Abstract—An initial study performed for the FAA and NOAA explores dual-polarization implementation options for a multifunction phased array radar (MPAR) that could replace the nation’s air and weather surveillance radars. The study focuses on approaches to acquiring polarimetric data and on array geometries, both of which drive phased array costs of an MPAR design. Two dual-polarized approaches are found to result in reasonable phased array polarization purity requirements. One of them (simultaneous collection of H and V data using orthogonal waveforms) additionally makes efficient use of the radar timeline available for weather observation and hard target search and track missions. Three array geometries—a flat rotating array, a four-faced pyramid, and a commutating cylinder—meet mission requirements, with varying degrees of cost and complexity. A key study finding is that dual-polarized capabilities can be added to MPAR with modest increase in complexity and cost.

Keywords—MPAR, radar, polarimetric, phased array, dual-polarized, weather radar

I. INTRODUCTION

The newest radar systems in the nation’s civilian network of radars for aircraft surveillance and the National Oceanic and Atmospheric Administration’s (NOAA) National Weather Service (NWS) were completed nearly 25 years ago, while many of the radar systems in use by the Federal Aviation Agency (FAA) for aircraft surveillance were developed 45 or more years ago. The radar networks that are used for the surveillance of air traffic and meteorological phenomena nationally are aging and costly to maintain. These aging radar systems could benefit greatly from the advances in performance, capabilities, and scalability that are offered by modern phased array radar technologies.

The scalability and multi-mission functionality of modern phased array radar systems offers the opportunity to replace several variants of aging legacy radars with a common phased array based radar system that is scalable to the mission needs of the installation location. A national implementation of approximately 350 S-band radars could replace the existing NWS and FAA radars, offering enhanced capabilities from a common scalable implementation supporting multi-mission functionality. This paper summarizes initial findings from a study commissioned by the FAA and NOAA into certain engineering analyses and cost trades for a dual polarization implementation strategy for a new Multifunction Phased Array Radar (MPAR) that might address weather and air surveillance needs.

The candidate systems whose capabilities were to be considered for replacement or consolidation in this study include the ARSR-4 en route and ASR-11 terminal air surveillance radars, the Terminal Doppler Weather Radar (TDWR), and the 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. With each implementation, three major classes of array geometry—a single rotating face, a four faced truncated pyramid, and a cylindrical commutating array—are studied, leading to a comprehensive matrix of dual-pol approaches and geometry options. In compliance with the study specifications, the study presents a scalable system that ranges from a basic configuration intended to perform the core air surveillance mission of the ASR-11 with the TDWR weather observation mission, up to a full MPAR system that can also perform either the precision weather observations of the dual-polarized WSR-88DP or the en route air surveillance mission of the ARSR-4.

<table>
<thead>
<tr>
<th>TABLE I. SELECTED SYSTEM REQUIREMENTS</th>
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<tr>
<td>Parameter</td>
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<tr>
<td>Frequency</td>
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<tr>
<td>Beamwidth</td>
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<td>Hard target sensitivity</td>
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A few representative key requirements are listed in Table 1.

A. 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; scalability, tasking agility, beam quality versus scan and cross-polar data collection are a few of these. TRL maturity is evaluated for system architecture, hardware, polarimetric data collection and processing, and test and calibration procedures. Costs were estimated at a ROM (rough order of magnitude) level using extrapolation from similar systems or from systems of comparable complexity. A simple summary of the rolled up metrics for each configuration will be presented at the end of this paper.

B. Benefits of Polarimetric Measurements

The benefits of polarimetric measurements have long been known to the weather observation community [4], and the currently deployed national network of WSR-88DP radar systems operated by NOAA and 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 H-V co-polar cross-correlation coefficient $\rho_{hv}$, differential phase, and differential reflectivity $Z_{hv}$. H-V cross-correlation is usually near unity for weather systems, so a low value ($\rho_{hv} < 0.95$) can indicate the presence of clutter for that pulse pair. Differential phase is used to estimate rain drop size and rain rate within a storm system. $Z_{hv}$ 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. Any new system must provide, at the least, the same co-polar capabilities as the existing WSR-88DP systems.

Additional polarimetric measurements include the cross-polar echoes HV and VH, which are not presently collected by the WSR-88DP. These measurements, which are used to form a quantity 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 (soft hail) [1], [4]. In research studies, the measurement of LDR has also indicated the presence of supercooled water [2], which is a factor in the icing of aircraft wings. Co-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.

II. POLARIMETRIC IMPLEMENTATION MODES

A. Simultaneous (WSR-88DP) Mode

The WSR-88DP operates in so-called Simultaneous mode, where power is passively split between the H and V feeds to the dish antenna to produce a linearly polarized wave that is, nominally, 45° slant polarized. Co-polar information is then collected through dual channels that receive and process both H and V echo returns at the same time. Cross-polar information cannot be obtained. Of the three polarimetric approaches, this Simultaneous mode is the most cost effective for a system with high peak power; Alternating mode would require a megawatt-class switch to toggle the transmit power between H and V, while the SWD mode would require two parallel and well-matched megawatt-class transmitters or modulators. The coupling of H and V upon transmit, however, imposes stringent receive purity requirements of approximately 45 dB of cross-polarization isolation (XPI) [3]. This is tolerable on a dish but can significantly drive up the manufacturing and test costs of an active electronically scanned array (AESA). Fortunately, fundamental differences between dishes and AESA’s open up other cost-effective avenues.

B. Polarimetric Performance and Cost for Phased Arrays

To understand the cost vs. polarimetry performance trade space of an AESA, it is useful first to look at the complexity and cost of design, manufacture and test versus XPI performance. The polarization purity and XPI of an AESA naturally degrades as the array is scanned away from broadside. Performance can be restored and maintained by adjusting H and V drive levels 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. It is possible to manufacture arrays such that successive units coming off of an assembly line are uniform to this level, so that a single set of compensation data obtained during Design Verification Test (DVT) serves for subsequent production units with random sample testing of production units sufficient to ensure quality. This is the “sweet spot” of cost and performance. In contrast, 45 dB of XPI is difficult to measure, requiring special preparation of the test range, carefully calibrated test instrumentation, and careful attention to process and procedure. At this level, it is likely that every phased array unit must be calibrated individually through a range of scan angles, a painstaking process that significantly adds to manufacturing costs. Continuous process improvement during the life of production becomes crucial to reduce expected rework, especially early in production. Figure 1 captures in graphical form these approximate breakpoints in AESA production cost versus XPI performance level.

C. Alternating Mode

It is straightforward to implement Alternating mode on a phased array by putting a polarization selection switch at each element, since individual array elements operate at relatively low power (typically 1 to 10’s of watts). A downside of Alternating mode is that two pulses are needed to perform a single data collection. The time lag between H and V
information can be easily corrected by using either standard pulse pair processing or pulse interpolation processing [4]. More serious is the 50% loss in time efficiency that makes it difficult to complete all of the MPAR missions (search, aircraft tracking, long range air surveillance, precision weather observation and clear air turbulence detection) within the available timeline.

D. Simultaneous With Waveform Diversity Mode

The Simultaneous with Waveform Diversity (SWD) mode, which has two power amplifier chips at each element so as to transmit a different orthogonal waveform on the H and V ports, is also straightforward on a phased array. This mode has full temporal efficiency, making it easier to satisfy radar mission timeline requirements. There are two families of coding, fast- and slow-time, that can be used for SWD.

Fast time orthogonal coding on H and V was first proposed (to the authors’ knowledge) for SWD polarimetric weather observations in 1991, with an analysis of both orthogonal phase coding and up and down chirps [5]. Up and down chirps are again being investigated, specifically for use in MPAR [6]. There are two potential issues with this approach. One investigation mentions that the auto- and cross-correlation properties of these waveforms may change with Doppler shift [7], a potential issue that was not investigated in [6]. A far more serious shortcoming is that this type of fast time SWD precludes the computation of the cross-correlation \( \rho_{hv} \) mentioned earlier that is used in current WSR-88DP data collections to indicate the presence of clutter; the reason is that \( \rho_{hv} = 0 \) for orthogonal pulses, of course, providing no information about correlation or clutter. It is conceivable that future research in fast-time coding could resolve these issues. Such innovations are either presently in their infancy or are awaiting invention, however, and thus have an extremely low TRL maturity.

An alternative is to use slow-time coding where H and V are orthogonal over the set of pulses collected during one dwell time or coherent pulse interval (CPI), but where each individual H-V pulse pair remains correlated. A slow-time SWD polarimetry implementation was successfully demonstrated for weather applications using a series of 180° phase shifts to produce symmetric, orthogonal Walsh-Hadamard coding on transmitted H and V pulse trains within a CPI [8]. 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.

Note that the XPI requirement for both Alternating mode and SWD mode is approximately 23-25 dB [3], achievable over a 60° electronic scan (±45° in both azimuth and elevation) without the need for rigorous and expensive manufacturing and test processes. Arrays for these modes fall in the “sweet spot” discussed in the previous section when used with both of these dual-polarization approaches. 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 SWD modes for implementing polarimetric measurements on 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.

III. 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 Fig. 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 [9] 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 [10]) to produce a 1° beam from a 90° sector, and due to the need for an upward-facing array on top to reach zenith. An additional significant cost driver is due to the size and complexity of the RF switching matrix needed to cross-connect receiver/exciters to commutating sectors. Recall that the 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. The maturity level of this candidate is lower, since a) cylindrical arrays and commutating RF switch matrices of this size have never been fielded, b) electromagnetic interference between simultaneously operating sectors is troublesome since they 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) and a large 12 m diameter turntable for an outdoor range.

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 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.

IV. 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.

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 Fig. 3.

The trades relating to geometry are extensive and complex, and the charts above 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 assumptions that were 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.

REFERENCES


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