An Ultra-Fast Scan C-band Polarimetric Atmospheric Imaging Radar (PAIR)

Jorge L. Salazar, *Senior Member, IEEE*, Tian-You Yu, *Member, IEEE*, Matt McCord, Jose Diaz, *Student Member, IEEE*, Javier A. Ortiz, *Student Member, IEEE*, Caleb Fulton, *Senior Member, IEEE*, Mark Yeary, *Fellow, IEEE*, Robert Palmer, *Fellow, IEEE*, Boon-Leng Cheong, *Member, IEEE*, Howard Bluestein, James M. Kurdzo, *Member, IEEE* and Bradley Isom, *Member, IEEE*

***Abstract*—This paper describes the novel hybrid front-end beamforming architecture of a C-band mobile Polarimetric Atmospheric Imaging Radar (PAIR) system for weather applications. PAIR, a state-of-the-art radar on a mobile platform, will be shared with the scientific and radar communities to further research frontiers using its unprecedented high-temporal resolution and scanning flexibility. The system under development achieves dual polarization through novel polarimetric phased-array antenna design; improved detection capability through integrated solutions provided by solid state technology; faster update time through digital beamforming (DBF) in elevation; and a robust structure for fast deployment in severe weather. The concept and research applications and the development progress of PAIR will be reported in this paper.**

***Index Terms*—phased array radar, imaging radar, dual-polarized, weather radar, digital beamforming, electronically scan.**

I. Introduction

The University of Oklahoma (OU) has a long history of severe storms research and field program activities using mobile radars, and has always pushed the limits of radar technology to further the science. In 2015, OU was awarded a large, five-year project by the National Science Foundation (NSF) to design, fabricate, and commission a next generation mobile polarimetric phased-array radar. Based largely on promising obtained by the Atmospheric Imaging Radar (AIR) [1]–[4], and experience gained from the development of an all-digital polarimetric phased array radar [5], [6], in the Advanced Radar Research Center (ARRC), this new Polarimetric Atmospheric Imaging Radar (PAIR) will be capable of the high spatial resolution afforded by a mobile system, with unprecedented temporal resolution using an imaging technique. The PAIR will be a shared facility that has the potential to allow new and important discoveries by scientists from around the world researching tornadogenesis and other severe weather phenomena such as lightning, fire detection, and hurricanes. Compared to AIR and other existing PAR systems, the new proposed system achieves dual polarization through novel polarimetric phased-array antenna design; improved detection capability through integrated solutions provided by solid state power amplifier (SSPA) technology; faster update time through digital beamforming (DBF) in elevation; and a robust structure for fast deployment in severe environments. As a result, PAIR is capable of providing volumetric polarimetric measurements of $360°\times20°$ with a broadside antenna beamwidth of $1.5°\times1.5°$, and range resolution of 10 m in approximately 6 s. The C-band architecture of the PAIR provides significantly less attenuation than typical X-band mobile platforms, better aliasing velocities, and offers differentiating tornadic debris estimates compared to most mobile platforms. PAIR represents a new paradigm for meteorological observations that will enable the exploration of new scientific frontiers related to severe storms such as tornadoes, hurricanes, and lightning, and improve numerical weather prediction and data assimilation.

J. Salazar is with the Advanced Radar Research Center (ARRC) and the School of Electrical and Computer Engineering, The University of Oklahoma, Norman, OK, 73019 USA, see http://www.arrc.ou.edu.

II. Enabling Science Research with PAIR

The unique capabilities of the PAIR and its unprecedented temporal resolution will enable new and exciting scientific research and engineering developments that no other current existing radar platforms can provide. Sequences of radar images, visual observations, and videos of tornadoes and sub-tornado-scale vortices confirm the need for observations with volumetric updates on the time scale of 6 - 10 s in order to capture their formation and evolution and their relationship to the parent storm [7]–[13]. In prior studies, the vertical depth of the volume scanned by the radar was compromised to enable adequate resolution at the shortest time scales possible [12]. Data collected at one elevation by a mobile Doppler radar every 2 s in a violent tornado clearly demonstrated the need for such rapidly scanning radars [12]. More rapid scanning radars such as PAIR are needed to probe deeper volumes (up to mid-levels and high-levels) in the parent storm [14]. Additionally, observations with fast volumetric updates are also required to resolve turbulent processes near the ground, an area that has a profound effect on tornadogenesis and structure [15], [16].

III. System Description

A. PAIR architecture and specifications

The proposed radar is a mobile, C-band, dual-polarized, 1D imaging system capable of fast scanning performance (Fig.1). A spoiled antenna beam of 20° in elevation and 1.5° in azimuth is transmitted with simultaneous horizontally and vertically polarized waves. In reception a linear array that contains between 64 and 160 elements in two rows, each row with 32 to 80 elements, due to the truncated corner in the array, will be arranged to perform as a sub-array. Every pair of

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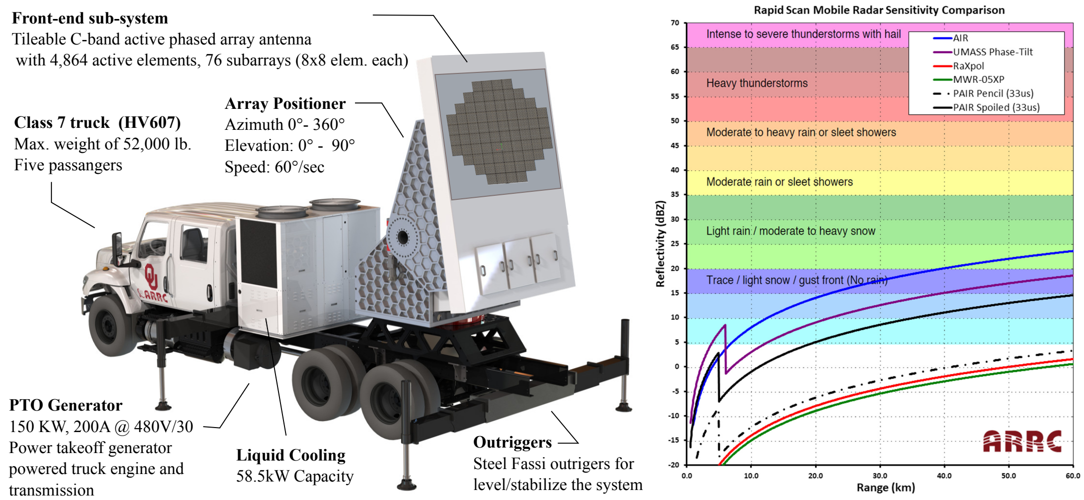

a) b)

Fig. 1: *C-band PAIR mobile radar concept with main sub-system components and radar sensitivity comparison*

sub-arrays will have an independent analog beam-former that will be able to connect to an independent up-down converter (UDC) and customized digital receiver to produce I/Q signals. Finally, an advanced cluster computing system will be exploited to aggregate and process the dual-polarimetric I/Q data from the 80 sub-arrays (double for H- and V-polarizations). After standard DBF processing, a flexible number of beams can be formed with regular beamwidth of $1.5° \times 1.5°$. In both reception and transmission, the spoiled beam and simultaneous multiple beams in elevation can be steered electronically in elevation. A mechanical pedestal is used for continuous scanning in azimuth. A real-time display of dual-polarimetric measurements, as well as a health monitor of the system, will be available through in-house development, similar to the system developed for the PX-1000 [17], another mobile radar developed in the ARRC. Fig.2 shows a high-level block diagram of the proposed PAIR system illustrating the most important sub-systems, tileable RF front-end, up-down converters, digital transceivers, and the digital radar back-end.

TABLE I: PAIR system performance overview

Parameter	Value
Operation frequency	5.35 - 5.45 GHz
Polarization	Dual Linear, RHCP, LHCP
Cross-polarization level	-45 dB @ SR
Transmit waveform	LFM/NLFM
Transmit power	5.0 W/polarization
Duty cycle	20 % (max)
Transmit pulse width	33 μ (100 μ max)
Transmit bandwidth	50 MHz
Element spacing	0.5 λo x 0.5 λo
Subarray panel size	8x8 elements
Total number of panels	76 panels
Total number of elements	4864 elements
Maximum scanning range	$\pm$ 45° in elev.
Dimensions	2.16 m x 2.16 m
Transmit Array gain	41.5 dBi (30.5 dBi Spoiled)
Receive Array gain	40.4 dBi (38.9 dBi @45° elev.)
Transmit beamwidth	1.46°x1.46°
Max. beamwidth (spoiled)	1.46°x20° (in Tx)
Worse-case radar sensitivity (1 pulse, pencil)	-12.3 dBZ at 10 km
Worse-case radar sensitivity (1 pulse, spoiled)	-0.95 dBZ at 10 km

B. PAIR front-end

1) Antenna array: The full array will be made up of 76 flat modular tile line replacement units (T-LRU), each containing 8×8 elements arranged in a square lattice as shown in Fig.3. Special design effort was focused on the aperture antenna to achieve a co-polar beam match (<0.1 dB) and cross-polarization isolation (better that -35 dB) needed in order to satisfy the polarization requirements for simultaneous transmit and receive (STSR) mode without prohibitively large corrections through calibration. The T/R modules will be placed in the back of the radiating antenna element (tile configuration) and a 2D fed network will interconnect all of the active elements in the array. The performance of a C-band radiating element and LRU array of 8×8 elements that satisfies these polarimetric requirements was previously developed [18], [19]. Fig. 5 illustrates PAIR dual-polarized antenna array architecture of a 8×8 elements, antenna stack-up configuration. Preliminary simulation results of the cross-polar patterns of a single element in an infinite array environment, return loss, isolation, and active reflective coefficient of a single element in an infinite array environment is illustrated in Fig. 4 .

2) T/R modules: The T/R modules, as shown in Fig. 5, will be designed to operate in STSR mode, but will also support alternate transmit and simultaneous receive (ATSR) mode, when polarization accuracy requirements may be relaxed. This architecture will make use of two customized IC's, a multicore chip (MCC), and a front-end chip (FEC) developed by RFcore. The MCC will contain four 6-bit digital phase shifters and attenuators, four gain blocks, a control unit, and a parallel-to-serial interface for controlling the amplitude and phase of each antenna element. The FEC contains a high-power amplifier, a low noise amplifier (LNA), and a switch. In transmission, each

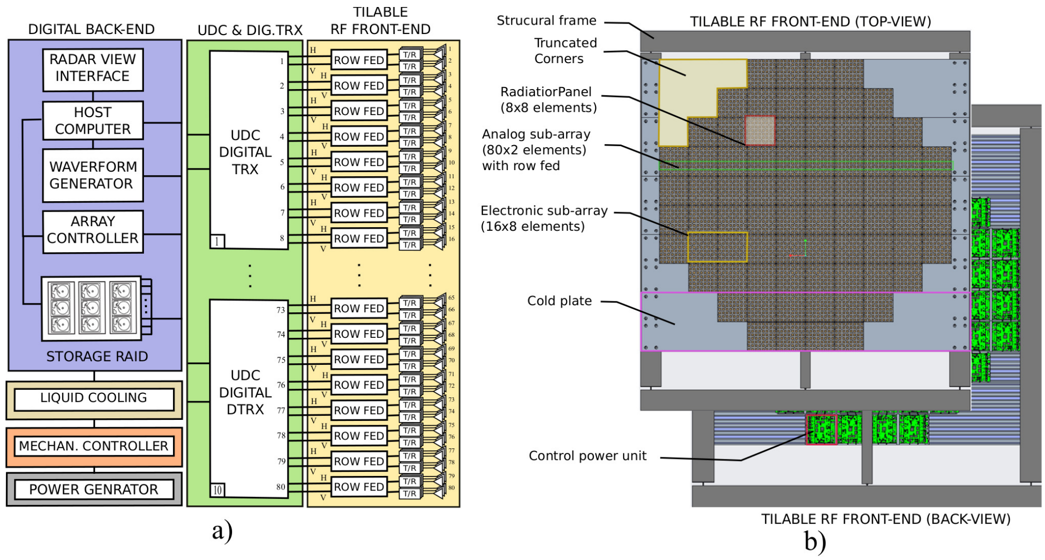

Fig. 2: *High-level system PAIR radar system. a) PAIR simplified block diagram b) PAIR front-end array, front and back view architecture*

T/R module can deliver peak power of 5 W at 20% maximum duty cycle for each polarization. A total power of 24.3 KW per polarization can be transmitted using all elements in the array. In this project, a phase-method synthesis approach will be used to produce the vertical fan beam of $20° \times 1.5°$ while maximizing the transmitted power [20], [21]. T/R modules are key components in the radar system and represent a significant portion of the overall cost. After considering the cost, size, the level of integration, and RF performance, CMOS for the MCC and GaN for the FEC IC's were selected as IC technologies. RFcore provides an impressive reduction in chip size and cost using a CMOS 0.13 μm process. Their two channel MCC in CMOS offers an important advantage in size over GaAs and SiGe, which is a key feature for the implementation of STSR T/R modules in a tile configuration [22]–[25]. Fig.5 illustrates the T/R modules in tile array architecture using the GaN FE IC and CMOS MCC IC block diagrams integrated with two radiating elements.

3) Up/down converter and digital receiver: Both the transmit and receive array front-end channels will connect directly to a digital transceiver array currently being developed internally at the OU ARRC. This transceiver array is being built around a commercial two-channel, direct conversion digital transceiver from Analog Devices. These devices filter and convert the digital signals to and from their analog baseband counterparts, and also provide direct up-and-down conversion to C-band for the I/Q baseband signals. Each transceiver connects to an FPGA (field programmable gate array) that is responsible for providing the control and timing signals for radar functions. Each FPGA will send a data stream output for each receiver row to the central processor. These simple transceiver solutions enable column-level waveform digitization without the excessive costs associated with traditional, military-style digitized sub-array radar solutions.

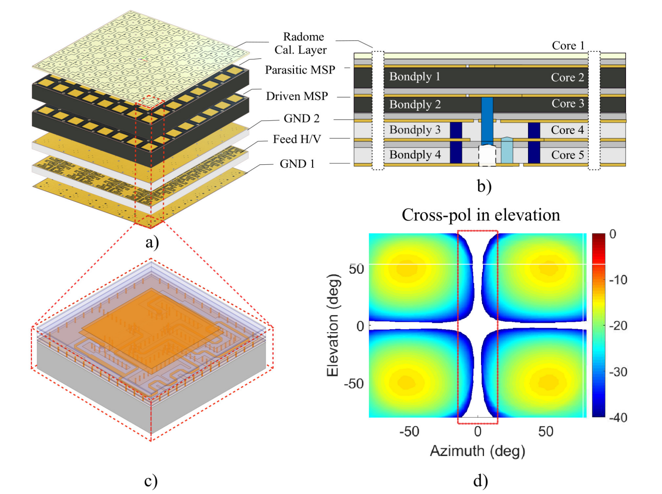

Fig. 3: *PAIR dual-polarized antenna array. a) Array of 8×8 elements. b) Antenna stack-up configuration. c) Antenna element geometry and d) Cross-polar patterns of a single element in an infinite array environment.*

4) Radar back-end and signal processing: Digital data transportation, storage, and real-time computing for the PAIR are significant challenges for the system. A scalable software architecture that converts these problems into multiple nodes will be implemented. That is, if a lack of computing power is encountered, it can be solved by adding more nodes. From our previous experience with the AIR [1] and PX-1000 [17], we know that a modern computer node can handle 8 channels of raw I/Q data storage and transportation with ease. We envision the data storage to be distributed, i.e., each node is responsible for storing the raw I/Q data locally on a self-connected storage device. While we do not anticipate all of the data to be available for real time beamforming and visualization, the DSP software can be designed so that the command center node can selectively request regularly spaced sets of the data for real-time beamforming, radar

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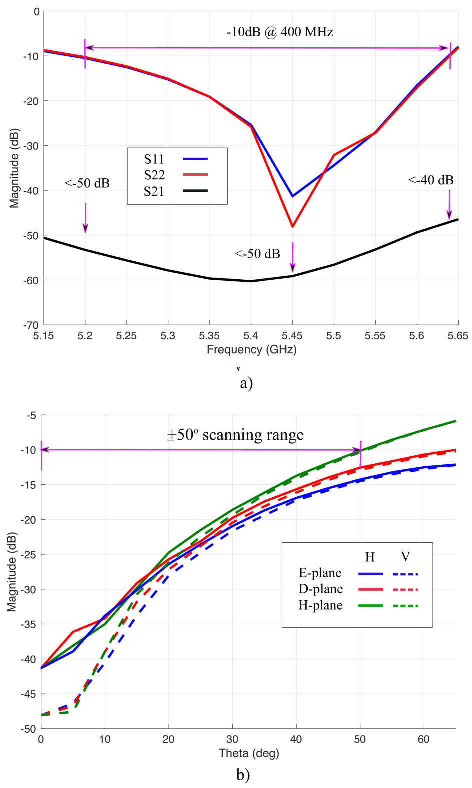

Fig. 4: *PAIR dual-polarized antenna array. a) S-parameters, S11 (dB), S22 (dB) and S12 (dB) versus frequency of an isolated antenna element. b) Active reflective coefficient of a single element in an infinite array environment.*

product derivation, and visualization during field campaigns. The timing we anticipate is on the order of 10-30 s. Real-time visualization would ensure that high quality data is collected. An ARRC in-house developed radar control and visualization tool, referred to as iRadar, was produced during the effort of [17]. A majority of the software components will be leveraged. Since only subsets of data are requested, the beamforming load is minimal and we do not anticipate a heavy computational burden on the command center node. Subsequent raw I/Q data processing is virtually identical to a conventional dish-like radar.

5) Mechanical design: The PAIR system will be mounted in a five passenger class 7 HV607 truck shown in Fig. 1. The entire system is designed to support the safe, reliable, and fast deployment of a tactically mobile radar mission in all types of severe operational conditions. All of the motors, drives, bearings and slip-rings have been designed for a long operational life cycle. Adding rotary table gives the e-scan radar more flexibility for large scanning angle capabilities. Azimuth scan can be performed at 60°/sec. The system provides for a versatile and stable line of sight for the array, while providing comfort and advanced operational capability for the crew. A 150 KW power generator is powered by the transmission and truck engine. The custom chiller that offers a capacity of 58.5 KW liquid cooling will keep all radar electronics within a narrow well-controlled temperature range. A custom mechanical riser structure to help the array clear the cab has been designed and fabricated

6) Array calibration: Dual-polarization phased array radar with improved scanning performance capabilities has led to an effort to better antenna array design and for new calibration techniques to compensate scan beam patterns imperfections of a dual-polarized radar in real operation. PAIR is a dual-polarized weather radar that requires a well matched co-polar beam patterns (<0.1dB) with high cross-polar isolation (<-35 dB). The PAIR system presents excellent isolation with very well matched beam patterns. PAIR architecture is designed in a tile array architecture, where the antenna integrated with RF electronics satisfy polarimetric scan requirements for a dual-polarized radar. PAIR calibration process will be performed using the Near-Field parking probe technique that includes the antenna embedded element patterns and all stages (amplitude and phase) of each T/R module in transmission, reception and for polarization. ARRC team developed several compensation techniques, one of them includes temperature gradient variation across the array produced by taper aperture illumination [26], [27].

IV. Conclusion

New dual polarization polarimetric imaging radar capability using a phased-array antenna concept is currently built. This concept enables improved atmospheric research detection capability through integrated solutions using a novel PAR architecture with state-of-the-art solid state technology providing faster update time through digital beamforming (DBF) in elevation. PAIR offers unique capabilities for atmospheric research as its unprecedented temporal resolution will enable new and exciting scientific investigations and engineering developments that no other current existing radar platforms can provide. PAIR, the first-ever C-band radar with rapid-scan volumetric imaging radar on a mobile platform, will be the first polarimetric rapid-scan with imaging capabilities for weather observation. This new phased array radar will enable transformative scientific studies with unprecedented spatial and temporal resolution.

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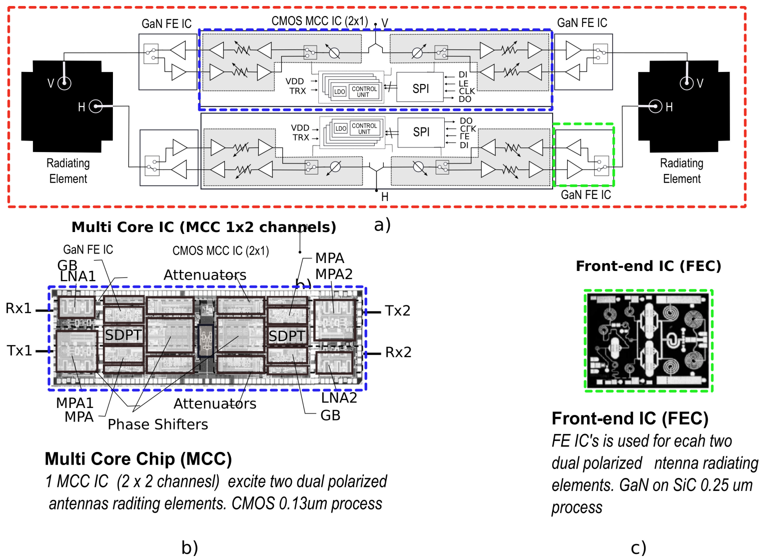

Fig. 5: *PAIR front-end T/R modules in tile array architecture. a) Antenna, GaN FE IC and CMOS MCC IC block diagram for 2 radiating elements. b) MCC IC for 2×2 channels in CMOS. c) Single channel GaN FE IC in GaN*

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