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***Abstract*—Phased Array Radar (PAR) technology provides advanced and flexible capabilities for observing a wide range of atmospheric phenomena. In conjunction with dual-polarization technology, PARs can provide high temporal and spatial resolution polarimetric weather data, needed to advance our understanding of complex atmospheric processes. To attain maximum scanning flexibility and overall capability, an all-digital system is desirable. This PAR architecture is based on digitizing every antenna element (and polarization). The University of Oklahoma's Advanced Radar Research Center (ARRC) is completing the integration of the mobile, all-digital, S-band, "Horus" rotating PAR for polarimetric weather measurements. This revolutionary radar system will provide unprecedented observations to advance our physical and dynamical understanding of the atmosphere. In this paper, we provide an overview of the Horus system, discuss preliminary system measurements and expected performance, and give an outlook for experiments envisioned to highlight Horus capabilities.**

***Index Terms*—phased array radar, weather radar, polarimetric radar, digital radar**

I. INTRODUCTION

Weather radars have improved our understanding of, and ability to forecast, increasingly frequent catastrophic weather events. Extreme weather can disrupt community functioning, severely impact commerce, civil infrastructure, and cause $100–200 billion in global damage annually (e.g., [1]). Unfortunately, current weather radars were never designed to capture rapidly evolving processes that lead to extreme events, which are fueled by climate change. The absence of high temporal resolution data causes uncertainty in climate projections [2] and increased vulnerability to climate change impacts. Significant improvements in forecasting of high-impact weather requires a new system that provides the needed temporal resolution along with the scanning capabilities afforded by a phased array radar (PAR).

Polarimetric PAR technology is emerging as a promising technology for the next generation of weather radars due to the capabilities it offers, which makes it ideal to observe a wide variety of atmospheric phenomena [3], [4]. All-digital PAR (or just "digital PAR") architectures offer high scanning flexibility, including the imaging technique [5] that is critical to reveal the elusive structure and dynamics of the atmosphere. Digital PAR technology allows precise control over each of the thousands of radiating elements that make up the antenna, maximizing observational flexibility [6]. With support from NOAA's National Severe Storms Laboratory (NSSL), the Advanced Radar Research Center (ARRC) at the University of Oklahoma (OU) has developed an S-band all-digital polarimetric rotating PAR system called "Horus," the ancient Egyptian sky god with *the all-seeing eye*.

Horus's all-digital architecture will enable rapid (volume scans in seconds) and adaptive scanning. By scanning storms from the ground to storm top with near-vertically continuous sampling, Horus observations will accurately capture 4D atmospheric processes including: microphysics governing the properties of hydrometeors that form the fundamental building blocks of weather systems, and dynamics involving 3D hydrometeor and air motions. A deep understanding of microphysics will be enabled with pristine dual-polarization data, achieved by exploiting the all-digital architecture. Horus will operate with minimal attenuation and excellent sensitivity in the S band (2.7—3.1 GHz), which is the ideal frequency for atmospheric observations providing a large observational range and well-understood scattering physics. Initial integration of the Horus radar was recently completed at the ARRC and initial deployments for polarimetric weather measurements are ongoing.

In this paper, we provide a brief overview of the challenges with PAR weather measurements, solutions provided by an all-digital architecture, expected Horus performance, and finally give an outlook for experiments envisioned to highlight Horus capabilities.

Fig. 1. Horus all-digital PAR during integration (partial array only) and initial field deployments.

II. CHALLENGES OF PHASED ARRAY RADARS FOR WEATHER OBSERVATIONS

Traditionally, weather radars are based on a dish antenna that mechanically rotates in a set pattern (“scan strategy”) in order to sample the hemispherical regional centered on the radar out to a range of hundreds of kilometers [7]. The mechanical steering of the large antenna constrains the overall update time to several minutes for a typical operational weather radar [8]. Furthermore, severe under-sampling in the vertical dimension is necessary to achieve this several-minute update time.

Due to cost advantages, it is likely that any future weather PAR would consist of a single, planar array on an azimuth-only rotating pedestal [9]. As is the case with all PAR systems, this rotating PAR (RPAR) would steer the beam electronically within its field of view allowing extremely rapid update times. For polarimetric RPAR for weather observations, some challenges do exist, which are summarized below:

- *Calibration:* As with all PAR systems, *polarization calibration* is dependent on pointing angle.
- *Mechanical Rotation:* Compared to a stationary, four-faced PAR, for example, the flexibility of the RPAR *scan strategy is constrained by it mechanical rotation*.
- *Temporal Resolution: Temporal resolution* may be limited for a RPAR due to inherent revisit time limited by the mechanical rotation.

Despite these challenges/limitations, a rotating PAR concept is the most promising architecture to meet the observational needs of the weather community [10], [11], while constraining costs. It should be mentioned that if the radar system were designed to meet multiple missions, including weather, a stationary, multi-faced (or cylindrical) system might be attractive [12]. Of course, other challenges would be present in such systems.

III. THE PROMISE OF ALL-DIGITAL PHASED ARRAY RADARS

As discussed, an all-digital architecture gives the highest flexibility to exploit PAR capabilities such as *beam agility, digital beamforming, adaptive scanning, and near-continuous vertical sampling*. Although constrained by a rotating PAR (RPAR) design, a digital architecture still allows the highest level of flexibility and capability. These radars can scan narrow pencil beams or wide imaging beams in any direction within the antenna’s field of view without the limitations of a sub-array architecture. Having digital signals at every element makes this architecture a “software-defined radar,” because the array can be reconfigured via software updates rather than through expensive hardware modifications. This architecture can also be considered “future proof” as it already implements the maximum level of digitization possible with a PAR and gives the largest number of degrees of freedom for future observational needs involving dynamic array reconfiguration.

Arguably the most important feature of an all-digital PAR is the potential for *routine and periodic field calibration based on mutual coupling* [13]. By exploiting the known geometry and inherent mutual coupling among elements, it has been shown that array alignment and polarimetric calibration can be performed, allowing excellent performance as polarimetric weather radar.

IV. THE HORUS PROGRAM - STATUS AND INITIAL MEASUREMENTS

As previously emphasized, meeting the requirements for weather monitoring may require an all-digital PAR architecture. Fortunately, the semiconductor industry has stepped up with offerings that enabled digitization (and control) at every element of a PAR large enough to meet operational needs. Furthermore, the defense industry has explored all-digital PAR technology, thus expanding the industrial base and the potential of use for weather observations. The "Horus" radar (shown in Fig. 1 during integration and initial field deployments) is a small-scale engineering demonstrator and the first-ever polarimetric all-digital radar for weather observations. Horus is an S-band, polarimetric, all-digital PAR and has started to be used for data collection in 2022. This proof-of-concept system will be used to demonstrate the benefits of all-digital technology for atmospheric observations. Leveraging the scalable architecture of the Horus radar, a full-scale system with an operational size is possible and has been conceptualized. The capabilities of such a system have been described and would enable transformative operational usage with unprecedented adaptability, spatial coverage, and temporal resolution.

The Horus array panel, which is defined as an 8×8 subarray of radiating elements [14] (shown in Fig. 2), is the primary building block of a larger Horus system. The antenna panel is supported by a tube-based frame providing mechanical support as well as a conduit for liquid cooling. The "OctoBlades," eight per panel, house all radar electronics and slide into the panel frame to connect: a) the liquid cooling system, b) the backplane, and c) the antenna array itself through blind-mate connectors that pass through cutouts in the backplane. The OctoBlades are the heart of the overall digital radar system since they comprise a 16-channel digital radar system (RF to bits). Each panel has a centralized module, the SuperBlade, that supports the active electronic components. This module also works with the panel's analog backplane and provides passive distribution of power, the local oscillator signal, and a reference clock to each of the OctoBlades. Operating with wideband waveforms in the 2.7—3.1 GHz frequency band (switchable from dwell-to-dwell), the aperture-coupled, stacked-patch elements provide high-quality polarimetric operation [15]. By digitizing at the element level, it has been shown in a laboratory setting that polarimetric calibration of a phased array weather radar can be robustly accomplished, as explained next.

Our near-field calibration uses a park-and-probe technique to measure amplitude and phase at each channel, generate and apply alignment weights, and then verify the resulting alignment. After deriving robust alignment coefficients, full array near-field data were acquired for all 64 channels with both polarizations setting up the scanner probe in the transmit mode and the Horus 8×8 in the receive mode. Determining the far-field radiation patterns of an antenna from near-field measurements requires a mathematical transformation and a correction for the characteristics of the measuring probe [16]. Normalized co- and cross-polar H and V far-field patterns are presented in Fig. 3. Dotted contours on the copolar H and V patterns indicate the half-power beamwidth (-3 dB); similarly, dotted contours in the cross-polar patterns indicate the -40 dB level.

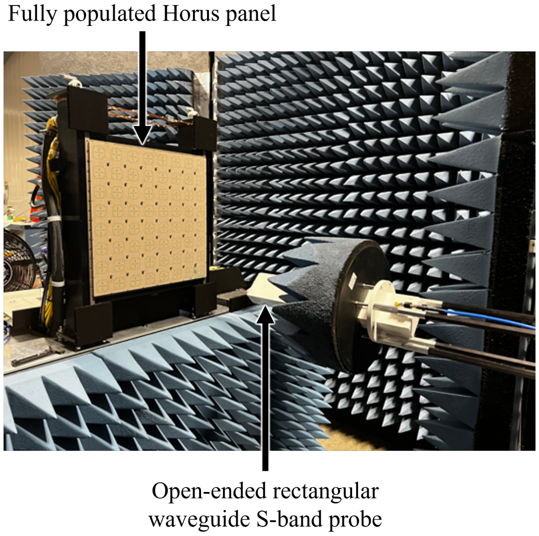

Fig. 2. Near-field scanner setup to fully characterize the H and V antenna patterns of the Horus system.

A qualitative comparison of these patterns shows excellent mainlobe agreement between the H and V polarizations. The sidelobe structure for each polarization appears to be symmetric about the mainlobe for the horizontal and vertical cuts. Cross-polarization levels are below -50 dB at the peak of the corresponding copolar patterns, and generally going from -55 to -45 dB across all angles. Achieving cross-polarization levels below -45 dB was one of the key goals in the design of the Horus antenna, given the importance of minimizing this contamination for accurate polarimetric measurements [17], [18].

In particular, the magnitude of the copolar cross-correlation coefficient (ρ_{hv}) is a key parameter defining the quality of polarimetric radar measurements [19]. The standard errors of the estimates of polarimetric variables are significantly reduced if the largest values of ρ_{hv} from weather signals exceed 0.99. This is the requirement on ρ_{hv} estimates for polarimetric weather measurements, as specified by NOAA [20]. Additionally, accurate measurements of ρ_{hv} are crucial for polarimetric detection of the melting layer and determination of its height [21], for identification of the areas of hail and quantification of its size [22], and for polarimetric tornado detection [23]. Therefore, the requirements for the ρ_{hv} measurements in the design of the radars for weather observations are extremely strict and important. Using the probe-corrected far-field patterns in Fig. 3, we computed the antenna-induced biases in ρ_{hv} as a function of steering angle [24]. These are shown in Fig. 4. It can be seen that biases induced by the Horus antenna in ρ_{hv} are below the requirement (i.e., bias in $\rho_{\mathrm{hv}} \leq 0.01$) through the entire scan sector. This is due to the significant agreement in copolar beams and the ultra-low cross-polarization levels achieved. In summary, our quantitative analysis based on *measured* antenna patterns suggests that any adverse impact of the Horus antenna on ρ_{hv} estimates will be negligible. We expect that the shapes of H and V beams are preserved for the full Horus array to produce

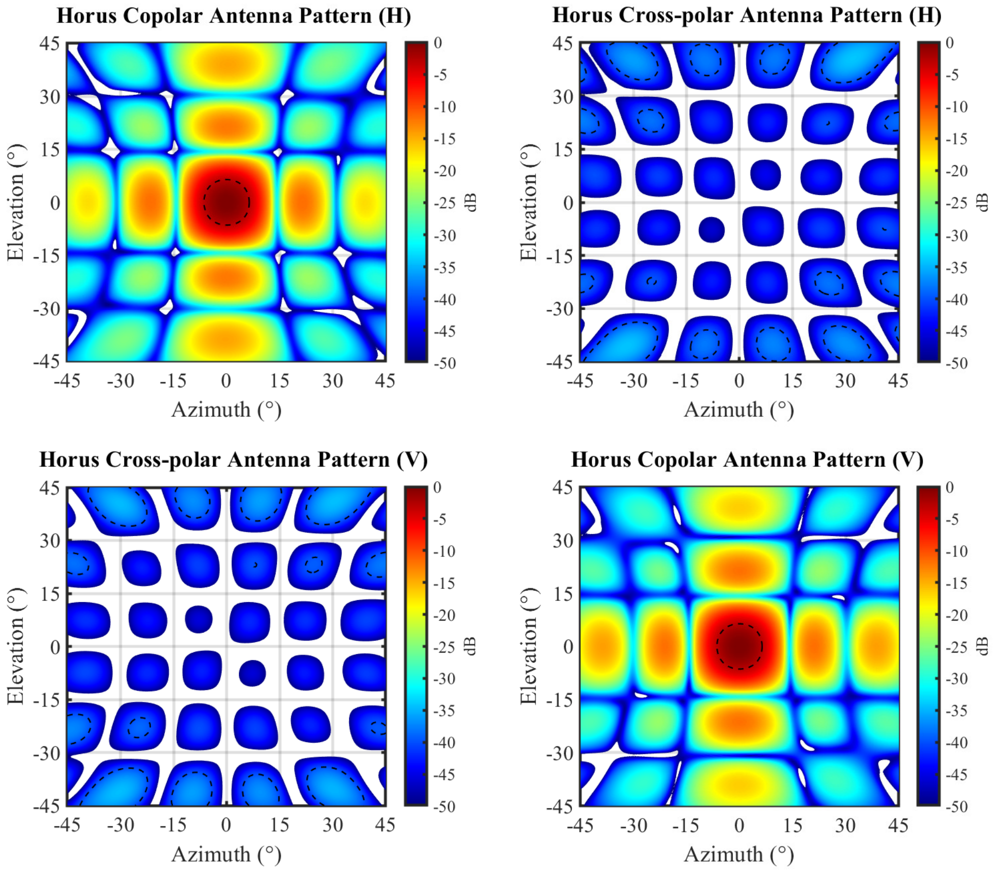

Fig. 3. Normalized co- and cross-polar H and V Horus far-field patterns, derived from near-field measurements. Dotted contours on the copolar H and V patterns indicate the half-power beamwidth (-3 dB); similarly, dotted contours in the cross-polar patterns indicate the -40 dB level.

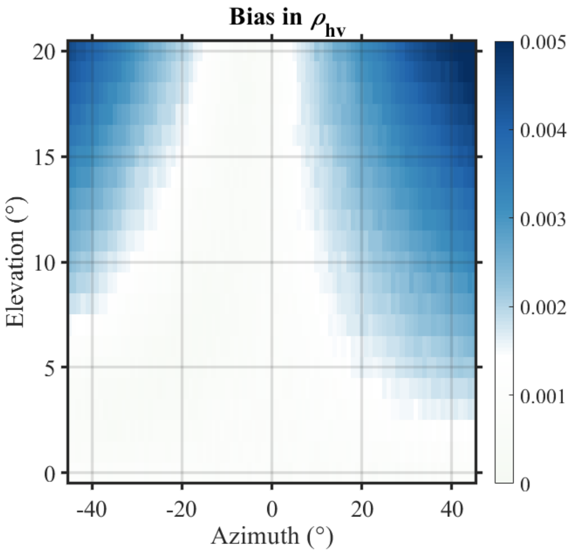

Fig. 4. Antenna-induced biases in ρ_{hv} as a function of steering angle, derived from the measured patterns shown in Fig. 3. Note that biases induced are below the requirement (i.e., bias in $\rho_{hv} \leq 0.01$) through the entire scan sector.

high-quality polarimetric weather measurements.

With the completion of the full Horus array, significant field deployments are planned for late 2022 and the 2023 spring storm season. The presentation will include the latest laboratory and field measurements of the Horus system.

V. CONCLUSIONS

The Horus radar program began with initial seed funding from the University of Oklahoma. Around the same time, NSSL started funding the development of the radar along with subsequent and complementary support from the Office for Naval Research (ONR). Although an extremely similar design, the ONR variant of the Horus radar (“Horus-D”) operates in the S-band as well [25], which was chosen to allow joint measurements between the two digital PAR systems.

In addition to the overarching Horus system development led by the ARRC’s engineering team, several complementary and supporting R&D efforts are currently underway. Results from that body of work will also be presented at this IEEE PAST symposium, and is provided in the following list. Please take time to meet with these authors and see the most-recent results.

- C. Fulton et al., Mutual Coupling-Based Calibration for the Horus Digital Phased Array Radar
- Y.-S. Kim et al., Fast Adaptive Beamforming Using Deep Learning for Digital Phased Array Radars

- R. Reinke et al., Evaluation of a Spline-Based Parameterization Scheme for Phase-Only Antenna Pattern Synthesis
- C. Salazar et al., Cross-Polar Canceller (XPC): A Technique to Reduce Cross-Polar Pattern Contamination in Polarimetric Weather Observations
- D. Schvartzman et al., A Polarimetric Antenna-Calibration Method for the Horus Radar based on E-Field Back Projection
- D. Zrnić et al., Effects of Horus Antenna Patterns on Polarimetric Weather Observations
- C. Fulton and J. Salazar, Tutorial: Digital Arrays

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