161 DUAL POLARIZATION IMPLEMENTATION APPROACHES AND GEOMETRY TRADES FOR MULTIFUNCTION PHASED ARRAY RADAR (MPAR)

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1. INTRODUCTION

The National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) and the Federal Aviation Agency (FAA) operate national networks of radar systems that are used for weather monitoring/observation and aircraft surveillance. These radar systems are aging and costly to maintain. The networks could benefit from the advances in multi-functional performance, capabilities, and scalability afforded by modern phased array radar technologies. The scalability and multi-mission functionality of modern phased array radar systems offers the ability to replace several different types of aging legacy radars that had been designed around different weather monitoring/measurement and air traffic surveillance missions with a common, phased array radar system implementation that is easily scaled to the mission needs of the installation location. Nationally, approximately 350 S-band radars could replace the existing NWS and FAA radar installations. This paper summarizes findings from a 2012 study commissioned by the NOAA and the FAA into certain engineering analyses and cost/performance trades dealing with dual polarization implementation strategies for a new Multifunction Phased Array Radar (MPAR) that might address the nation's future weather and air traffic surveillance needs.

The radar functionality and mission considerations for the following radars were addressed in our study:

- ARSR-4 en route
- ASR-11 terminal air surveillance radars
- Terminal Doppler Weather Radar (TDWR)
- Doppler and polarimetric WSR-88DP weather observation radars

Particular attention is paid to comparing and contrasting various dual-pol implementation approaches, including Simultaneous, Alternating, and Simultaneous-with-Waveform-Diversity (SWD) modes. Three major classes of array geometry—a single rotating face, a four faced truncated pyramid, and a cylindrical commutating array—are also studied, leading to a comprehensive matrix of dual-polarization approaches and geometry options. The outcome represents a scalable system that ranges from a basic configuration intended to perform the core air surveillance mission of the ASR-11 and the TDWR weather observation mission, up to a MPAR system that can also perform the precision weather observations of the Doppler/polarimetric WSR-88DP weather radars and the en route air surveillance mission of the ARSR-4. Some representative key requirements for the MPAR study are listed in Table 1.

Table 1. Selected System Requirements

Parameter	Value
Frequency	2.7 – 3.0 GHz
Beamwidth	1 deg at scan angles below 20 deg elevation <4 deg up to zenith
Hard target sensitivity	1 m^2 at 60 nmi (ASR-11)
Weather sensitivity	0 dB SNR for -4.5 dBZ_e at 50 km
Differential reflectivity bias	0.1 dB
Update rate	4.8 s (ASR-11) 2 – 14 minutes, depending on mode (WSR-88D)

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1.1 Study Metrics

To compare strengths and weaknesses of the polarimetric approaches and geometries, each possible configuration is assessed according to three categories: radar capabilities and performance, maturity of the technologies required to implement the approach using the DoD Technology Readiness Level (TRL) scale, and cost factor relative to a simple baseline system. Because MPAR must perform both weather and air surveillance missions, the performance criteria give equal weighting to weather and hard target performance. Points are awarded for a variety of performance features including scalability, tasking agility, beam quality versus scan and cross-polar data collection capability. TRL maturity is evaluated for system architecture, hardware, polarimetric data collection and processing, and test and calibration procedures. Costs were estimated at a Rough Order of Magnitude (ROM) level using extrapolation from similar systems. A summary of the rolled up metrics for each configuration will be presented at the end of this paper.

1.2 Benefits of Polarimetric Measurements

The benefits of polarimetric measurements are well-known, as summarized, e.g., in Bringi and Chandrasekar (2001). The nation's network of WSR-88DP radar systems, operated by NOAA's National Weather Service (NWS), has recently been upgraded to perform polarimetric measurements utilizing horizontally (H) and vertically (V) polarized signals. These systems collect co-polar echoes HH and VV, from which three key quantities are derived: the co-polar correlation coefficient ρ_{hv}, differential phase ϕ_{dp}, and differential reflectivity Z_{dr}. The co-polar correlation is usually near unity for weather systems, so a low value (ρ_{hv}<0.95) can indicate the presence of non-meteorological targets. Differential phase is used to estimate rain drop size and rain rate within a storm system, while Z_{dr} can be used to detect mean size and shape of hydrometeors, to provide some classification of their type (rain, snow, hail, etc.), and to determine rates of rainfall. An objective requirement for the new MPAR system is to provide the same co-polar capabilities as the existing WSR-88DP systems.

Our study briefly examined the potential benefits of cross-polar measurements HV and VH, which are not presently collected by the WSR-88DP. A quantity derived from these cross-polar measurements called linear depolarization ratio (LDR) can increase the detection sensitivity to various forms of frozen and partially frozen precipitation, and to more accurately determine whether they are snow, hail, sleet or graupel (Liu and Chandrasekar 2000, Bringi and Chandrasekar 2001). In research studies, the measurement of LDR has also indicated the presence of supercooled water (Moisseev, et al 2009), which is known to be a factor in the icing of aircraft wings. Cross-polar measurements may therefore have potential future value to the weather observation and forecasting communities as well as to the air surveillance community. For these reasons, array hardware and polarimetric approaches that can collect the full matrix of polarimetric data (HH, VV, HV and VH) are included in our study and are awarded additional points for performance capability.

2. POLARIMETRIC IMPLEMENTATION MODES

2.1 Simultaneous (WSR-88DP) Mode

The present WSR-88DP systems collect polarimetric data using a form of Simultaneous Mode transmission where transmit power is divided equally into the H and V ports to the dish antenna. This produces a linearly polarized wave that is nominally slant polarized at 45°. Dual receive channels and receivers then collect simultaneous but independent H and V returns, from which co-polar information is extracted. Note that this type of Simultaneous mode operation cannot collect cross-polar components directly. It is cost effective for a system such as the WSR-88DP that operates at high peak power, because it avoids the megawatt-class switches that would be needed to toggle the transmit power between H and to V (Alternating Mode), or the high power phase shifters or low-power phase shifters plus matched high power amplifiers needed to implement waveform diversity modes.

Dish antennas with single H and V feeds can be built and adjusted to achieve very high levels (typically over 33 dB) of cross-polarization isolation (XPI). This is needed for the Simultaneous mode operation because coupling H and V signals upon transmit expends virtually the entire available cross-polarization error budget. The allowable error remaining for the receive system is very small, resulting in a stringent specification for this mode of operation—XPI must exceed approximately 45 dB if the bias in differential reflectivity Z_{dr} of 0.1 dB is to be approached (Wang and Chandrasekar 2006). While this level of XPI performance may be achievable (at some cost) on a dish, achieving comparable levels on an active electronically scanned array (AESA) can result in unacceptably high manufacturing and test costs as we show next. Fortunately, fundamental differences between the design and architecture of dishes and AESA's make other cost-effective avenues available.

2.2 Polarimetric Performance and Cost for Phased Arrays

It is useful to look at the complexity and cost of array design, manufacture and test versus XPI performance in order to understand the cost vs. polarimetry performance trade space of an AESA. Unlike a dish antenna, which always points in the direction of broadcast/reception, an AESA is electronically scanned and its polarization purity and XPI naturally degrade away from broadside. In practice, polarization performance is maintained through compensation; H and V drive levels are adjusted as a function of scan angle from a lookup table that is obtained from calibration tests of the array in a specialized RF test range or near-field scanner. As a general rule of thumb, XPI up to about 25-30 dB is straightforward to achieve with an AESA. At this level arrays can be manufactured with enough precision and repeatability that successive units coming off of an assembly line are uniform, so that a single set of compensation data obtained during Design Verification Test (DVT) serves for subsequent production units. Random sample testing of production units suffices to ensure quality. This is the "sweet spot" of cost and performance. In contrast, 45 dB of XPI is challenging. XPI is difficult to measure to this level, requiring special preparation of the test range, carefully calibrated test instrumentation, and careful attention to process and procedure. (This is equally true, by the way, when measuring a dish to this level.) It is likely that every phased array unit must be calibrated individually through a range of scan angles at this level, a process that significantly adds to manufacturing costs. Continuous process improvement during the life of production becomes crucial to reduce expected rework needed to achieve the stringent performance requirements, especially early in production. Figure 1 captures in graphical form these approximate breakpoints in AESA production cost versus XPI performance level. As a result, polarimetric implementations that have relaxed XPI requirements for the same level of polarimetry data performance will have lower AESA manufacturing, test and maintenance costs. The following sub-sections examine the performance and the XPI requirements of three such polarimetric implementation strategies.

2.3 Alternating Mode

Since the elements in a very large phased array typically operate at relatively low powers (of order 10 W, e.g.) compared to a dish, a small polarization selection switch can easily be included at each array element to alternate pulse transmission between the H and V ports. This approach has the disadvantage, of course, that two successive pulses are needed to collect the data for a single co-polar data set. The time lag that is introduced between H and V data collection can be easily corrected by using either standard pulse pair processing or pulse interpolation processing (Bringi 2001). More serious is the 50% loss in time efficiency that makes it difficult to complete all of the MPAR missions (precision weather observation, search, aircraft tracking, long range air surveillance, and clear air turbulence detection) within the revisit times specified for the study.

2.4 Simultaneous With Waveform Diversity Mode

In the Simultaneous with Waveform Diversity (SWD) mode, each element has two power amplifier chips that transmit a different orthogonal waveform on the H and V ports. Since full polarimetric information is collected with each pulse, temporal efficiency is high making it easier to satisfy radar mission timeline requirements. This approach is also straightforward to implement on a phased array, particularly if the waveforms are phase coded. In this case, a simple low power 180° phase shifter before each amplifier is all that is required to produce the modulation. There are two options for SWD, employing fast-time or slow-time coding.

2.4.1 SWD With Fast Time Coding

SWD with fast time orthogonal coding on H and V was first proposed (to the authors' knowledge) for polarimetric weather observations in 1991. That article contained analyses of both orthogonal phase coding and of up and down chirps (Giuli, et al 1990). The latter has been recently investigated by Al-Rashid, et al (2012) for use in MPAR. There are two potential issues with the fast-time approach, however. First, it has been suggested that the auto- and cross-correlation properties of these waveforms may change with Doppler shift (Giuli, et al 1993), a potential issue that was not investigated in (Al-Rashid, et al 2012). A second and far more serious shortcoming is that this type of fast time SWD precludes the computation of the cross-correlation ρ_{hv} mentioned earlier that is used in current WSR-88DP data collections for hydrometeor classifications. The reason is that ρ_{hv} is zero for pulses that are orthogonal, by definition, providing no information about correlation or clutter. While future research into fast-time coding techniques might resolve these issues, such innovations are either presently in their infancy or are awaiting invention. The fast time coding approach thus has an extremely low TRL maturity today.

2.4.2 SWD With Slow Time Coding

An attractive alternative is the use of slow time phase coding. Coding takes the form of 180° phase flips applied in slow time to subsequent H and V pulses throughout one dwell period or coherent pulse interval (CPI), such that H and V are orthogonal over the CPI sequence. With this coding, the H and V waveforms that are simultaneously transmitted in each pulse are perfectly correlated ($\rho_{hv} = \pm 1$), thus preserving the clutter detection capability of the current WSR-88DP. The H and V data are separated once the full data set is acquired.

A slow-time SWD polarimetry implementation was successfully demonstrated for weather applications using a series of 180° phase shifts in the form of symmetric, orthogonal Walsh-Hadamard coding on transmitted H and V pulse trains within a CPI (Chandrasekar and Bringi 2009). This coding provides convenient spectral separation of co- and cross-polar terms, and was shown to have good Doppler properties. Since this technique was successfully demonstrated in a relevant environment, it has moderately high TRL maturity.

2.5 Summary of Polarimetric Approach Study

The XPI requirement for both Alternating mode and SWD mode operation at Z_{dr} accuracy of 0.1 dB is approximately 23-25 dB (Wang and Chandrasekar 2006). This is achievable over a 60° electronic scan (±45° in both azimuth and elevation) without the need for rigorous and expensive manufacturing and test processes, as suggested in Fig. 1, and stands in contrast to the extreme >45 dB XPI requirement for Simultaneous mode operation. Arrays using Alternating and SWD modes fall in the “sweet spot” of manufacturing and test complexity that was discussed in the previous section. Both of these modes have the further advantage of measuring the full polarimetric matrix, including the cross-polar information needed to derive the LDR parameter. Thus Alternating and slow-time SWD modes for polarimetric measurements with an AESA are cost effective, can duplicate existing measurement capabilities, and offer the potential of new measurement capabilities that we expect to be useful in the next generation of air and weather surveillance radars. SWD has the added advantage of twice the temporal efficiency of Alternating mode, better accommodating the many required functions within the radar timeline.

Our team presented this polarimetry analysis, and proposed using the SWD with Slow Time Coding approach for MPAR, to NOAA and FAA personnel and program consultants in 2012 at program reviews, and in the program Final Report. Since then, SWD with Slow Time Coding has gained favor within the MPAR community.

3. CANDIDATE ARRAY GEOMETRIES

Three candidate geometries are considered in the study: a rotating flat-faced array, a four-faced truncated pyramid, and a commutating cylindrical array. Examples of these geometries are depicted in Figure 2.

The rotator and pyramid faces are tilted back from vertical to allow scan coverage up to zenith, while the cylinder requires an upward-looking array for that purpose. The choice of best geometry is complicated by the number of parameters in the trade space. A single-face rotating phased array has the fewest elements, giving it a low initial acquisition cost but high maintenance costs due to the rotating machinery. It has a high TRL since rotating radars are a mature technology.

The pyramid has four times more elements, increasing the initial acquisition cost, although the power at each element is considerably lower. The absence of moving machinery results in lower life cycle maintenance costs. Performance of this geometry is generally higher since time on target is four times greater than the rotator, and each face can be steered and tasked independently. Ensuring adequate isolation between adjacent faces separated by a corner is being examined in the next MPAR study. Finally, maturity of this configuration is high due to the many fielded large radars with multiple flat faces.

The cylinder is unconventional and therefore merits more detailed discussion. The cylindrical array (Zhang, et al 2011) provides an optimal and unchanging beam shape at all azimuth scan angles because it scans by commutating an angular sector of active elements. The array is divided into four sectors that operate simultaneously to improve throughput. The unchanging beam shape performance of this implementation comes at the cost of reduced beam tasking agility (all sectors must commutate simultaneously), however, and the highest cost of any of the options studied. The high cost arises from having the greatest number of elements of any of the candidate geometries, since the array must be larger (12 m diameter (Karmkashi and Zhang 2012)) to produce a 1° beam from a 90° sector, and due to the need for an upward-facing array on top of the cylinder to meet the program requirement of observing to zenith. The size and complexity of the RF switching matrix needed to cross-connect receiver/exciters to commutating sectors is an additional cost driver. This matrix must provide parallel channels to form beam clusters for maximum likelihood hard target tracking in each sector or, at the least, sum beams as well as azimuth and elevation monopulse beams in each sector. If multiplexing and beam formation are done digitally instead, then a very large number of digital receivers is needed (there are 592 switched columns in (Karmkashi and Zhang 2012)), which is again a cost driver.

The maturity level of this candidate is lower, since a) cylindrical arrays of this size have never been fielded, b) electromagnetic interference between simultaneously operating sectors is troublesome since adjacent sectors abut and are not separated by an isolating physical feature such as a corner, and c) factory test and calibration requires a special curved near-field scanning instrument for each size system (scalability is difficult), while a large 12 m diameter turntable for an outdoor range is a major piece of infrastructure.

The notional system used in the present study for the purpose of systems engineering analyses consists of a flat 4x4m “core” array of 6,400 elements that can perform air traffic and basic weather surveillance (including TDWR wind shear). A simple geometric restacking produces a 2x8m ASR-variant having the same range, sensitivity and performance, but that mimics the beam shape of existing ASR radar systems. Adding thinned array panels around the 4x4 core array completes the full 10x10m MPAR array that provides complete functionality for air surveillance and precision weather observations.

4. COMPARISON OF CONFIGURATIONS

Both Alternate mode, and Simultaneous with Waveform Diversity mode using slow-time orthogonal phase coding, duplicate existing WSR-88DP capabilities and collect, in addition, the cross-polar data needed for estimating LDR and the full polarization scattering matrix. Of the two, slow-time SWD is more time efficient, leading to better tasking capability and utilization. By implementing the 180° phase shift with a simple one bit phase shifter at each element, the additional complexity and cost of implementing this dual-polarized approach are minimal when compared to a single-polarized transmitter.

5. CONCLUSIONS

This short paper has briefly presented a few of the factors relating to comparative performance, cost and maturity level. The scores in these areas are summarized via notional graphs in Figure 3.

The trades relating to geometry are extensive and complex, and the charts in Figure 3 represent a single notional viewpoint. The scores will change when individuals and communities apply their own mission priorities to these trades. For this reason, our study report strives to include all raw data relating to the factors that determine the performance, cost and maturity metrics, and to provide clarity into the assumptions made in its preparation. While it might be argued that there is a “winner” amongst the dual-polarization implementation approaches, keep in mind that all three geometry candidates appear to have the potential to fulfill the preliminary MPAR mission goals defined in this study. In summary, this study compares various architectural options available to realize the MPAR vision. Perhaps the most important conclusion of this investigation is that dual-polarized data collection capability can be added into a solid state AESA-based MPAR system with minimal cost and polarization purity impact to the phased array antenna.

6. REFERENCES

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Note: The views and conclusions expressed in this paper are those of the authors and not necessarily those of the FAA or NOAA.

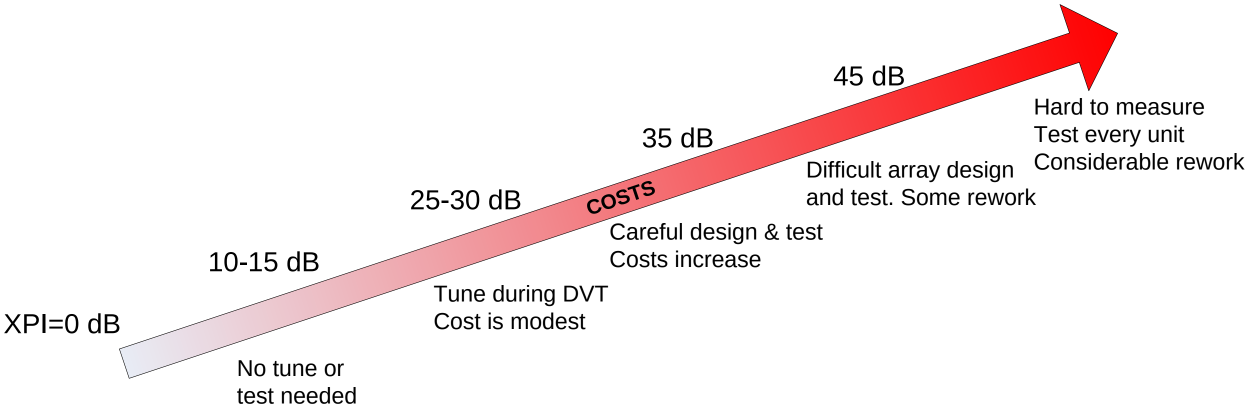

Figure 1. Approximate breaks in design, manufacture and test costs to achieve cross-polarization isolation. Costs escalate rapidly from left to right, with 45 dB of XPI lying at the high end.

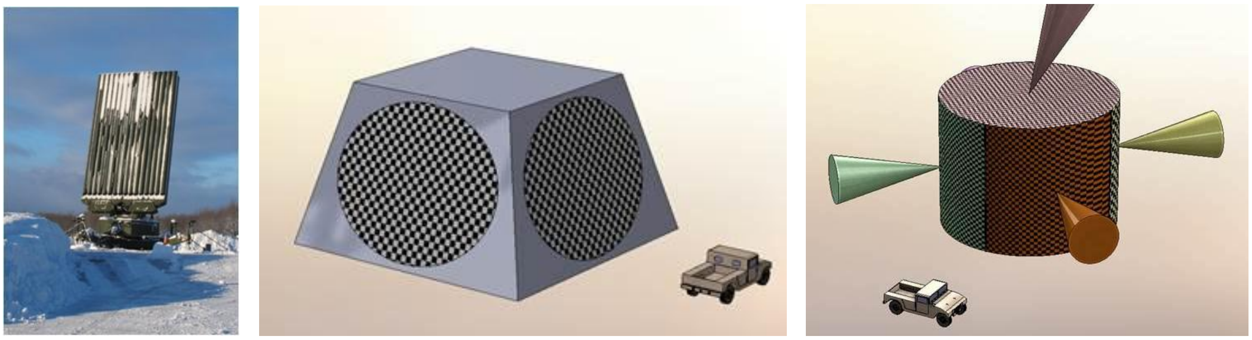

Figure 2. Representative examples of each candidate geometry (rotating array, multifaced truncated pyramid, and multi-sector commutating cylinder with top array geometries). From left: the 3-D Expeditionary Long Range Radar (Saab Sensi), four-faced pyramid, and commutating cylindrical array.

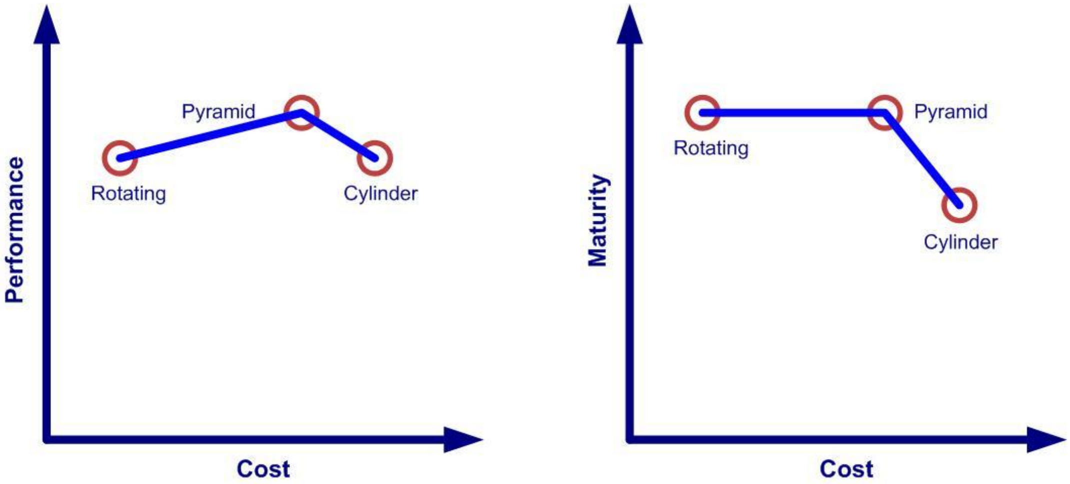

Figure 3. Summary charts of relative performance, cost and technological maturity for the rotating face, four-faced pyramid, and commutating cylinder geometries. All are assumed to use a slow-time SWD mode dual-polarization implementation.