Update 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 designed to operate in the 2.7 – 3.1 GHz frequency band, which is being designed and built at the University of Oklahoma's Advanced Radar Research Center (ARRC). This is radar build 1 of 2 for our group in the S-band. 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]. 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. To provide some background: over the last 15 years, the ARRC has been engaged in the national Multifunction Phased Array Radar (MPAR) initiative, and subsequently the Spectrum Efficient National Surveillance Radar (SENSR) Program, as initially coordinated by the Federal Aviation Administration (FAA), the Department of Defense (DoD), the Department of Homeland Security (DHS) and the National Oceanic and Atmospheric Administration (NOAA). Consequently, the ARRC is developing a scalable all-digital polarimetric S-band phased array. The array will is designed to support a variety of operational radar modes, including Multiple-Input and Multiple-Output (MIMO). 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. Hardware

A mobile, S-band, dual-polarized phased array system is currently under development by the ARRC, as depicted in Fig. 1. 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. Fig. 2 depicts an Octoblade. Through careful design, each OctoBlade drives an eight-element column of the panel's high-performance antenna array with nearly ideal polarization along the principal planes, consisting 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. 1: S-Band Mobile Radar.

A. OctoBlade Electronics:

The top half of each OctoBlade principally contains the RF electronics, while the lower half contains the FPGAs. These two halves are separated so that upgrades can be conveniently supported as needed. The FPGA board is the data processing backbone of the Horus system. It integrates the functionality of several COTS FPGA boards and custom adapters into the compact OctoBlade form factor. The board has local DC power conversion, monitoring, and sequencing (single DC rail operation). Its design incorporates 2x powerful Arria 10 FPGAs, DDR4 RAM, Cyclone V MitySOM module, gigabit ethernet, etc.

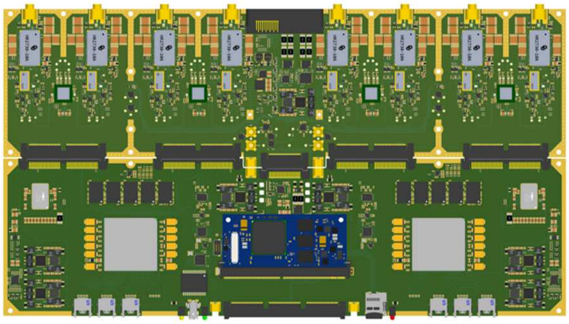

Fig. 2: Sideview of an OctoBlade. The top half principally contains the RF electronics, while the lower half contains the FPGAs.

As depicted in the upper portions of Fig. 2, the grey boxes (below the SMA connectors) house the GaN front-end modules (FEM), which 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. Each FEM 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 by a fractal-inspired distribution network.

At the same time, the OctoBlades 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 the benefits 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 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. Fig. 3 depicts the relationship between an OctoBlade an a single panel.

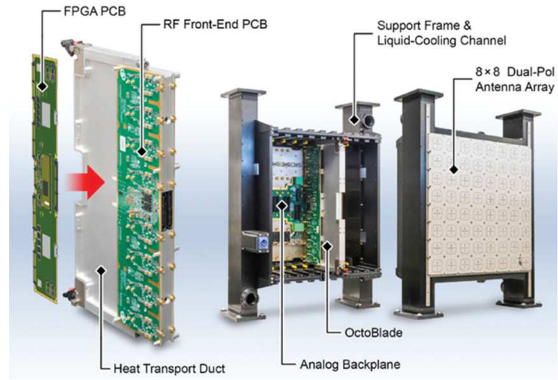

Fig. 3: LEFT: OctoBlade. MIDDLE: one OctoBlade inserted into a panel that supports eight of them. RIGHT: front side of the panel.

For normal radar operation, typical digital beamforming [17-21] and etc., will be accomplished over a RapidIO network feeding the back of the panels, enabling beam-bandwidth products that far exceed 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 [21-24], 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 completed 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 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 [25]-[27], etc.

B. Antenna Subsystem:

The antennas for the mobile demonstrator are discussed in this section, and Fig. 4 depicts a set-up of our initial laboratory measurements for a 2x2 panel case. This fully digital active and dual-pol phased array antenna is designed for full control of transmitted and returned signals of each antenna element. Fig. 5 illustrates comparisons of simulations to actual measurements. In brief, we have:

- Frequency: 2.74 GHz to 3.13 GHz
- XP isolation: -40 dB (E- and H-planes)
- XP better than -33 dB (D-plane L3 Sim.)
- Scanning range: ± 45° @ ARC < 0.3
- Efficiency: >85% (passive array)
- Bandwidth: ~ 15%

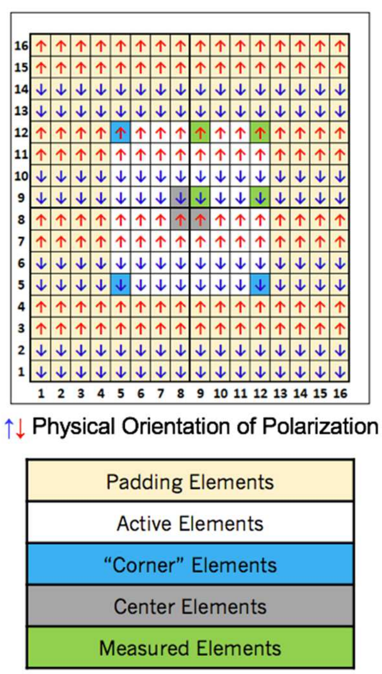

Fig. 4: 2x2 Panel Measurement Set-up.

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. A new stacked cross MS patch radiator with electromagnetic coupling was developed for this project [28]. 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.

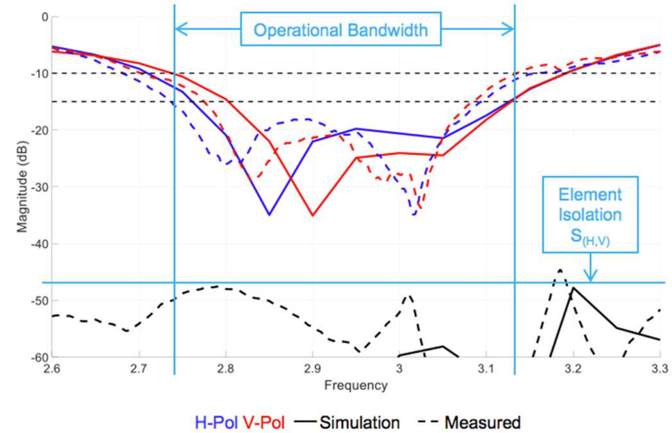

Fig. 5: Measured Embedded Element S-Parameters using 2x2 LRU Array

III. 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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