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Updates on Next-Generation Array-Based Weather Radar Developments at the University of Oklahoma

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***Abstract* — The University of Oklahoma's Advanced Radar Research Center has been developing several weather radar systems that leverage modern phased array technologies to provide advanced functionality as well as multi-function capability. This paper details the latest achievements during the development of these systems, as well as some notional plans for future research opportunities that these systems will enable.**

***Index Terms* — Phased arrays, weather radar, digital beamforming, multifunction radar.**

I. Introduction and Overview

The weather radar technology landscape has been rapidly changing in recent years. In particular, there has been a push towards the use of phased array technology in future systems that will serve multiple functions – systems for which some form of electronic scanning is virtually required, as well as dual polarization. In addition to the cost, architectural, and digital beamforming implications of such a fundamental change in technology, there are several challenges associated with establishing and maintaining beam quality and polarization purity for the weather mission that go beyond what is required of many traditional phased array applications.

The University of Oklahoma's Advanced Radar Research Center (ARRC) has developed or is developing several array-based systems that are exploring this new technology landscape for weather radar. Over the last decade, three novel, first-of-their-kind demonstrators have shown the promises of imaging and adaptive digital beamforming, particularly for tornadic supercells (with the X-band Atmospheric Imaging Radar [1]); the challenges and opportunities afforded by a cylindrical approach to achieving beam and polarization invariance vs. scan angle (with the S-band Cylindrical Polarimetric Phased Array Radar [2]); and even a means by which reflectarray technology and modern, X-band solid state electronics and integrated transceivers can drastically lower the cost of a simple multi-beam radar (Fig. 1).

This paper summarizes two larger systems that are currently under development at the ARRC, both of which are fully active and/or digital, dual-polarization phased arrays with numerous opportunities not just for weather radar research, but for fundamental array-based engineering science explorations. These opportunities are then detailed following the summaries, as well as where these systems fit into the broader technology landscape.

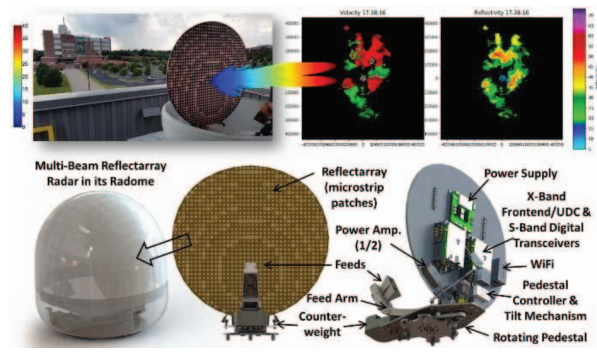

Fig. 1. Dual-Beam X-Band Reflectarray Weather Radar for Weathernews, with recent data from May, 2017.

II. System One: The Horus All-Digital Polarimetric Phased Array

A. System Summary

The first of these larger-sized demonstrators, code-named "Horus," is an S-band, fully digital, dual-pol array of a scaled-down Multifunction Phased Array Radar (MPAR) system; this system concept is to combine the missions of the aging WSR-88D (dish antennas) as well as air traffic monitoring and surveillance radars in the USA into a network of a common phased array systems, notionally having four faces, each on the order of 20,000 elements in order to provide a 1 deg. beam (for weather radar requirements); see [3] for further details.

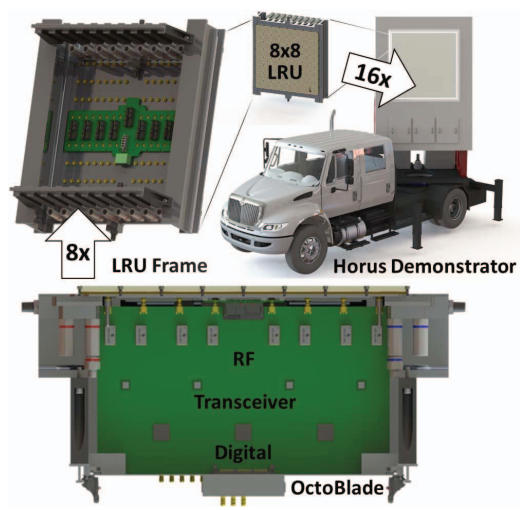

Fig. 2. The Horus Demonstrator: An all-digital S-band dual-polarization testbed for multifunction radar (NOAA/OU-funded)

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Fig. 2 summarizes the Horus demonstrator, which consists of 1024 elements divided into 16 line replaceable units (LRUs). Each LRU houses eight "OctoBlades," which in turn contain practically all of the radar electronics. Each OctoBlade drives an eight-element column of a high-performance antenna array, and consists of a PCB-metal-PCB sandwich with liquid cooling to support heat loads from 16 GaN-based frontends (> 10W per element, per polarization), eight dual-channel Analog Devices 9371 digital transceivers, four front-end FPGAs for processing, and two FPGAs for control (three FPGAs per side). Each digital transceiver IC has more than 86 dB of dynamic range per channel, and provides full RF-to-bits operation for both transmit and receive on two separate channels. A RapidIO network interconnects the backs of the LRUs, enabling digital beamforming with beam-bandwidth products in excess of what would be needed for a notional MPAR system.

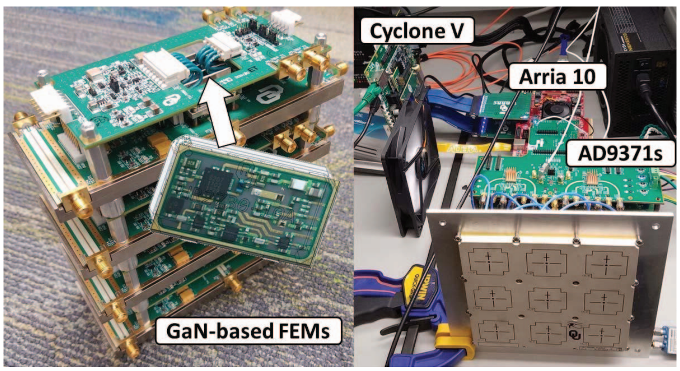

Fig. 3. Testbed activities towards a Horus Demonstrator: (left) a four-channel GaN frontend testbed, with all biasing/triggering electronics for design down-selection and debugging, and (right) a frontend-bypassed four-channel digital transceiver testbed with representative electronics for all stages.

Table I: Horus System-Level Specifications and Performance

System Performance Overview (16 Panel System)		
Operating Frequency Range		2.7-3.0 GHz
Element Polarization		Dual-Linear, RHCP, LHCP
Transmit Waveform Type		LFM/NLFM
Transmit Power (Single Element)		10.0 W (per Polarization)
Max Transmit Pulse Width		50.0 μs
Max Transmit Duty Cycle		5.0 %
Max Transmit Waveform Bandwidth		50 MHz
Element Spacing (Horizontal x Vertical)		0.50 x 0.50 λ at 2.951 GHz
Radiator Panel Size (Elements)		8 x 8 (64) elements
Total Number of Panels		16 panels
Total Number of Radiating Elements		1024 elements
Maximum Elevation Scan Angle		60.0 deg
Horizontal Aperture		1.63 m (5.33 ft)
Vertical Aperture		1.63 m (5.33 ft)
Tx Aperture Gain (Uniform Excitation)		34.92 dBi
Rx Aperture Gain (Uniform Excitation)		32.12 dB
Total Assumed SNR Losses	Transmit	3.00 dB
	Receive	6.80 dB (Includes NF)
Min Beamwidth (Azimuth x Elevation)		4.38 x 4.38 deg at 0-deg El
(1.38xUniform Excitation Beamwidth)		4.38 x 8.76 deg at 60-deg El
Sensitivity (1 Pulse)	Weather	3.5 dBz @ 30.0 km
	Hard Target	1.29E-03 m^2 @ 30.0 km

Fig. 3 summarizes the progress that has been made towards demonstration of OctoBlade-level electronics in the near future. The next step will be to integrate all of these representative electronics into a single board, like shown in Fig. 2, following a finalization of initial power supply and LO distribution designs (currently underway). Additionally, a clear plastic testbed for the liquid cooling solution has been fabricated and used to verify both the uniformity of liquid flow as well as mechanical reliability of the dripless connectors, and an aluminum mockup of the full LRU (including "dummy" heat loads on the PCBs) is currently being fabricated; the presentation will provide any updates to these activities. System-level performance estimates are shown in Table I for the 1024-element (16-LRU) demonstrator. Owing to funding and timeline limitations on its size (and, hence, beam width), it is only on the cusp of what will be a useful weather radar science testbed. Instead, as described in the following, it is intended to be an *engineering science* testbed that is capable of basic weather radar functions.

B. Horus-Related Research and Technology Landscape

In addition to demonstrating the overall viability of a fully-digital approach for multifunction purposes, the Horus Demonstrator will provide for a number of more fundamental engineering science research opportunities, including:

- Adaptive digital beamforming architecture studies through element-level data collection.
- Advanced array calibration routines for digital arrays [4], especially including those for maintaining exceptionally low sidelobes and pristine polarization purity through on-line calibration techniques that work at the element-level.
- Integration of fixed and tunable front-end filtering technologies for direct-conversion systems, and a study of the effects of interference within the notional band for MPAR systems (S-band) as commercial enterprises encroach on both sides of it.
- Implementation of nonlinear equalization and other spur decorrelation mechanisms for extending digital array dynamic range [5-6], especially in the complicated interference environments that are expected for MPAR.
- Generic digital array (e.g. MIMO radar) demonstrations and studies, including an evaluation of the most appropriate digitization scheme (e.g. subarray- or element-level) for a larger-scale system.

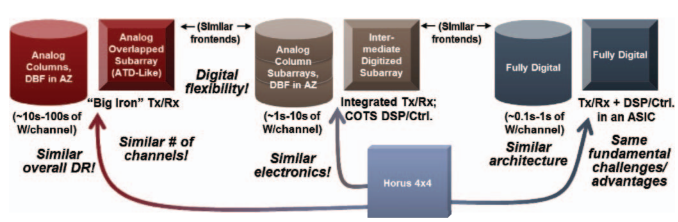

Fig. 4. Summary of overall technological landscape for MPAR digital transceivers and architectures, and aspects it that are being addressed by the Horus All-Digital Demonstrator

Most importantly, the Horus demonstrator will provide a snapshot of current phased array R&D progress that will speak to a broad landscape of technologies as far as MPAR is concerned, as summarized in Fig. 4. Though the Horus demonstrator will be a planar array, there is still the possibility that the ultimate solution would be cylindrical [2], and this may impact the digital transceiver trade-space (namely, a practical cylindrical solution would have at least one digital transceiver pair per column). Either way, the front-end electronics are likely to be very similar for any implementation – they would use efficient RF processes (GaN) and inexpensive plastic packaging to provide on the order of 10W per element per polarization.

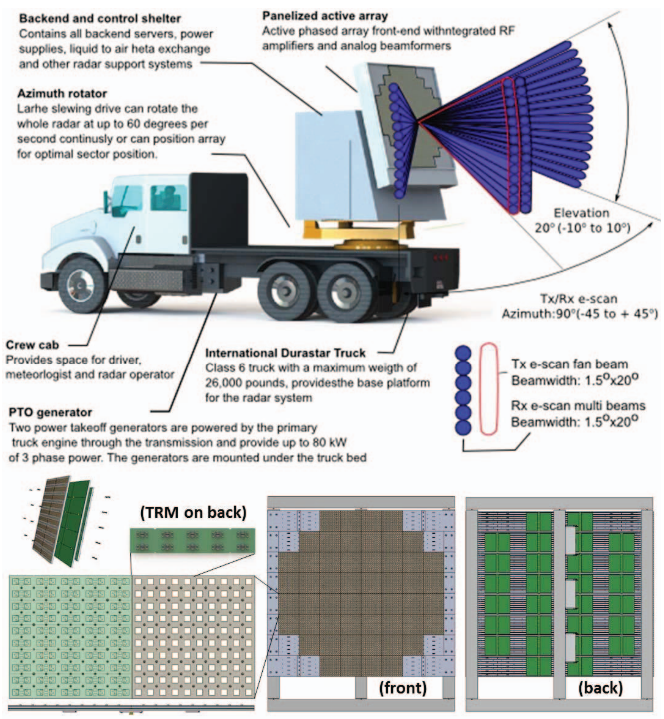

Fig. 5. The C-Band Polarimetric Atmospheric Imaging Radar, featuring a first-of-its-kind combination of adaptive imaging in EL with dual-polarization, in a fully-active array.

Instead, one of the most significant emerging design decisions from the system perspective revolves around the appropriate choice of digitization schemes, both on transmit and receive. With 2048 digital transmit/receive channels, the Horus demonstrator would have a similar number of total digital beamforming channels as a large-scale system that makes use of traditional, rack- and server-based digital receiver/exciters that consume 10s-100s of Watts per channel (left of Fig. 4). Owing to the large dynamic range of the Analog Devices digital transceivers (~86 dB) and a smaller power-aperture product, the Horus demonstrator would have similar overall dynamic range to a single face of such a system (depending, of course, on the precise definition of dynamic range). It has very similar electronics to an array based on modern, integrated COTS-based digital transceivers, burning 1-10s of Watts per transceiver, also with similar dynamic range (middle of Fig. 4); these types of systems would likely have several elements (8, 16, etc.) interface to a small number of digital transceivers, potentially with multiple analog beamformers to provide critical multi-beam functionality. As such, it shares many of the same packaging, cooling, and cost-related challenges as such a system. Finally, as an element-level-digital system, it shares many of the I/O density, beamforming, and architectural/control challenges that will be associated with an element-level-digital MPAR system in the future, even if the latter features more highly-integrated and lower-power transceiver electronics. It will provide an important data point in the overall power consumption vs. dynamic range (and filtering/interference suppression) trade space associated with an architecture that must provide digital functionality and robustness in an S-band lattice. It will also, of course, be capable of implementing arbitrary imaging and multi-beam configurations, even if part of the processing is non-real-time, for the purposes of evaluating the usefulness of such schemes on a much larger system. Finally, the Horus demonstrator features an antenna array with exceptional polarization characteristics along the principle planes, providing a foundation for precise polarimetric calibration [7].

III. System Two: The Polarimetric Atmospheric Imaging Radar

A. System Overview

The second large-scale system, the Polarimetric Atmospheric Imaging Radar (PAIR, Fig. 5), is a fully active, C-band array of nearly 5000 elements that is a dual-polarized follow-on to the aforementioned X-band AIR [1] that will use the same truck platform as Horus. While this array will also be liquid-cooled, it will have all of the active front-end electronics integrated into panels, connected to the antennas and to row-level analog beamformers through fuzz-button connections. Each pair of rows has its two polarizations digitized by modified OctoBlades from the Horus Demonstrator (as the transceiver chips work through C band). With 5W per polarization, per element, the system will be capable of both long-range weather surveillance as well as its primary operating modality, which is imaging. As with the AIR, the PAIR will be able to scan a vertical fan beam back and forth through a structured storm of interest, forming multiple simultaneous receive beams during reception through off-line adaptive digital beamforming. Unlike the AIR, the PAIR will be able to scan electronically in azimuth for wider range and/or faster scans, will feature dual polarization for the first time in such a system, and will also be able to perform real-time non-adaptive beamforming to ensure that the desired portions of the storm are being captured. Its expected performance parameters are shown in Table II. The development of this system is being funded by the National Science Foundation.

Table II: PAIR System-Level Performance and Specifications

System Performance Overview (2.2m Target Aperture)		
Operating Frequency Range		5.35-5.45 GHz
Element Polarization		Dual-Linear, RHCP, LHCP
Transmit Waveform Type		LFM/NLFM
Transmit Power (Single Element)		5.0 W (Single-Pol)
Transmit Pulse Width		33.0 µs (100µs MAX)
Max Transmit Duty Cycle		20.0 %
Max Transmit Waveform Bandwidth		50 MHz
Element Spacing (Horizontal x Vertical)		0.50 x 0.50 λ at 5.552 GHz
Radiator Panel Size (Elements)		10 x 10 (100) elements
Total Number of Panels (50% Truncate)		8 x 8 (52) panels
Total Number of Radiating Elements		5200 elements
Maximum Elevation Scan Angle		45.0 deg
Horizontal Aperture		2.16 m (7.09 ft)
Vertical Aperture		2.16 m (7.09 ft)
Radiating Element Gain		6.0 dBi
Array Gain ($10\log_{10}N$)		37.16 dB
Total Assumed SNR Losses	Transmit	15.25 dB (Includes Spoil)
	Receive	5.00 dB (Includes NF)
Min Beamwidth (Azimuth x Elevation) (1.18xUniform Excitation Beamwidth)		1.50 x 1.50 deg at 0-deg El
		1.50 x 2.12 deg at 45-deg El
Estimated Sensitivity (1 Pulse)	Weather	-3.8 dBz @ 10.0 km
	Hard Target	8.13E-06 m^2 @ 10.0 km

B. PAIR-Related Research Opportunities

Because the PAIR is first and foremost being developed as a scientific instrument for storm-scale polarimetric imaging, its primary purpose is not to provide an engineering testbed for exotic/advanced functions. Nevertheless, as a first-of-its-kind system, the dual-polarization imaging mode of operation will present a number of interesting research and development challenges, including:

- Precise creation of a fan beam through primarily phase-only transmit weighting, without biasing scientific estimators.
- An adaptive digital beamforming scheme that does not significantly degrade polarimetric accuracy.
- Precise *far-field* calibration of polarization as a function of scan angle, as the aperture size is electrically much larger than Horus.
- On-line calibration of a mixed analog/digital transceiver array using mutual coupling mechanisms, potentially using phase coding techniques for element-level separation of signal chains.
- Waveform designs to provide optimal sensitivity and range-sidelobe performance as a function of a region of interest in range; fill pulse research for blind zone mitigation.
- Limited real-time multiple beamforming (imaging) through fixed coefficient beamforming in elevation.

These are of course in addition to the primary scientific research objectives of the PAIR, which include:

- Studying the formation and evolution of tornados, and their relationship to their parent storm; this requires both dual polarization and rapid update times (1-10sec)
- Hurricane boundary layer investigations across a wide variety of surface conditions to better understand the length scale, vertical extent, and turbulence of the coastal transition regions; C-band radar is essential to mitigate attenuation over the mesoscale domain needed to observe the boundary layer transition from across the water to land.
- Potential for lightning *warnings*, not just detection, since ice particle alignment through cloud electrification temporarily generates negative ϕ_{DP} (differential phase propagation).
- An improved understanding of the distribution and density of animals in the planetary boundary layer and the processes that drive those patterns.

VII. Conclusion

The two systems presented here are helping to pave the way towards the next generation of large-scale research-oriented and operational weather/multi-mission radar systems. Along the way, will provide exciting opportunities for phased array engineering science as well as new capabilities for advancing radar-based atmospheric research.

Acknowledgement

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