Recent Advances on an S-band All-Digital Mobile Phased Array Radar

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***Abstract*—This paper provides an update on an S-band, polarimetric phased array radar, which is being designed and built at the University of Oklahoma's Advanced Radar Research Center (ARRC). Providing optimum radar flexibility, this phased array radar, known as Horus, is digital at every element and polarization.**

***Keywords*—radar; digital array; MIMO; digital beamforming; polarimetric.**

I. Introduction

The move toward element-level digital beam forming (DBF) architectures (e.g., Australia's CEAFAR naval radar [1], the US Navy's FlexDAR radar, Space Fence [2], the UK's SAMPSON, and Elta's MF-STAR [3]) has driven future sensors to incorporate large numbers of digital data streams with large aggregate data rates. These future sensors begin to resemble present-day data and servers farms with aggregate data rates approaching tens of Tbps and individual channels running 10 Gbps for elemental DBF systems [4]. "All-digital" element-level DBF has many attractive features which will allow the next generation of radars to supersede the performance of "mostly digital" radars that rely on digital beamforming at the sub-array level; for instance, a recent example is BAE System's MESAR-2 radar [5]. It is also acknowledged that for a given number of digitized channels or degrees of freedom (DOFs), sub-arrays are not the best choice of array architecture [6]. Most importantly, element-level DBF enables simultaneous beams anywhere in the field-of-regard (FoR) for efficient time/energy management. Equally important, element-level DBF enables exquisite null pattern formation. In addition, element level DBF will have impacts to MIMO arrays, e.g., [7] and AFRL's BEEMER [8]. As pointed out by Talisa, et. al. in [9], for small arrays, the digital beamforming functions can be performed in a general-purpose processor. For larger arrays, DBF is generally performed in FPGAs distributed across the array [9], which is also our focus. The next section discusses our current work, which leverages the team's experience, e.g. [10]-[16], and other current and previous projects within the ARRC.

II. Background of Current Work

In phased array systems, each antenna element is driven by circuitry that approximates relative time delays between antennas selected to steer toward a particular direction relative to the array face. A beam is produced upon signal summation using array-level electronics on receive (Rx) or through radiation on transmit (Tx). The traditional phased array hardware implementation is shown in Fig. 1(a) [10]. This architecture may have active, solid-state front-end electronics (as depicted) or passive splitting/combining and element-level electronics; in either case, the electronics are primarily analog.

Modern "digitized subarray" phased arrays with multiple transceivers, as in Fig. 1(b), are providing increasing functionality and performance at reduced cost, size, and weight compared to their predecessors. This has been accompanied by advances in efficient front-end circuitry, improvements in packaging and integration, and an increased role of digital electronics closer to the aperture itself. In this modern architecture, Tx/Rx beamforming is accomplished with analog combiner networks (usually passive) and phase shifters within each subarray to approximate true time delays. Digital transceivers drive the combined input/output (I/O) signals of each subarray, in turn connecting to digital beamformers that operate at the subarray level.

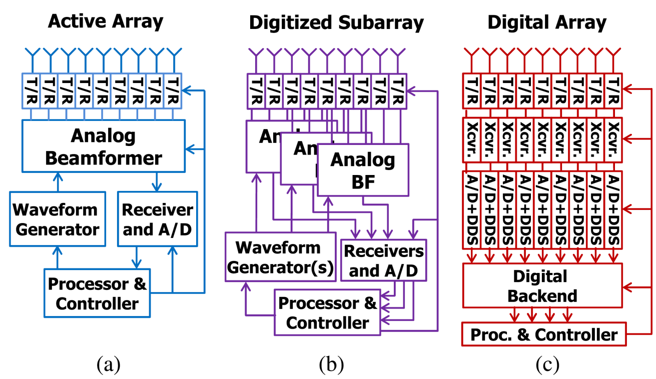

Fig. 1: Three generic beamforming architectures with digitization [10].

Digitization of multiple subarray channels enables adaptive beamforming, space-time adaptive processing (STAP), and multiple concurrent functions, an important requirement for future systems like the multifunction phased array radar (formerly MPAR) concept [17][18], now under the SENSR program[19][20]. To form P simultaneous beams in arbitrary directions, the phase shifters and front-end analog beamformers

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must be instantiated *P* times. Arrays with analog beamforming are inherently constrained to the beamforming scheme imposed by the exact configuration of front-end beamforming electronics. The digital Horus demonstrator that is under development at the ARRC is based on Fig. 1(c), and is instead limited only by the overall beam-bandwidth product of distributed digital beamformer.

III. Hardware Design

A mobile, S-band, dual-polarized phased array system is currently under development by the ARRC, as depicted in Fig. 2. It has a fully digital architecture, and this system will consist of 1024 elements divided into 16 panels, which each house eight "OctoBlades" wherein virtually all radar electronics reside. Each OctoBlade, drives an eight-element column of the panel's high-performance antenna array with nearly ideal polarization along the principal planes through careful design, and consists of a metal cooling plate with PCBs on each side to house a total of 16 GaN-based frontends (> 10W per element, per polarization), eight dual-channel digital transceivers from Analog Devices, four front-end FPGAs for processing, and two FPGAs for control. In summary, with each panel having 64 elements (8x8), then 16 of these renders 1024 total radiating elements.

Fig. 2: Mobile S-Band, Dual-Pol, Digital-at-Every-Element Radar [13].

A. Electronics Subsystem:

As depicted in the upper portions of the blue boxes in Fig. 3, the GaN front-end modules (FEM) are based on commercial, off-the-shelf (COTS) components with the exception of a moderate power GaN amplifier capable of putting out at least 10W from 2.7-2.9 GHz. It is packaged using traditional surface-mount-technology (SMT) processing, with a few bond wires and a metal top. The FEM, digital transceiver, and FPGA sections are all thermally connected through numerous thermal vias to a single, contiguous aluminum baseplate; this baseplate, in each OctoBlade, is in turn cooled by a liquid cooling path that is supported through a fractal-inspired distribution network. At the same time, they are modular in the dimension normal to the array face, allowing for future exploration of different technologies at each layer; this is in contrast to a planar approach, where all of these electronics are integrated onto a single plane to save cost. This cost vs. flexibility tradeoff has been carefully considered for this particular demonstrator, and the reduced overall risk associated with a "slotted card" architecture far outweighed that of a panelized approach. The direct-conversion transceivers feature on-chip FIR equalization, built-in I/Q balancing, up to 100 MHz of bandwidth, and a 16-bit resolution delivering 86 dB of dynamic range – far beyond what is needed for an element-level digital radar application of this sort. Incidentally, the team's mobile C-band radar of [14] employs the same digital portion of these flexible Octoblades and the data networking, as discussed next.

For normal radar operation, typical digital beamforming [21-25] and etc., will be accomplished over a RapidIO network feeding the back of the panels, enabling beam-bandwidth products that are far in excess of what would be needed for a notional multifunction system (e.g., 200-MHz beams at suitable dynamic range). To elaborate, RadioIO is a commercial open standard interface that supports high-bandwidth, low-latency, packet-switched interconnect between multiple DSP processing elements, and between DSP processing elements and bulk memory. For the Horus team, RapidIO is used to distribute the reference clock, trigger, and control to two Octoblades, and RadioIO helps to form the distributed backend of the radar. In general, an array's beam bandwidth product has been an area of intense study over the last several years [26-28], as it is an ideal metric to understand an array's resources. To mitigate any ambiguity, we've defined the following terms:

- Real-Time Beamforming: Forming time-series IQ beams in real-time during operations
- Real-Time Processing: Producing radar products from IQ beams generated by beamforming in real-time
- Beam Bandwidth Product: The total amount of bandwidth that can be divided between beams in a single polarization
- Beam Bandwidth Polarization Product: The total amount of bandwidth that can be divided between beams and polarizations

Once the complete hardware is in place, studies and implementations to increase the beam bandwidth product of this all-digital polarimetric phased array will begin. In brief, the beamformer is an innovative two step process derived from column level beamforming and 2nd stage beamforming.

Because the system will have limited arbitrary waveform generation capabilities at the element level, owing to element-level RAM, it will allow for exploration of a number of advanced processing algorithms offline, such as (space-time) adaptive beamforming, multiple-input, multiple-output (MIMO) radar, and more, in non-real-time. Other future plans for research include nonlinear receiver equalization, advanced

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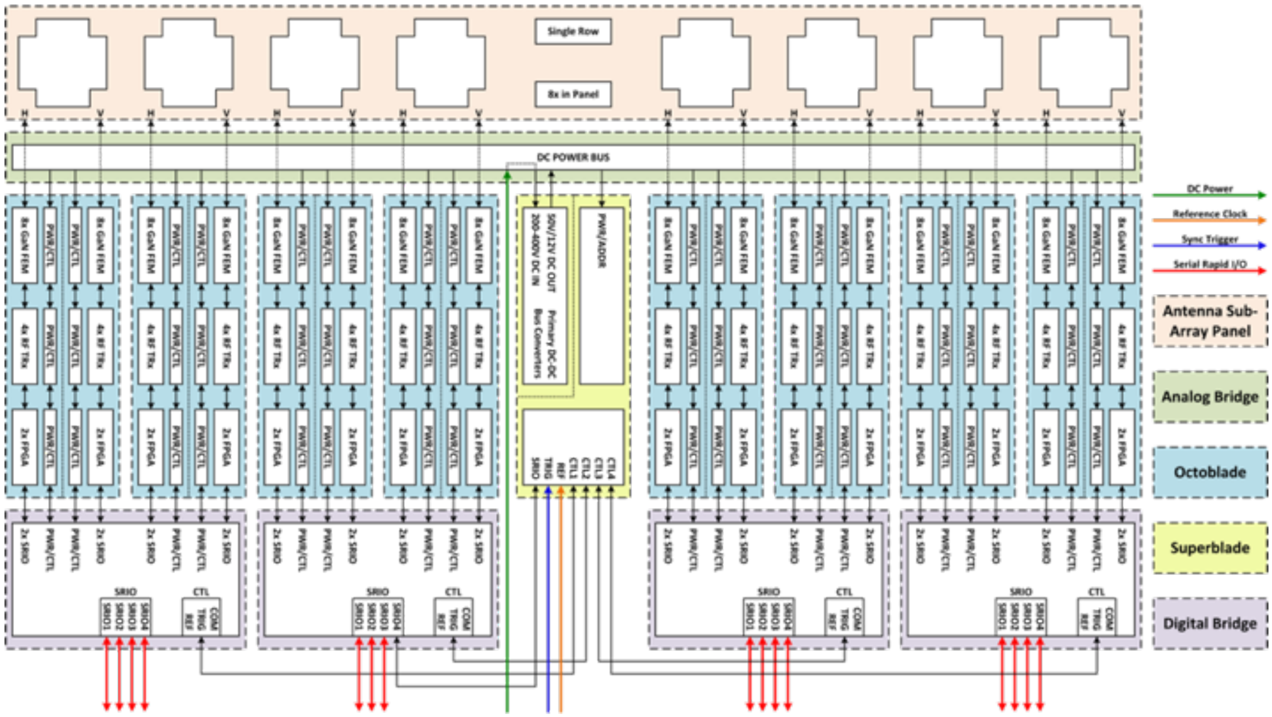

Fig. 3: A Panel's Block Diagram Depicting Eight OctoBlades (in blue).

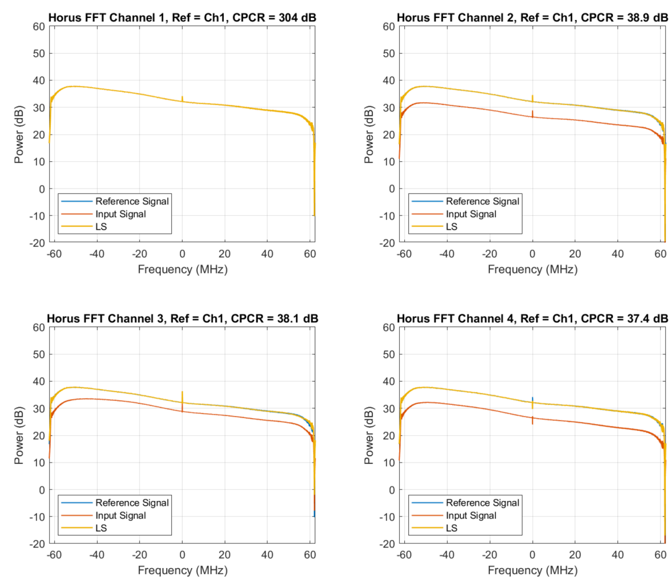

Fig. 4: Channel Equalization Results for Several Sample Channels.

mutual coupling-based calibration (aided in terms of dynamic range by the bypass path in the front-end module), element-level tunable filtering at the antenna terminals, and more – all of this is enabled by the modular and digital approach taken to the overall system.

Digital control at the subarray and element levels allows the quality of data received by radars to be enhanced using methods like adaptive digital beamforming (ADBF), which mitigates interference and clutter for the cost of a little computation, see [29]-[31], etc. To achieve maximum performance, ADBF algorithms require precise steering, meaning that the channels must be well matched; this may require use of an equalizer on the IQ data. Consequently, this was confirmed via a digital loopback experiment. In brief, a 500 microsecond chirp spanning 124 MHz was passed through a prototype Horus receiver and the signals at the outputs of the four channels were collected, after being mixed down to baseband, at a sampling frequency of 125 MHz. There was noticeable channel mismatch throughout the bandwidth; the Fourier transforms of the signals at the receiver input and at each receiver channel's output are shown in Fig. 4. Digital equalization was performed using a least mean squares method [32].

Because the input signal to the receiver was available and had good behavior across the spectrum, it was used as the reference signal for the equalization calculation; because that information — the signal at the input to the receiver — is likely not to always be available, the calculations were repeated using the Channel 1 receiver output as the reference signal. The Fourier transforms of the signals before and after equalization using a 128 tap equalization filter can be seen in Fig. 4. With equalization using 128 filter coefficients, the signals matched the reference signal very well. The channel pair cancellation ratio (CPCR) was the metric that was used here to assess the quality of the channel matching [33]. Other than Channel 1, the CPCR for the other three was: 38.9 dB, 38.1 dB, and 37.4 dB. Note: that under this definition, a higher CPCR means that better cancellation has been achieved; infinite CPCR would be perfect cancellation.

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*B. **Antenna Subsystem:***

The antennas for the mobile demonstrator are discussed in this section, and Fig. 5 depicts our laboratory measurements [34]. This fully digital active and dual-pol phased array antenna is designed for full control of transmitted and returned signals of each antenna element. The design of the antenna for ARRC's project is focused on achieving the same or improved performance compared to WSR-88D parabolic antennas [35]. These design specifications are critical, given that the weather mission presents more challenging polarimetric requirements, in terms of target identification, than aircraft surveillance. Dual-polarized radars require both low cross-polarization levels (better than -40 dB) and well-matched patterns (lower than 0.1 dB) to successfully determine the polarimetric variables of the scanned atmosphere sector.

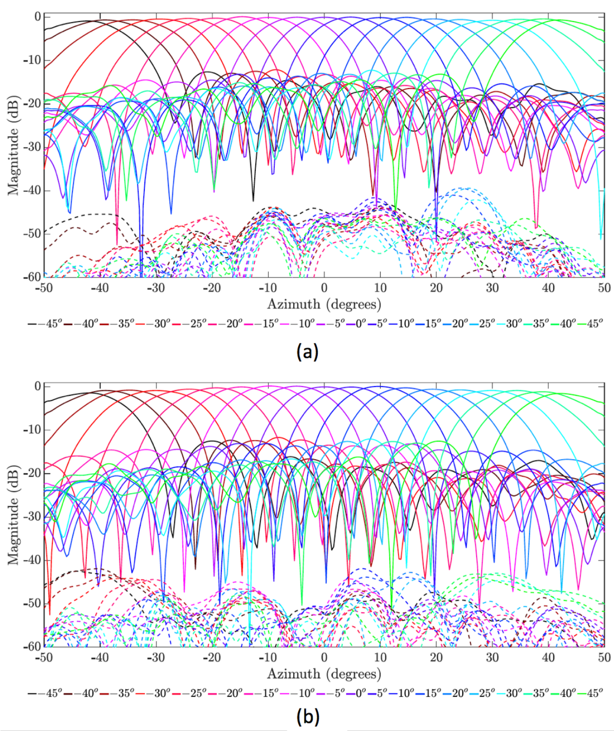

Fig. 5: (a) and (b) Measured radiation patterns of 2 x 8 array (for H- and V-polarizations) in the azimuth plane [20].

In general, when the cross-polarization levels of the antenna increase, all the biases in the polarimetric variables are increased. Multiple factors in the antenna element were investigated during the design process of the 8x8 array in order to comply with the current antenna requirements of MPAR. These factors include: edge diffraction suppression [20]; bandwidth in excess of 10% with a central frequency of 2.8 GHz; port-to-port isolation in the element -50 dB; cross polarization levels below -45 dB and co-polar mismatch below 0.1 dB at $\pm 60^{o}$ and $\pm 10^{o}$ for scanning range at the azimuth and elevation planes, respectively, after careful calibration; active reflection coefficient < -10 dB at $\pm 60^{o}$ and $\pm 10^{o}$ for scanning range at the azimuth and elevation planes, respectively. A new stacked cross MS patch radiator with electromagnetic coupling was developed for this project [36]. The radiators and the feeding network were separated into two different assemblies to prevent them from bending after fabrication. The radiator assembly consists of two conducting layers and a radome of RT/Duroid 5880LZ bonded with RO4450F.

IV. Summary

This paper provides an update on a project that will provide solutions to modern day radar challenges by delivering the full flexibility of digital at every element (i.e., digital TX and RX for both H and V on every element). The bulleted list below provides a brief summary of possibilities for demonstrations with the Horus system:

- Advanced aperture and waveform agility, performing many different tasks/objectives simultaneously;
- Multiple Input Multiple Output (MIMO) radar - multiple transmit and receive antennas;
- Spectrally agile active phased arrays;
- Advanced Digital Beamforming (DBF) for a higher angular resolution with wide coverage;
- Array imaging – efficient systems of reduced size and cost;
- Exquisite control of polarimetry: single H, single V, simultaneous H&V for slant 45, LHC, RHC, or arbitrary polarization states.

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