer et al. (2023).

a. Traditional weather radar scan modes. Traditional scan modes provide high-quality observations but are inherently limited in temporal resolution because multiple elevations or azimuths must be sampled sequentially to cover a volume. With electronic beam steering, Horus can rapidly steer its beam within sectors up to about 90° without antenna motion, performing PPI and RHI scans and omitting regions without storms to reduce overall scan time (Torres et al. 2016; Torres and Schwartzman 2020). Although adaptive scanning has also been demonstrated with mechanically beam steering systems such as the Collaborative Adaptive Sensing of the Atmosphere (CASA) (Chandrasekar et al. 2008), electronic steering enhances agility and avoids mechanical wear, making real-time strategies more practical. At the present, Horus allows operator changes to scan settings in real time; automated, dynamically driven adjustments are planned for future observations.

1) PPI SCANS. PPI scans (Fig. 2a) sweep the beam conically at a fixed elevation to generate 2D fields. A 3D volume requires sequential elevations, so update times typically span 60–90 s for 90° azimuthal sectors covering 0° – 20° in elevation with 1° azimuth sampling.

2) RHI SCANS. RHI scans (Fig. 2b) capture vertical cross sections at a fixed azimuth, providing detailed insight into storm structure. As with PPIs, RHIs must be sequenced in azimuth for volumetric context, which can limit temporal resolution; frequent RHIs also increase antenna motion on conventional systems.

b. Multiple transmit beams. Horus’s digital architecture supports multiple simultaneous or quasi-simultaneous transmit beams, improving temporal resolution by simultaneously observing different regions within the field of view, with controlled impacts on detectability and sidelobes.

1) SIMULTANEOUS TRANSMIT BEAMS. The simultaneous beam mode (Fig. 2c) consists of multiple concurrent beams in different directions, which is especially advantageous at low elevations where rapid updates aid warning decisions and where strong reflectivity gradients may be present. Cross-beam interference is mitigated using optimized beamforming coefficients (Schwartzman et al. 2024). Digital synthesis of transmit/receive beams uses precomputed element weights. Because available power is divided among beams, per-beam gain and the minimum detectable signal degrade relative to a single beam (Melnikov et al. 2015; Zrnich et al. 2015). This mode is used in the examples of section 3 (see Fig. 7).

2) QUASI-SIMULTANEOUS TRANSMIT BEAMS. In this mode, the pointing direction alternates from pulse to pulse; the successive pointing directions are separated in time by approximately one pulse width (Melnikov et al. 2015; Schwartzman et al. 2024). This interleaving reduces mainlobe-to-sidelobe contamination across sharp gradients while preserving full-aperture gain. The trade-off is that, for a fixed duty cycle, the pulse length per steering direction decreases roughly in proportion to the number of interleaved beams, which reduces echo detectability.

c. Radar imaging. Imaging modes illuminate a wider field with a broadened (“spoiled”) transmit beam and form many narrow receive beams digitally [digital beamforming (DBF)], trading some angular resolution and detectability for much faster updates. Figures 2d and 2e illustrate 1D and 2D configurations, and applications are shown in section 3 (see Fig. 5).

1) ONE-DIMENSIONAL SPOILING. One-dimensional spoiling (Fig. 2d) broadens the beam in elevation and is typically combined with mechanical azimuthal rotation for 360° coverage over 20° in elevation. Update times of 10–30 s are common, providing dense vertical sampling with improved temporal resolution compared to conventional approaches (Isom et al. 2013; Kurdzo et al. 2017; Griffin et al. 2019; Bodine et al. 2022).

2) TWO-DIMENSIONAL SPOILING. Two-dimensional spoiling (Fig. 2e) broadens the transmit beam in both azimuth and elevation, allowing sector updates as fast as 2–4 s over 90°. This mode is most effective when scatterers are close to the radar or at higher elevation angles, where the path to precipitation tops is short and rapid surveillance reduces overall volume time. Because broader beams reduce detectability and angular resolution, we recommend reserving 2D spoiling for high-temporal-resolution surveillance aloft, while using multiple simultaneous narrow beams at low elevations to preserve sensitivity and fidelity (Schvartzman et al. 2021a).

d. Trade-offs and limitations. Advanced modes enable rapid updates but introduce trade-offs in angular resolution, detectability, and temporal resolution across elevation angles.

Steering the beam away from broadside in both azimuth and elevation can introduce distortions in the co- and cross-polar antenna patterns, which may bias polarimetric measurements (Zrnic et al. 2012; Fulton et al. 2018; Ivic et al. 2020). These effects are particularly important when using wide-angle or asymmetrically shaped beams and are the subject of ongoing research in the radar community (Ivic et al. 2019; Ivić 2023). Mitigation strategies include pulse-to-pulse phase coding (Ivić 2022) and cross-polarization cancellation techniques (Sánchez-Barbetty et al. 2012; Yeary et al. 2013; Salazar et al. 2024). A more detailed discussion of polarization purity challenges and potential solutions for digital PARs is provided by Palmer et al. (2022).

Beam spoiling reduces transmit antenna gain and thereby lowers the radar’s ability to detect weak returns. When phase-only beamforming weights are used to broaden the transmit beam, detectability loss is minimized and can be approximated by

$$\text{Loss (dB)} = 10 \log_{10} \left(\frac{\theta_{\text{spoiled}}^{\text{az}} \cdot \theta_{\text{spoiled}}^{\text{el}}}{\theta_{\text{narrow}}^{\text{az}} \cdot \theta_{\text{narrow}}^{\text{el}}} \right),$$

where $\theta_{\text{spoiled}}^{\text{az}}$ and $\theta_{\text{spoiled}}^{\text{el}}$ are the spoiled beam widths in azimuth and elevation and $\theta_{\text{narrow}}^{\text{az}}$ and $\theta_{\text{narrow}}^{\text{el}}$ are the intrinsic (full aperture) narrow pencil beam widths. For example, increasing the transmit beam from 1° to 10° in elevation results in a 10-dB detectability loss, while a 5° × 5° beam results in a 13.97-dB loss. These estimates set the operational limits of advanced scanning strategies in Horus. Additionally, wider beamwidths may increase sidelobes on transmit and receive, leading to contamination from scatterers outside the main lobe, especially in strong reflectivity gradients where polarimetric variables may degrade (Nai et al. 2020). Consequently, imaging modes are less suitable for observing strong gradients or compact intense cells, where narrow-beam scanning provides better data quality.

Multiple simultaneous beams improve temporal resolution while preserving detectability and minimizing sidelobe contamination at low elevations. However, this mode does not reduce

TABLE 1. Estimated MDS at 50 km for representative Horus scan modes.

Scan mode	Spoiling factor or splitting	MDS (dBZ) @ 50 km
PPI/RHI (pencil beam)	—	12.52
1D spoiling (15° EI)	$10 \log_{10}(15/3.1) = 6.87$ dB	19.39
2D spoiling (5° × 5°)	$10 \log_{10}(25/9.61) = 4.14$ dB	16.66
2D spoiling (10° × 10°)	$10 \log_{10}(100/9.61) = 10.19$ dB	22.71
Multibeam (3 peaks)	$10 \log_{10}(3) = 4.77$ dB	17.29

volume scan time as much as 1D or 2D imaging, because the number and spread of beams are limited. Furthermore, multiple beams are typically offset in elevation, so storm features at different levels may evolve between volume scans, introducing potential inconsistencies when tracking rapidly changing features.

To further illustrate the practical limitations of each scanning mode, Table 1 summarizes the estimated minimum detectable signal (MDS defined as Z per pulse for which $\text{SNR}=0$ dB) at 50 km for representative Horus configurations. The values assume an intrinsic beam-width of $3.1^\circ \times 3.1^\circ$ at broadside and incorporate additional losses due to beam spoiling or transmit power splitting with multiple simultaneous pencil beams. These values serve as a guide for evaluating the trade-offs in detectability associated with rapid scan imaging and multibeam modes.

Overall, each scanning mode involves trade-offs between spatial resolution, temporal resolution, and data quality. An optimal scanning strategy requires balancing these factors according to the meteorological scenario, ensuring that radar resources are allocated efficiently to capture critical weather features while maintaining data integrity. This extreme flexibility in scanning modes, a fully digital array is well positioned to support.

The flexibility of Horus enables a range of scanning configurations summarized in Table 2, each tailored to specific observational needs. This concise overview replaces detailed parameter listings and connects the capabilities described above with the examples in section 3.

e. Potential applications. Advanced modes (simultaneous beams; 1D/2D spoiling) are most valuable when high temporal resolution is required. A practical “precipitation mode” volume coverage pattern could use multiple simultaneous beams at low elevations (e.g., 0.5° ,

TABLE 2. Summary of Horus scanning configurations and representative applications. *Notes:* Update times are approximate and depend on sector size and scan geometry. Electronic steering is limited to $\sim 90^\circ$ sectors; thus, 360° azimuth coverage requires mechanical rotation, while 90° sectors are collected without rotation. The 1D spoiled modes use mechanical azimuthal rotation with DBF in elevation. ATSR and STSR are compatible with all modes listed above; only the pulse-to-pulse polarization sequence differs between ATSR and STSR.

Scan mode	Beam control	Azimuth coverage	Elevation coverage	Mechanical rotation	Typical update (s)	Representative use case
Pencil-beam PPI/RHI	Single narrow beam	90°	0° – 20°	No	60–90	Baseline scans with high angular resolution and high sensitivity
1D spoiled (elevation)	Phase-only broadened beam	360°	20°	Yes	10–30	Rapid convective storm evolution and dense vertical sampling
2D spoiled	Dual-axis beam broadening	90°	20°	No	2–4	Ultrafast updates of convective storm cores or tornadic regions
Multiple simultaneous beams	Three–seven concurrent beams	360°	20°	Yes	60–90	Fast low-level coverage with high resolution

0.9°, 1.3°) to sample storm inflow while limiting two-way sidelobes and 1D/2D spoiling at mid–high elevations or in stratiform regions to maximize coverage efficiency. The examples in section 3 illustrate these trade-offs in practice.

Imaging modes are particularly beneficial for widespread precipitation events, such as stratiform rain, where large-area surveillance is needed. In these cases, 2D spoiling enables efficient high-temporal-resolution monitoring at the expense of detectability. This ensures continuous coverage, supporting the detection of hazardous storm cells. Even for slowly evolving stratiform precipitation, 2D imaging enables rapid scans freeing radar resources to focus on more dynamic areas, such as convective storm cores.

In convective environments, where strong reflectivity gradients exist, scanning modes must balance spatial resolution with data quality. Multiple simultaneous beams at low elevations enhance temporal resolution while reducing sidelobe contamination, ensuring accurate detection of features such as updrafts, downdrafts, and hail cores. At mid–high elevations, 1D spoiling provides continuous vertical coverage, supporting frequent updates across storm profiles. This mode is particularly effective for tracking storm evolution in real time and identifying severe weather signatures.

Beyond tornado and hail cores, these modes support additional use cases. Multiple simultaneous beams at low elevation are well suited for mapping convergence lines and gust fronts relevant to convective initiation and monitoring microburst/downburst outflows. One-dimensional spoiling provides rapid vertical updates aloft for early signals of storm growth and echo-top trends, while two-dimensional spoiling enables fast sector-scale surveillance in stratiform or winter precipitation, including brightband evolution, and snow-band shifts.

By integrating these techniques into a flexible scanning strategy, future PAR systems could dynamically optimize their volume-coverage pattern (VCP) based on evolving meteorological conditions. Low elevation beams would enhance convective storm tracking and weather surveillance, while beams at higher elevations would focus on quantifying storm potency (e.g., cell heights, growth rate, max Z). This adaptive approach allows seamless transitions between high-temporal-resolution wide-area scanning and high-spatial-resolution-focused observations, improving severe weather surveillance, warning decision-making, and the future operational capabilities of radar networks. In practice, we favor multiple simultaneous beams for the lowest elevation angles to retain sensitivity and minimize sidelobe contamination and 1D/2D spoiling at mid–high elevations (or at close ranges) to accelerate volume updates. Even though spoiled-beam imaging already yields short volume-update times (Table 2), these scan geometries are still predefined. Adaptive or artificial intelligence (AI)-based scanning would use them as building blocks, automatically selecting when to employ wide 1D/2D spoiling for situational awareness and when to switch to narrow or multibeam scans over regions where signatures of tornadoes, gust fronts, microbursts, or other high-impact features are detected.

f. Concept of operations. The operational concept for PAR systems like Horus leverages advanced scanning capabilities in both stationary and rotating configurations. The radar supports simultaneous transmit simultaneous receive (STSR), alternating transmit simultaneous receive (ATSR), and alternating transmit alternating receive (ATAR) modes (Doviak and Zrnic 2006; Ryzhkov and Zrnic 2019). In STSR, horizontal H and vertical V polarization waves are transmitted and received simultaneously. Adaptive mode switching could enable retrieval of additional variables, such as the linear depolarization ratio (L_{DR}) in ATSR, or operation in dual-circular polarization (dual-CP) mode, which may be useful for detecting ice crystal alignment. For these dual-polarization modes, the underlying electronic scan strategy is the same whether Horus is used in a stationary four-face or a single-face rotating

configuration; only the pulse-to-pulse polarization sequence differs, and mechanical rotation is applied only in the rotating mode described next. This article focuses on STSR, which is the most relevant mode for meteorological observations with Horus, and the example volume scans in Table 2 are all defined for STSR operation.

1) FOUR-FACE PAR CONCEPT. Although Horus has a single antenna face, it can emulate one quadrant of a stationary four-face PAR [e.g., the multifunction PAR (MPAR) concept; Office of the Federal Coordinator for Meteorology Services and Supporting Research 2006] by scanning within a 90° azimuth sector. In this configuration, Horus supports simultaneous weather surveillance and aircraft tracking with high-temporal-resolution updates over the sector (Kim et al. 2024; Yearly et al. 2024). In a full four-face implementation with simultaneous beams, careful frequency planning (e.g., nonoverlapping spectra) and high-performance filtering are required to avoid face-to-face interference (National Research Council 2008). Each face is stationary (no mechanical azimuthal rotation) and electronically scans its $90^\circ \times 20^\circ$ (az $\times$ el) sector, so that four faces together provide full 360° azimuthal coverage. The same pencil-beam, multibeam, and spoiled-beam volume scans summarized in Table 2 could, in principle, be implemented on each face over its 90° azimuth sector, with the effective volume-update time scaling with the azimuthal coverage assigned to each face.

2) SINGLE-FACE ROTATING ANTENNA. Horus can also function as a single-face rotating antenna, combining mechanical azimuthal rotation with electronic elevation steering for full 360° coverage. This operating mode is commonly used in Horus deployments and in many other polarimetric phased array weather radars (e.g., Isom et al. 2013; Wu et al. 2018; Kikuchi et al. 2020) due to several practical advantages. First, digital beamforming is limited to the elevation plane (vertical), reducing implementation complexity. Second, because all beams lie in the vertical principal plane of the array, polarimetric calibration is simplified and more robust. Finally, cross-polarization contamination is minimal in this configuration, improving the accuracy of dual-polarization measurements. This setup balances spatial coverage and resource efficiency, making it ideal where multiface PARs may be impractical for single-mission applications. In this single-face rotating configuration scans are electronic over a 20° elevation sector using a one-dimensional spoiled beam (as in Fig. 2d). This configuration also serves as the reference for Table 2: Entries with 360° azimuthal coverage correspond to full-rotation scans, whereas the 90° entries represent electronically steered sectors (e.g., a $90^\circ \times 20^\circ$ subvolume in azimuth/elevation) without mechanical rotation, which naturally yield shorter volume-update times.

3. Experimental demonstration

For all data collection experiments presented, Horus was operated at a center frequency of 3.070 GHz using nonlinear frequency-modulated (NLFM) pulse-compression waveforms with a $60\text{-}\mu\text{s}$ pulse over a 5-MHz bandwidth, yielding a range resolution of 60 m (Torres et al. 2017; Schwartzman and Torres 2019). The receiver sampling rate was 7.8125 MHz, corresponding to a range-gate spacing of 19.2 m. Horus digitizes both polarizations at every antenna element; however, when the required spoiled-beamwidths are modest—as in this experiment—we record per-panel, digitally formed beams (13 panels $\times$ 2 polarizations; 26 streams) to limit in-phase/quadrature (I/Q) volume, and avoid returns through grating lobes. Under pencil-beam operation, the intrinsic two-way beamwidth was approximately 3.1° in both azimuth and elevation. Unless otherwise noted, all scans used a 1-ms pulse repetition time (PRT) and 64 pulses per beam position.

a. Traditional scans. To assess data quality, Horus was deployed alongside rapid scan, X-band, polarimetric Doppler radar (RaXPol) on 8 August 2023, collecting RHI scans of convective

storms (Fig. 3). Data were collected at 1039:00 UTC for direct polarimetric comparisons.

As already described, Horus operated with a 13-panel array. For this deployment, real-time beamforming was performed in the array's back end using a systolic processing network to combine signals from all digital elements and synthesize a single dual-polarization beam per pointing angle (as these scans do not require digital beamforming). Therefore, only two digitized channels—one for horizontal and one for vertical polarization—were recorded. RHI

scans were made at a fixed azimuth with 0.5° elevation increments from 0.5° to 32° . This fine angular sampling (compared to the beamwidth) was chosen to facilitate visualization and allow flexible resampling for comparison with operational radar data. A $30\text{-}\mu\text{s}$ NLFM waveform was used over a 5-MHz bandwidth, yielding a 60-m range resolution. Using a 1-ms PRT and 128 pulses per beam position, Horus completed an RHI scan every approximately 8 s.

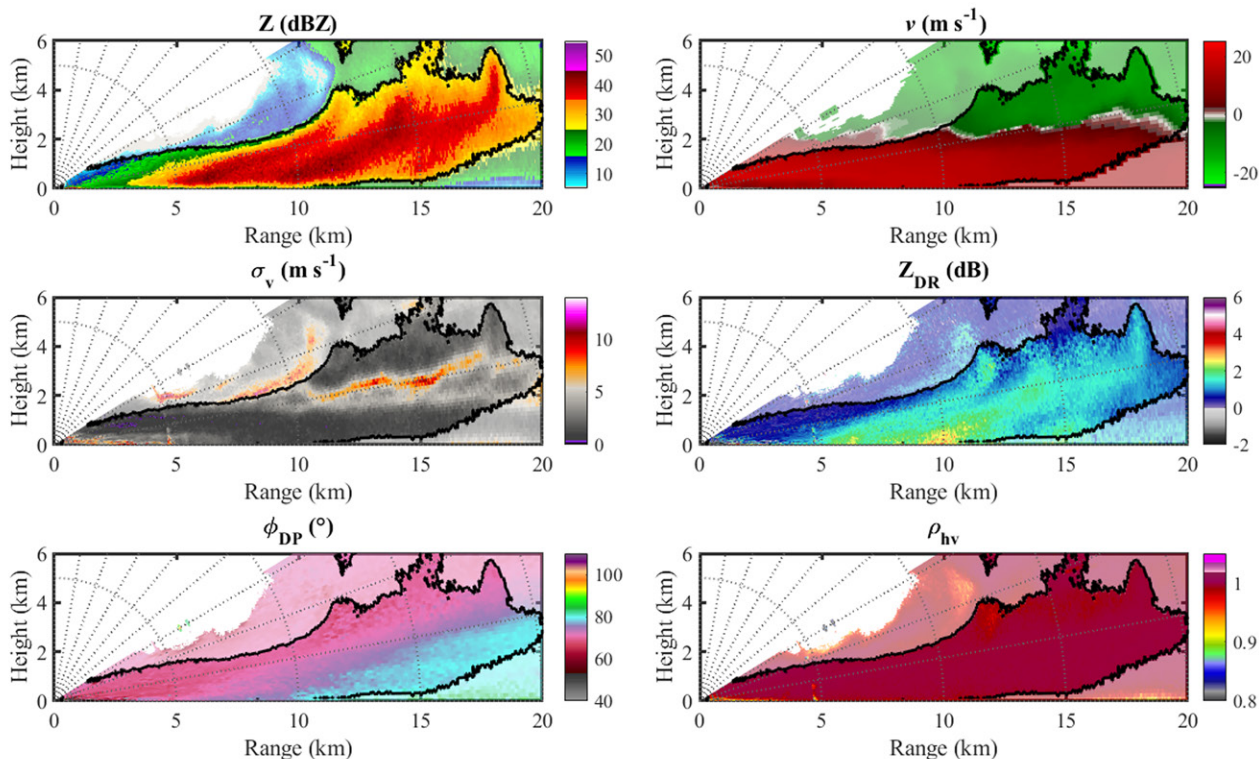
RaXPol was deployed alongside Horus to provide a reference dataset. It operated at 9.730 GHz, using a $1.5\text{-}\mu\text{s}$ traditional pulse and the same 1-ms PRT. RaXPol's antenna has a 3-dB beamwidth of 1° and a peak transmit power of 20 kW. Data were recorded using simultaneous dual polarization, 16-bit I/Q sampling, and 30-m gate spacing. The antenna was mechanically scanned in elevation at approximately $7.8125^\circ \text{ s}^{-1}$, yielding 128 pulses per degree—comparable to Horus's dwell time. While the goal of this comparison is not to quantify gate-to-gate differences between data collected with these systems, we note that Horus and RaXPol differ in operating frequency, beamwidth, and other system parameters. These differences may influence polarimetric estimates and have been extensively discussed in prior literature (e.g., Ryzhkov and Zrnić 2005; Kumjian and Ryzhkov 2008; Ryzhkov and Zrnić 2019). Here, we focus on demonstrating qualitative agreement among key meteorological features.

Figure 4 presents vertical cross sections (RHIs) of radar variables from Horus and RaXPol. Reflectivity Z_h fields from both radars capture similar storm structures, including the intense core and stratiform region. Doppler velocity v_r patterns are also consistent, reflecting a comparable detection of the inflow and outflow regions. Spectrum width σ_v fields align well, highlighting turbulence within the storm. The differences are more pronounced in differential reflectivity Z_{DR} and correlation coefficient ρ_{hv} . Although Z_{DR} shows expected variability, it generally agrees between the radars. The ρ_{hv} fields exhibit similar distributions, with minor discrepancies likely due to intrinsic system differences such as frequency, beamwidth, and peak transmit power. The differential phase Φ_{DP} compares well (about a threefold smaller increase with range for Horus due to its longer wavelength), demonstrating Horus's ability to capture polarimetric phase information accurately. For quantitative comparison, data were processed to align resolution volumes, matching PRTs and sample counts. A high correlation (Pearson > 0.9) was observed in Z_h , v_r , and Φ_{DP} , while Z_{DR} showed a slightly lower correlation (≈ 0.8), consistent with expected variance in polarimetric measurements (Melnikov and Zrnić 2004; Ryzhkov et al. 2005).



FIG. 3. Horus and RaXPol radars deployed on 8 Aug 2023, around 1039:00 UTC, to evaluate polarimetric data quality of Horus scans compared to a known reference system (RaXPol).

Horus



RaXPol

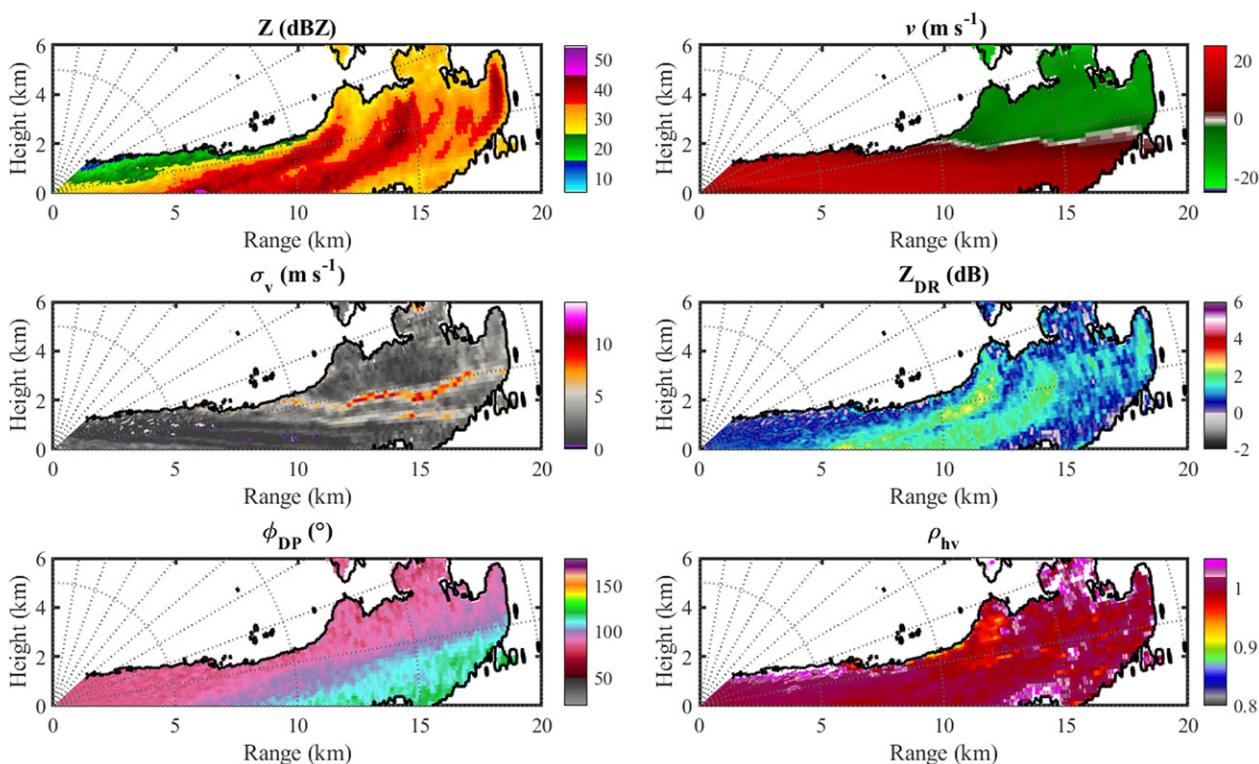


FIG. 4. Comparative RHI scans collected by (top) Horus and (bottom) RaXPol during the deployment shown in Fig. 3, highlighting key radar variables: reflectivity Z_r , Doppler velocity v_r , spectrum width σ_r , differential reflectivity Z_{DR} , differential phase Φ_{DP} , and correlation coefficient ρ_{hv} . The scans capture the vertical structure of a convective storm, with both radars displaying consistent meteorological features across variables. Minor variations in Z_{DR} and ρ_{hv} reflect inherent differences between the systems.

These RHI observations demonstrate that Horus is capable of capturing vertical storm structures with fine spatial and temporal resolutions, producing high-quality traditional scans that are consistent with those from RaXPol. The agreement across polarimetric and

Doppler variables validates Horus's performance in conventional scanning modes. Beyond this deployment, Horus's rapid-update capabilities have been demonstrated in other contexts, including detection of lightning plasma reflections with 2-s temporal resolution scans (Goede et al. 2025). These results form a foundation for exploring the radar's advanced imaging and multibeam capabilities in subsequent sections.

b. Radar imaging. The severe weather outbreak of 27–28 April 2024 provided an opportunity to evaluate Horus's capabilities across multiple advanced scanning modes, including 1D and 2D spoiling and multiple simultaneous transmit beams. This event, which produced multiple tornadoes in Oklahoma and north Texas, including an EF1 near Norman, enabled a detailed assessment of storm-scale evolution with high temporal and spatial resolutions.

Horus was deployed at the University of Oklahoma's Lloyd Noble Center and operated continuously through the evening of 27 April. After calibration, test scans confirmed the system readiness. At 0103:42 UTC 28 April, Horus began scanning a convective line moving north-northeast toward Oklahoma City, capturing rapid volumetric observations with the beamforming techniques described in this study.

1) ONE-DIMENSIONAL SPOILING AND MECHANICAL ROTATION. To evaluate the concept of rotating PAR (RPAR) for rapid volumetric scanning, Horus operated in 1D spoiling mode, broadening the transmit beam in elevation while mechanically rotating in azimuth (Schvartzman 2020). This configuration, combined with DBF, contains multiple narrow receive beams with fine angular resolution in elevation while achieving rapid full-volume updates.

The spoiled transmit beam spanned 15° in elevation (although this is variable), and continuous azimuthal rotation enabled full volumetric coverage. This mode balances update speed and data quality, enabling high temporal resolution which is ideal for updrafts, downdrafts, and hail cores. Rapid vertical sampling enhances storm dynamics characterization, improving upon traditional scanning methods constrained by fixed elevation angles and sequential updates.

The 1D spoiling technique used by Horus is conceptually similar to the approach employed by the Atmospheric Imaging Radar (AIR), which transmits a wide vertical fan beam and in the receiver digitally forms multiple simultaneous elevation beams (Isom et al. 2013; Kurdzo et al. 2017). AIR enables rapid sector volume updates while continuously sampling the vertical dimension of a storm. The AIR is optimized for imaging within confined azimuthal sectors. In contrast, Horus extends this concept to a full 360° mechanically scanned domain, providing broader spatial coverage while preserving high spatial resolution in elevation. Additionally, the fully digital architecture of Horus enables greater flexibility in synthesizing different transmit beams (e.g., for different beamwidths) and future enhancements incorporating dynamic scan optimization.

Unlike mechanically scanned radars that sequentially step through elevation angles, 1D spoiling in a rotating phased array system enables near-continuous vertical sampling while retaining the ability to electronically refine the receive beam structure. This approach mitigates issues such as undersampling of critical storm layers while maintaining high data quality. By efficiently combining mechanical and electronic scanning, Horus provides a versatile framework for rapid, volumetric weather observations, bridging the gap between traditional mechanically scanned radars and advanced phased array systems designed for operational deployment in next-generation networks.

Rotating phased array radars that combine vertical digital beamforming with mechanical azimuthal rotation—as implemented in Horus and illustrated in Fig. 2d—can also be realized using partial digital architectures, like 1D digital PARs that digitize the outputs of vertically stacked rows. These systems have demonstrated great value in field studies and

early operational prototypes, providing rapid vertical sampling and preserving polarization purity (Kikuchi et al. 2020). However, their beamforming flexibility is limited by the analog constraints in the azimuthal dimension. In contrast, fully digitized output of every antenna element, like on Horus enables real-time dynamic control over both azimuth and elevation beam characteristics. This facilitates additional capabilities such as simultaneous transmit beams (steered in both azimuth and elevation), 2D spoiling to support advanced techniques in this mode (e.g., Schwartzman et al. 2021a), motion-compensated steering to mitigate beam smearing (Schwartzman et al. 2021b), and flexible scan reconfiguration, offering a richer set of tools for rapid and adaptive storm surveillance.

2) TWO-DIMENSIONAL SPOILING. In 2D spoiling mode, Horus transmitted a broad beam in both azimuth and elevation, covering a wide atmospheric sector per pulse. DBF on receive enabled high-resolution data collection across multiple beams. The radar employed a raster scan strategy with 55 transmit beams spanning from -30° to $+30^\circ$ in azimuth and 0° – 30° in elevation. Each beam was illuminated for 64 pulses with a 1-ms PRT. NLFM pulse compression waveforms ($60\text{-}\mu\text{s}$ pulse width) provided 60-m range resolution. Progressive pulse compression (PPC) mitigated blind range effects, with a range sampling interval of 19.2 m, covering 0.5–60 km (Salazar et al. 2021, 2024). For this experiment, Horus was deployed west of Norman, with its antenna broadside pointed to an azimuth of 243° , scanning a 60° sector about that direction.

Figure 5 illustrates the raster scanning strategy employed by Horus, highlighting the locations of the 2D spoiled transmit beams (colored circles) and the overall angular extent of the transmitted beam (green square), along with the corresponding digital receive beams

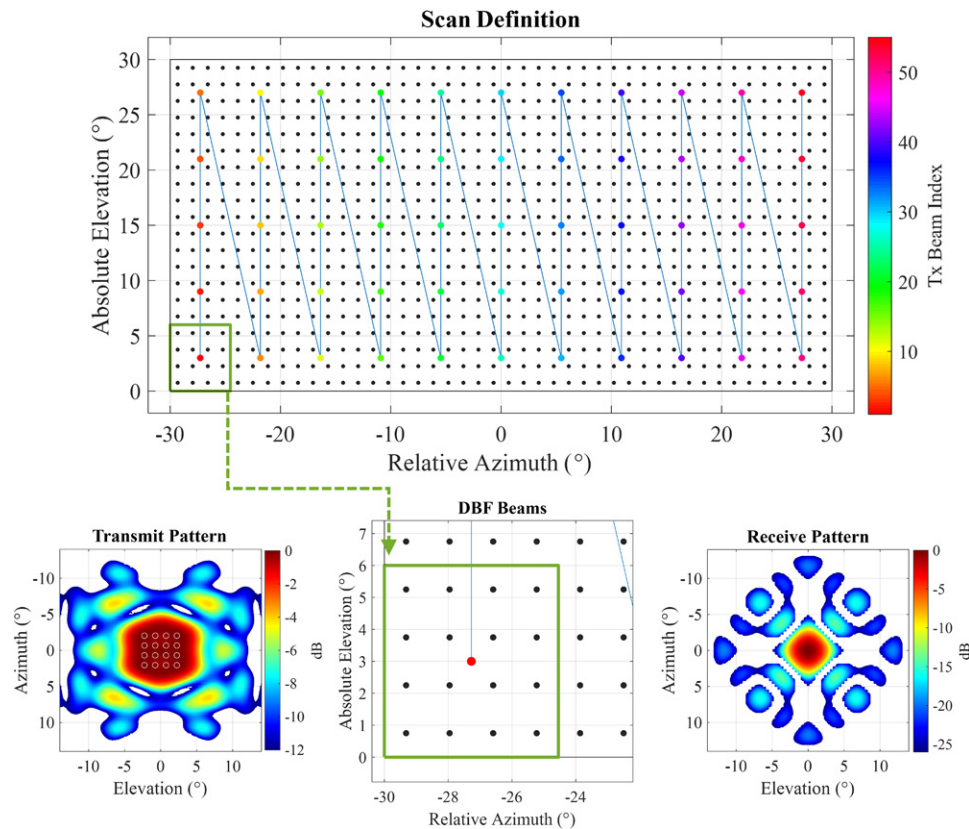


FIG. 5. Horus raster scanning with 2D spoiling. The 55 transmit beams (colored circles depict center of pointing angle) span from -30° to $+30^\circ$ in azimuth and 0° – 30° in elevation; black dots indicate digitally formed receive beams. The Tx beam index shows the serpentine temporal order (64-ms dwell per index; 1-ms PRT $\times$ 64 pulses), giving a 3.52-s sector update. This configuration was used to collect the observations shown in Fig. 6.

(black dots). The transmit and receive beam patterns are also depicted, showcasing the system's ability to provide rapid updates.

With 2D spoiling, Horus completed a sector scan in 3.52 s, significantly faster than mechanically scanned radars, which require several minutes. This rapid update rate enabled continuous monitoring of storm-scale rotation and microphysical characteristics during the EF1 tornado near Norman.

Figure 6 depicts polarimetric measurements and a 3D reflectivity rendering of the tornado. Variables Z_h , v_r , Φ_{DP} , and ρ_{hv} provide insight into storm structure and tornado dynamics. The 3D rendering highlights a 40-dBZ reflectivity isosurface surrounding a tornado-centered weak-echo hole (WEH) associated with the broader updraft. With sector updates of approximately 3.52 s in this 2D-spoiling configuration, consecutive scans capture rapid evolution. Between successive scans shortly after tornadogenesis, the WEH deepens and narrows slightly while its centroid ascends, consistent with a strengthening updraft. During the same interval, the low-level velocity couplet tightens and shifts incrementally along the hook echo, indicating increased gate-to-gate shear and a modest reorientation of the vortex. These sub-10-s changes would be difficult to document with minute-scale updates, underscoring the value of fully digital PAR sampling for continuous severe-storm surveillance.

Beyond meteorological applications, the wide-area electronic scanning capability enabled by 2D spoiling is well aligned with the concepts explored in MPAR research. The ability to scan large atmospheric sectors at high refresh rates without mechanical movement makes this mode adaptable to additional sensing missions, such as civil aviation surveillance and space debris monitoring (Weber et al. 2007; Zrnic et al. 2007).

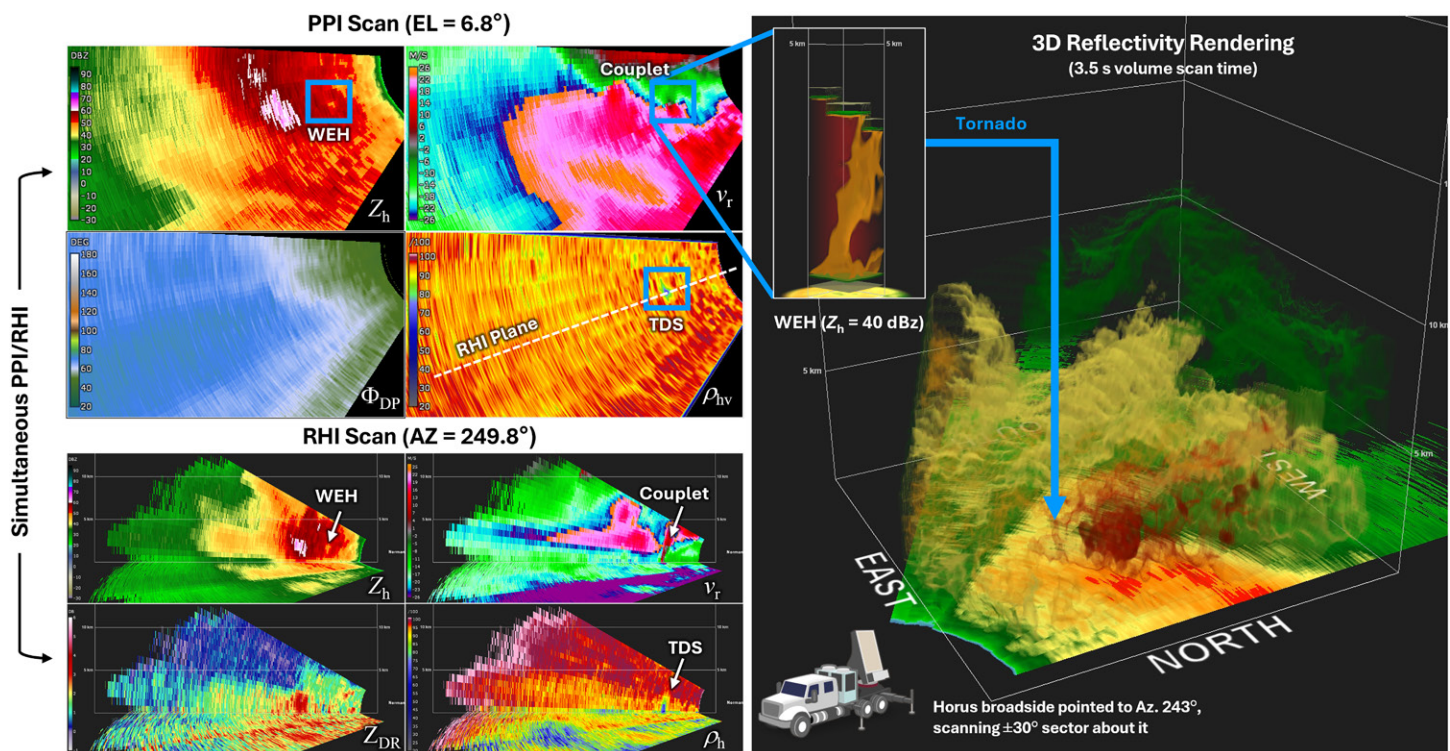


FIG. 6. Horus observations of the EF1 tornado near Norman, Oklahoma, on 28 Apr 2024. (left) Synchronized PPI and RHI views of radar variables collected during the event, including reflectivity Z_h , Doppler velocity v_r , differential reflectivity Z_{DR} , differential phase Φ_{DP} , and correlation coefficient ρ_{hv} . Key storm features—such as a tornado-centered WEH [or a weak-echo column (WEC), if vertically continuous], a velocity couplet, and a tornado debris signature (TDS)—are highlighted. (right) A 3D reflectivity rendering (40-dBZ isosurface) aligned with the RHI plane, revealing vertical storm structure associated with the tornado. The radar antenna was pointed broadside to 243°, and the beam scanned a 60°-wide azimuthal sector centered on that direction. Volume scans were completed in 3.52 s.

In aviation applications, real-time aircraft tracking could benefit from rapid electronic scanning, enabling simultaneous weather monitoring and target detection within the same observational sector. Similarly, space debris tracking is becoming an increasingly relevant challenge as the number of satellites and reentering objects continues to grow. Wide field-of-view radars are critical for detecting and characterizing small, fast-moving debris that may pose a risk to aviation safety or ground impact hazards. Although Horus is primarily a meteorological radar, the flexibility afforded by fully digital beamforming suggests that future phased array systems could be configured to support both weather and nonweather missions within a shared operational framework.

Rapid scan observations from this event highlight the transformational potential of fully digital phased array weather radars. The combination of wide-area electronic scanning, high-temporal-resolution volume updates, and multimission adaptability demonstrates how 2D spoofing can enhance severe weather monitoring while offering additional sensing capabilities for broader atmospheric and aerospace applications. While a detailed meteorological analysis of this case is beyond the scope of this article, such studies are forthcoming and will build on this technical foundation. Benefits of high-temporal-resolution volume updates, which motivate the use of these advanced PAR modes, have been shown to improve storm evolution tracking and warning decision-making (e.g., Heinselman et al. 2012; Bluestein et al. 2010; Wilson et al. 2017; Kuster et al. 2019).

c. Multiple simultaneous beams. During the 27–28 April 2024 severe weather event, Horus demonstrated multiple simultaneous transmit beams (Fig. 2c). This mode used three synthesized peaks, offset in elevation, to improve temporal resolution without significantly compromising data quality. The experimental setup was similar to previous scans but used a different mode. The radar produced three transmit peaks at 2°, 12°, and 22° elevation, aligned in azimuth and offset by 10° in elevation to minimize beam blockage and enable clutter-free observations at higher angles. All other scan parameters are the same as those used in section 3b.

Figure 7 shows the synthesized antenna pattern, where three transmit peaks in different directions improve temporal resolution while minimizing sidelobe contamination.

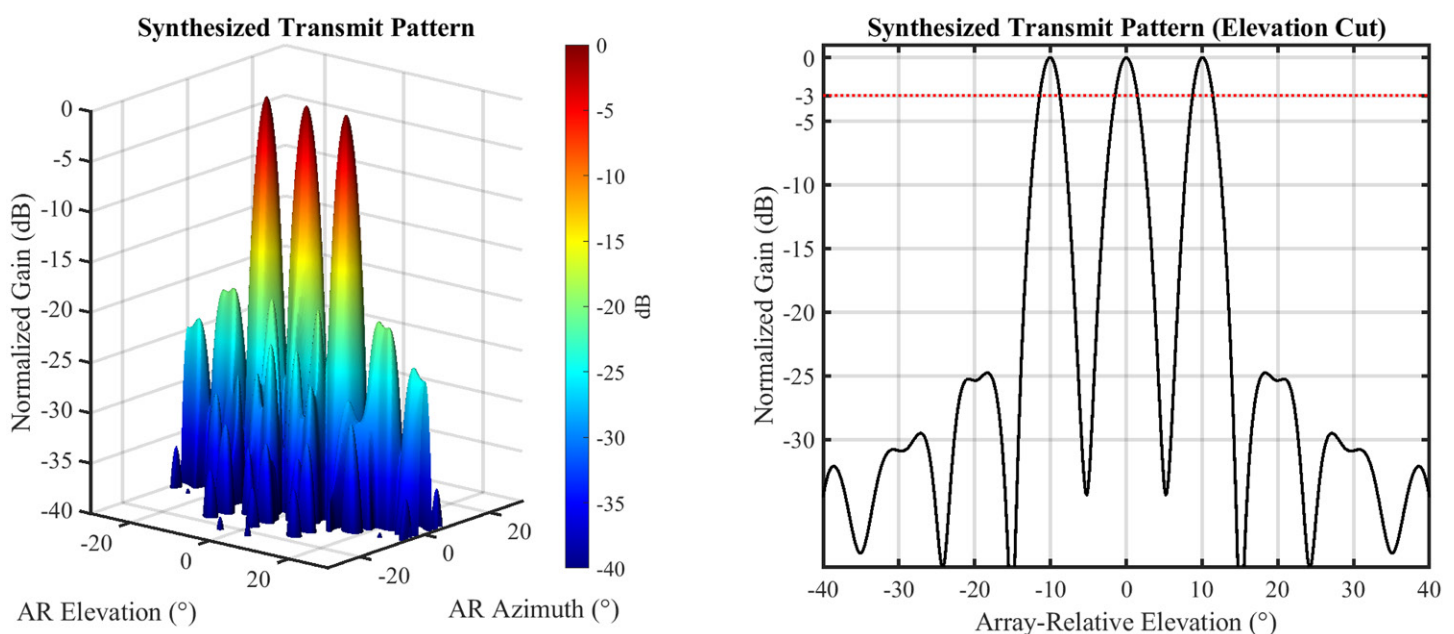


FIG. 7. Synthesized antenna pattern of Horus radar showing three simultaneous transmit peaks, with array-relative (AR) alignment in azimuth and spacing of 10° in elevation.

This configuration enabled efficient data collection with high-quality polarimetric measurements. This transmit setup was used to acquire the dataset in Fig. 8.

Figure 8 demonstrates high-temporal-resolution, multielevation observations with consistent polarimetric calibration. The example was collected at 0304:56 UTC 28 April 2024.

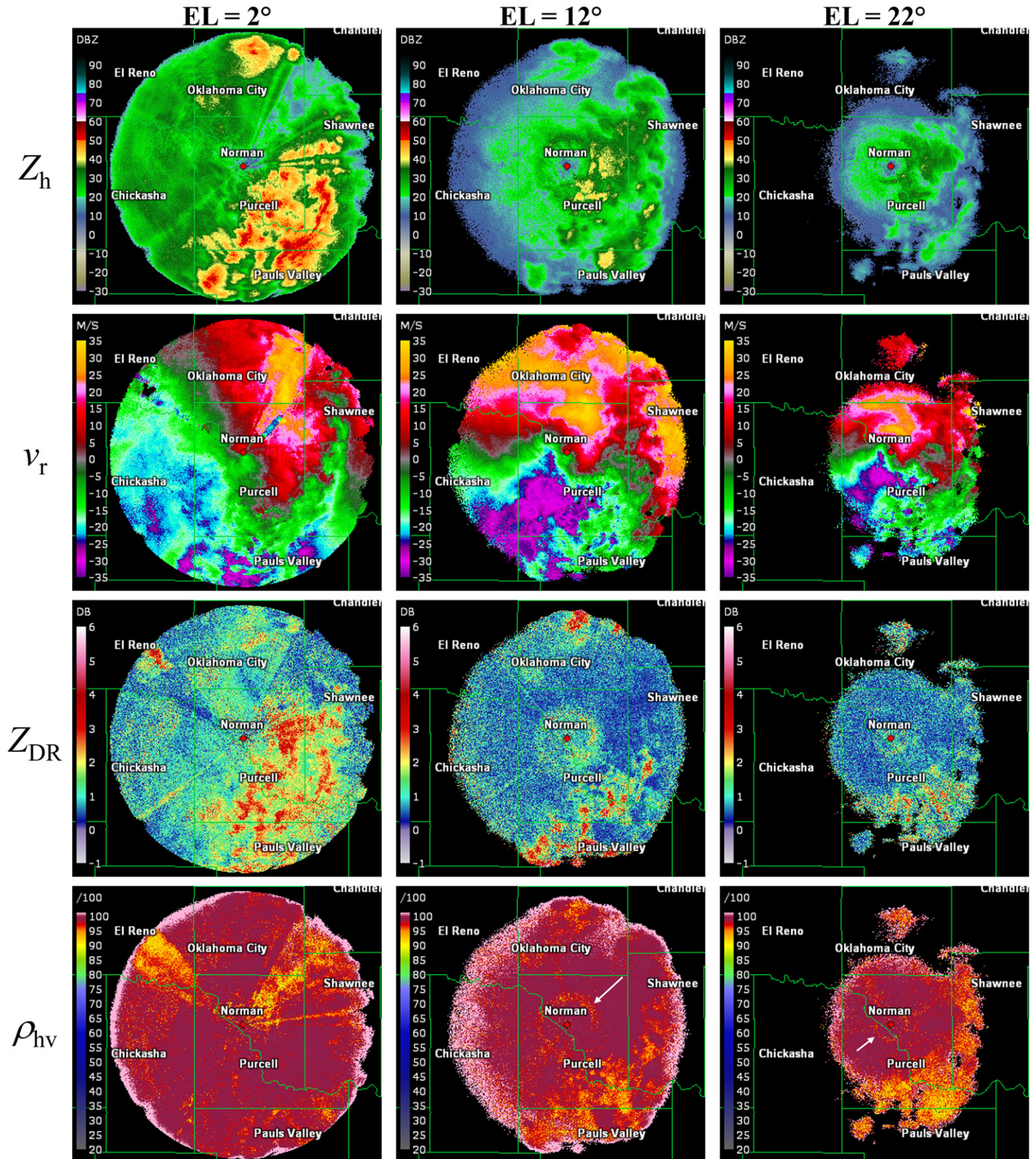


FIG. 8. Simultaneous PPIs at 2°, 12°, and 22° collected with the multiple simultaneous transmit-beam mode (scan concept in Fig. 2c; transmit patterns in Fig. 7). Rows show Z_h , v_r , Z_{DR} , and ρ_{hv} . The fields exhibit expected storm signatures (e.g., convective cores, melting layer, and decreasing Z_h with height) with no obvious interbeam seams or calibration artifacts.

Comparisons with KCRI (Norman, Oklahoma) data (not shown) indicate general consistency, though differences in radar architecture and signal processing prevent precise evaluations. See Schwartzman et al. (2025) for more details about this mode.

4. Conclusions and future outlook

Horus has been tested in severe weather, demonstrating the value of rapid volumetric scanning for tracking evolving storm structures. Continuous observation of convective systems reveals storm-scale processes that are difficult to capture with conventional radars. The ability to switch scanning modes and adjust spatial and temporal samplings is central to this capability; in practice, multiple simultaneous beams are most effective at the lowest elevation angles to preserve sensitivity and data quality near the surface, while 1D/2D spoiled beams aloft accelerate volume update. These capabilities extend beyond severe weather events to convective initiation and other rapidly evolving boundary layer and stratiform/winter processes, where rapid updates and flexible scan geometry improve surveillance. This is crucial for weather observations, where frequent volumetric updates improve conceptual modeling and situational awareness.

The success of the Horus program has important implications for the future of operational weather radar networks. The National Weather Service “Radar Next” program (Gallagher et al. 2024; Zachman et al. 2025) is currently evaluating technologies to replace the aging WSR-88D network. The fully digital architecture demonstrated by Horus provides a compelling model for this transition. Unlike mechanically scanning radars, a nationwide network of digital phased array radars could offer continuous, adaptive, and high-temporal-resolution weather surveillance, significantly improving the ability to monitor severe convective storms, tornadoes, and other weather hazards. Electronically steered beams would dramatically reduce volume update times while preserving high data quality, enhancing severe weather warnings, and advancing the nation’s ability to respond to extreme weather events.

The capabilities demonstrated by Horus underscore the transformational potential of fully digital weather radars and provide a clear path from research to operations. With continued advances in adaptive scanning (e.g., AI-based scanning), phased array systems can further improve observation, forecasting, and hazard mitigation. Beyond meteorology, the same flexible scanning supports multifunction PAR concepts, including civil aviation surveillance and space-object tracking within a shared framework. Future work will explore adaptive scanning and AI to move beyond manual strategies, enabling scans that respond to evolving storms, prioritize regions of interest, and maximize the operational value of PAR observations.

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Data availability statement. Several high-resolution datasets are available at the ARRC data portal (<https://arrc.ou.edu/data.html>), including phased array data. Requests are always encouraged for other archived radar datasets as described on the ARRC data portal. The ARRC’s RadarHub visualization platform can be used to view several years of archived mobile radar data (<https://radarhub.arrc.ou.edu>). In addition, select radar datasets and supporting visualizations from the Horus deployments discussed in this manuscript are available at <https://doi.org/10.5281/zenodo.15700983>.

APPENDIX

Beam Types and Phased-Array Terminology

Figure A1 summarizes different types of beam types used in Horus. The left panels show 3D gain patterns for a conventional pencil beam, a trident beam formed by three simultaneous pencil beams, and a spoiled beam whose mainlobe is deliberately broadened. The right panel contains elevation cuts of a spoiled transmit beam and multiple narrow, digitally formed receive beams within it. Observation requirements impose trade-offs between beamwidth, sidelobe level, and number of simultaneous beams. The terms below are defined to inform readers less familiar with phased array radar concepts.

Phased array antenna: An antenna that electronically directs its beam without mechanical movement by adjusting the phase of signals at each radiating element.

Antenna elements: The individual radiating components of a phased array antenna. Each element can be independently controlled in phase and amplitude, allowing for precise beam shaping and steering.

Antenna patterns (transmit and receive): The spatial distribution of radiated energy (transmit) and sensitivity (receive) across the antenna elements, defining the radar's ability to focus and detect signals from specific directions. In phased array radars, these can be different on transmission and reception and are usually designed with different element-level excitations.

Intentional beam broadening (spoiling): A technique that increases the width of the transmitted radar beam to improve temporal resolution and spatial coverage at the expense of radar detectability. Used for observing widespread precipitation or rapidly updating storm structures.

Digital beamforming (DBF): A signal processing technique that digitally combines signals from each antenna element to form and steer one or several radar beams with high precision. This is used on reception to form simultaneous beams within the transmit beam (e.g., spoiled beam or multiple simultaneous transmit beams).

Radar imaging: A scanning strategy in which a broad (spoiled) transmit beam covers a large area, while digital beamforming on receive enables simultaneous observations in multiple directions. This technique increases the vertical or horizontal sampling density.

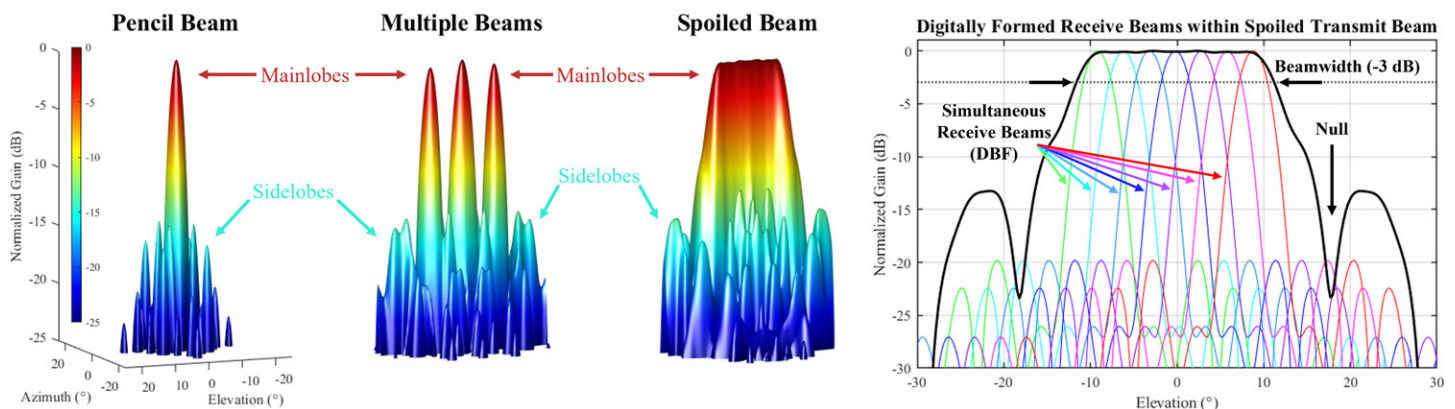


FIG. A1. Horus beam patterns. (left) 3D normalized gain patterns of a pencil beam, a three-beam trident, and a spoiled transmit beam with broadened mainlobe. (right) Elevation cuts of the spoiled transmit beam (black) and simultaneous narrow receive beams (colored). The -3 -dB transmit beamwidth and the synthesized null are indicated.

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