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MULTIFUNCTION PHASED ARRAY RADAR: TECHNICAL SYNOPSIS, COST IMPLICATIONS AND OPERATIONAL CAPABILITIES*

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1. INTRODUCTION

Current U.S. weather and aircraft surveillance radar networks vary in age from 10 to more than 40 years. Ongoing sustainment and upgrade programs can keep these operating in the near to mid term, but the responsible agencies (FAA, NWS and DoD/DHS) recognize that large-scale replacement activities must begin during the next decade. In addition, these agencies are re-evaluating their operational requirements for radar surveillance. FAA has announced that next generation air traffic control (ATC) will be based on Automatic Dependent Surveillance – Broadcast (ADS-B) (Scardina, 2002) rather than current primary and secondary radars. ADS-B, however, requires verification and back-up services which could be provided by retaining or replacing primary ATC radars.

The North American Aerospace Defense Command (NORAD) has overall responsibility for maintaining surveillance of U.S. airspace and initiating appropriate responses if security threats are detected. Following the events of 11 September 2001, NORAD's mission has emphasized identification of threats from aircraft flying within the U.S. For example, an Enhanced Regional Situation Awareness (ERSA) system (Davis et al., 2006) has been deployed as part of the Integrated Air Defense System in the National Capital Region (NCR). ERSA uses data from both existing FAA surveillance radars, and special sensors (cameras and military radars) that can determine target altitude and identify aircraft type.

The Departments of Defense and Homeland Security are now involved in maintenance of U.S. surveillance radars, including a major Service Life Extension Program (SLEP) for 68 long-range air route surveillance radars (ARSR). The *Strategy for Homeland Defense and Civil Support* (Department of Defense, 2005) directs DoD to cooperate with the FAA and other agencies "to develop an advanced capability to replace the current generation of radars to improve tracking and identification of low-altitude airborne threats".

Finally, our nation's weather radar networks are vital for severe weather detection and forecasting, for quantitative measurement of precipitation over wide areas and as an input to numerical weather prediction (NWP) models. The tri-agency (NWS, FAA, DoD) WSR-88D radar network is being upgraded with modern, high-capacity processors and a dual-polarization measurement capability (Saffle et al., 2006). FAA's Terminal Doppler Weather Radar (TDWR) network and dedicated weather processing channels on Airport Surveillance Radars (ASR) are essential for detection of wind shear and other hazardous low-altitude weather conditions near airports.

In 2005, the FAA asked Lincoln Laboratory to evaluate technology issues, operational considerations and cost-trades associated with the concept of replacing current national surveillance radars with a single network of multifunction phased array radars (MPAR). In this and an accompanying paper (Herd et al., 2007) we describe a conceptual MPAR high-level system design and our initial development and testing of critical subsystems. This work in turn, has provided a solid basis for estimating MPAR

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costs for comparison with existing, mechanically scanned operational surveillance radars. To assess the numbers of MPARs that would need to be procured, we present a conceptual MPAR network configuration that duplicates airspace coverage provided by current operational radars. Finally we discuss how the improved surveillance capabilities of MPAR could be utilized to more effectively meet the weather and aircraft surveillance needs of U.S. civil and military agencies.

2. MPAR CONCEPT DESIGN

A conceptual MPAR design was described by Weber et al. (2005). Figure 1 repeats the architectural overview presented there, and Table 1 details specific parameters of the radar. The 2.7-2.9 GHz operating band is the current NWS/FAA surveillance band and provides an excellent technical operating point with respect to wavelength dependencies for precipitation cross-section, path-length attenuation, and range-Doppler ambiguity challenges.

The radar is taken to consist of four, planar active arrays each of which scans a 90° quadrant. Each face contains 20,000 transmit-receive (TR) modules at half-wavelength spacing. These can form a 1 degree pencil beam (smaller at broad-side), thus duplicating the angular resolution provided by today's operational weather radars. As shown in Figure 1, the transmit-receive modules utilize parallel bandpass filters to channelize signals into three separated frequency channels within the 2.7 to 2.9 GHz band. Separate amplitude and phase weightings applied to these channels allow for the formation and steering of three, simultaneous but independent beam clusters. Notionally, two of these channels would be devoted to volumetric weather and aircraft surveillance. The third channel could be employed to track and characterize features of special interest such as unidentified aircraft targets or areas of severe weather.

The overlapped subarray beamformer combines the TR-element signals such that its outputs can be digitized and processed to form multiple, parallel receive beam clusters for each frequency channel (Herd et al., 2005). In angular volumes where the full sensitivity of the array is not required, the transmit beam pattern can be spoiled so as to illuminate multiple resolution volumes. Parallel clusters of digitally-formed, full-resolution receive beams can thereby support more rapid scanning while maintaining the inherent angular resolution provided by the array. Use of the multi-channel TR modules and overlapped subarray beamformer to meet weather and aircraft surveillance timelines is discussed in Weber et al. (2005).

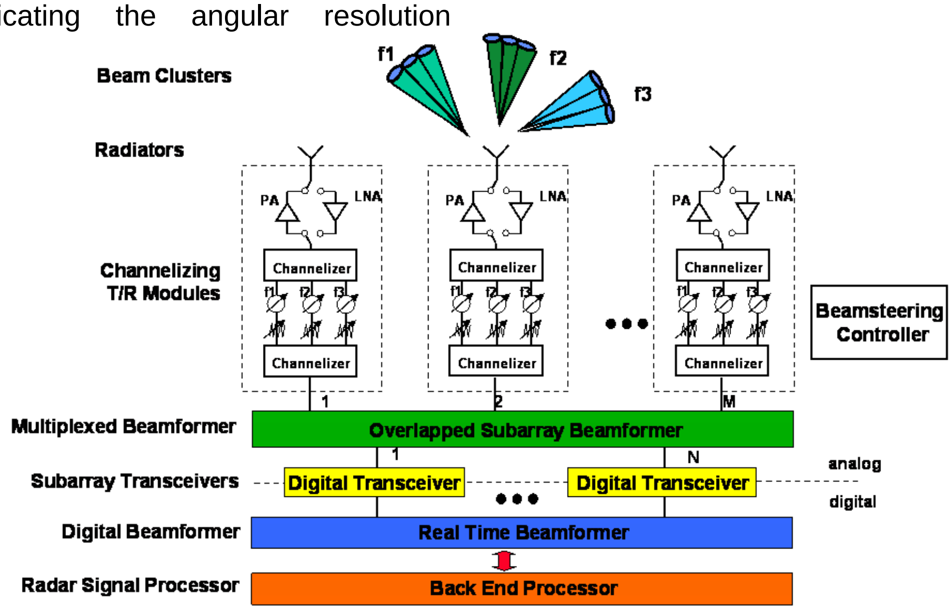

Figure 1. MPAR architecture overview.

Table 1. Concept MPAR parameters

Transmit/Receive Modules	Wavelength (frequency) TR-element Peak Power Bandwidth (per channel) Frequency Channels Pulse Length	10 cm (2.7-2.9 GHz) 1- 10 Watt 1 MHz 3 1-100 usec
Active Array (4-faced, planar)	Diameter TR-elements per face Beamwidth - broadside - @ 45^o Gain	8 m 20,000 0.7^o 1.0^o >46 dB
Architecture	Overlapped sub-array - # sub-arrays - max # concurrent beams	 300-400 ~160

3. TRANSMIT PEAK POWER AND PULSE COMPRESSION

A key cost-containment strategy for MPAR is the use of low peak-power, commercially manufactured power amplifiers in the TR-modules. Point designs for 1 W and 8 W peak-power TR-modules have indicated that parts costs scale roughly linearly with peak-power. The target signal-return to an active array radar is proportional to the product P_T L N^3, where P_T is peak-power, L is pulse length and N is the number of TR-modules. Given this dependency, required sensitivity can be achieved in a cost-effective manner by utilizing low peak-power TR-modules, and by increasing as necessary the duration of the transmitted pulses (using pulse-compression to maintain required range-resolution) and/or the number of TR-modules in the array.

Figure 2 compares minimum detectable weather reflectivity versus range for the most sensitive current operational radar (TDWR) and for an MPAR utilizing either 1 or 10 W peak-power TR-modules and a pulse length necessary to match TDWR sensitivity (100 or 10 usec respectively). It is assumed that pulse compression is used to maintain TDWR's 150 m range resolution, and that corresponding-resolution 1 usec "fill pulses" are used to provide coverage at the short ranges eclipsed by the long pulse. The obvious drawback to the use of very low peak-power TR modules is the loss of sensitivity at ranges approaching the minimum range of the long-pulse coverage annulus. As peak-power is reduced, the required long-pulse length is increased, correspondingly increasing the maximum coverage range for the low-energy fill pulse. Given weather's range^{-2} (or aircraft's range^{-4}) dependence of echo strength, this increase in required fill-pulse range coverage has a significant impact on worst-case sensitivity for the radar.

Figure 3 summarizes the MPAR trade space relative to TR-module peak power and long (compressed) pulse duration. The most stressing performance requirement is the relatively short-range airport wind shear detection function, which dictates the capability to detect "dry wind shear" phenomena (-15 dBz or greater) out to the range corresponding to short-to-long pulse transition. The sensitivity requirement at long range is taken to be equal to that currently provided by TDWR or NEXRAD (~7 dBz at 230 km). Given the MPAR aperture size and TR-module peak-power, these requirements dictate the minimum and maximum long-pulse durations as shown in figure 3. The figure indicates that even a 2 W peak power TR-module, using 30 usec pulses can marginally meet both requirements. The requirements are easily met by 4 W or 8 W peak-power TR-modules, using long-pulse lengths between approximately 10 and 50 usec.

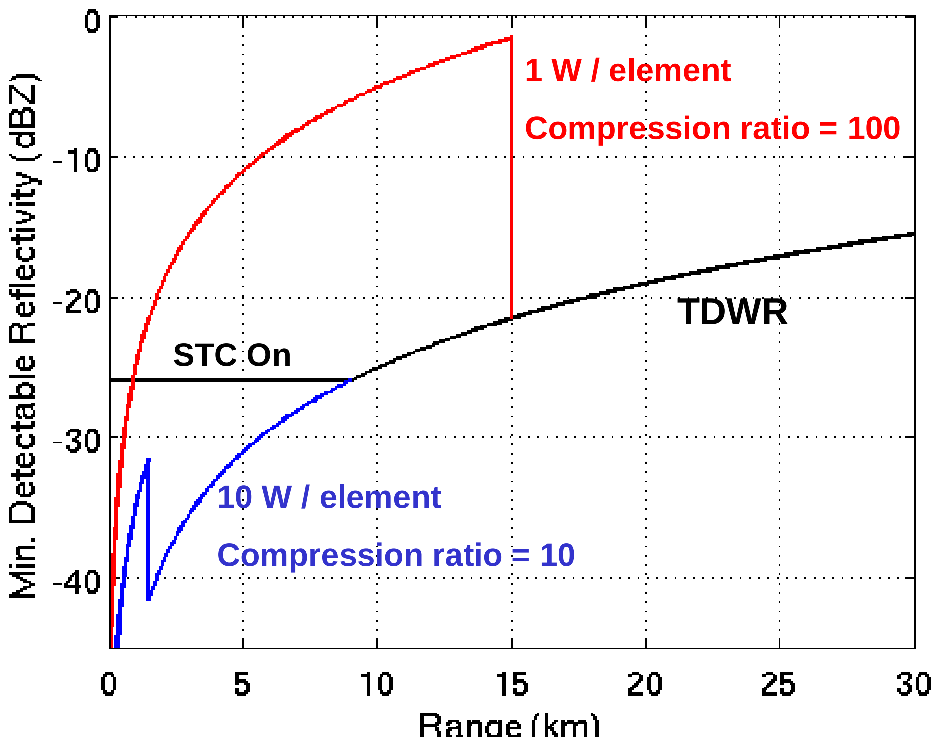

Figure 2. Minimum detectable weather reflectivity versus range for TDWR (black) and for MPAR using 1 W peak-power TR-modules and a 100 usec pulse length (red), and for MPAR using 10 W peak-power modules and a 10 usec pulse length (blue).

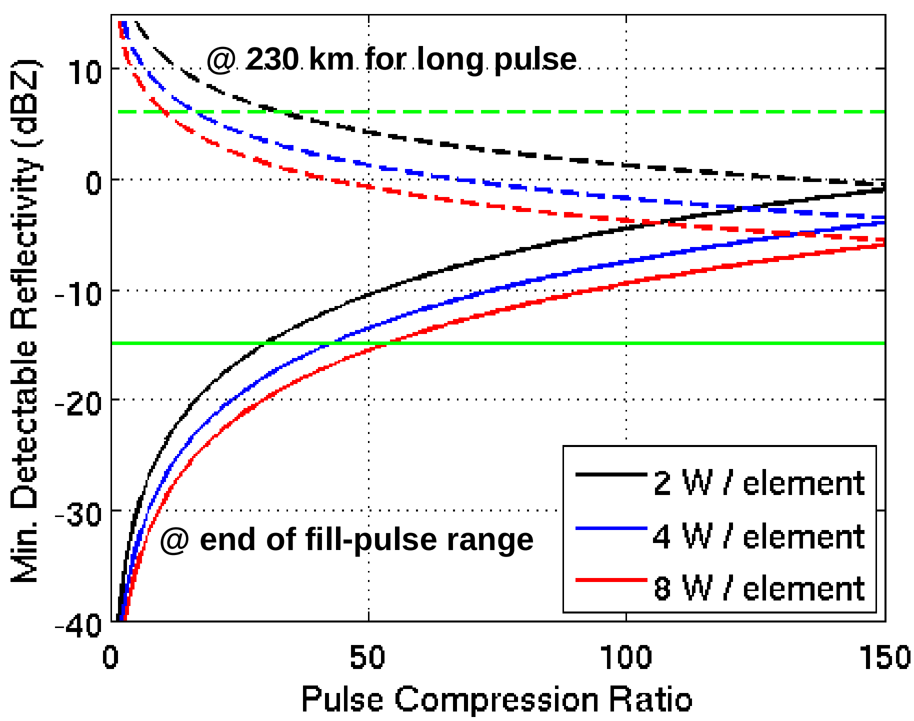

Figure 3. MPAR minimum detectible weather reflectivity versus pulse compression ratio at the short-long pulse transition range (lower curves) and at a range of 230 km (upper curves). For the assumed 1 usec compressed pulse length, pulse compression ratio is equivalent to long-pulse length.

4. AIRSPACE COVERAGE

Today, a total of 510 Government-owned weather and primary aircraft surveillance radars operate in the CONUS. To quantify the potential reduction in radar numbers, we developed a three-dimensional data base that defines the current airspace coverage of these networks. High-resolution digital terrain elevation data were used to account for terrain effects. An iterative siting procedure was used to delineate MPAR locations that at least duplicate current coverage. Figure 4 shows that 334 MPARs would provide near-seamless airspace coverage above 5,000 ft AGL, replicating the national scale weather and aircraft coverage currently provided by the NEXRAD and ARSR networks. Approximately half of these MPARs are necessary to duplicate low-altitude coverage at airports that today is provided by TDWR and ASR-9 or -11 terminal radars. The maximum-range requirement for these “Terminal MPARs” would be significantly reduced because they need only cover airspace beneath the radar horizon of the national-scale network. As discussed in Weber et al. (2005), Terminal MPAR would be a smaller-aperture, lower cost radar employing the same scalable technology as the full-sized MPAR.

5. COST MODEL

The current operational ground radar network is composed of 7 distinct radar systems with separate Government program offices, engineering support organizations and logistics lines. A single, national MPAR network could reduce life-cycle costs by consolidating these support functions. As noted, the total number of deployed radars could also be reduced since the airspace coverages from today’s radar networks overlap substantially. If the reduced numbers of MPARs and their single architecture are to produce significant future cost savings, however, the acquisition costs of MPAR must be at least comparable to the mechanically scanned radars they replace.

Based on our concept development work, Herd et al. (2007) have commenced detailed design of a scaled “pre-prototype” MPAR array that incorporates the required technologies. This design work is providing technical and cost details that can be used to evaluate the viability of the MPAR concept. Table 2 summarizes MPAR subsystem parts-cost estimates based on the pre-prototype array development. The tabulated numbers are normalized to a per-TR-element basis. Cost estimates in the left hand column are based on available technology and small-quantity pricing for subsystem components. The cost reductions indicated in the right-hand column result from either economies-of-scale, or new technologies expected to mature over the next three years (see Herd et al. [2007]).

The indicated TR-module cost is based on parts-cost totals for 1W and 8 W peak-power module designs exploiting WiFi components. The parts-cost for these designs were respectively $14 and $110. For the 2 W peak-power module required for MPAR (see section 3) we estimated a cost of $30 based on interpolation between these design points.

The component costs of the full MPAR system summarized in Table 1 would be approximately $11.5 M. Although we have not fully worked out the Terminal MPAR design concept, it is reasonable to assume that this down-scaled radar would utilize approximately 2,000 TR-modules per face, and a roughly equivalent number of thinned receive-only modules to provide necessary angular resolution (see Weber et al., 2005). Parts-cost for such a configuration would be approximately $2.8 M. The pre-prototype subsystem designs support automated fabrication and integration so that, in quantity, the average per-radar cost of the terminal and full-aperture MPAR networks may be expected to be cost competitive with the $5-15 M procurement costs for today’s operational ATC and weather radars.

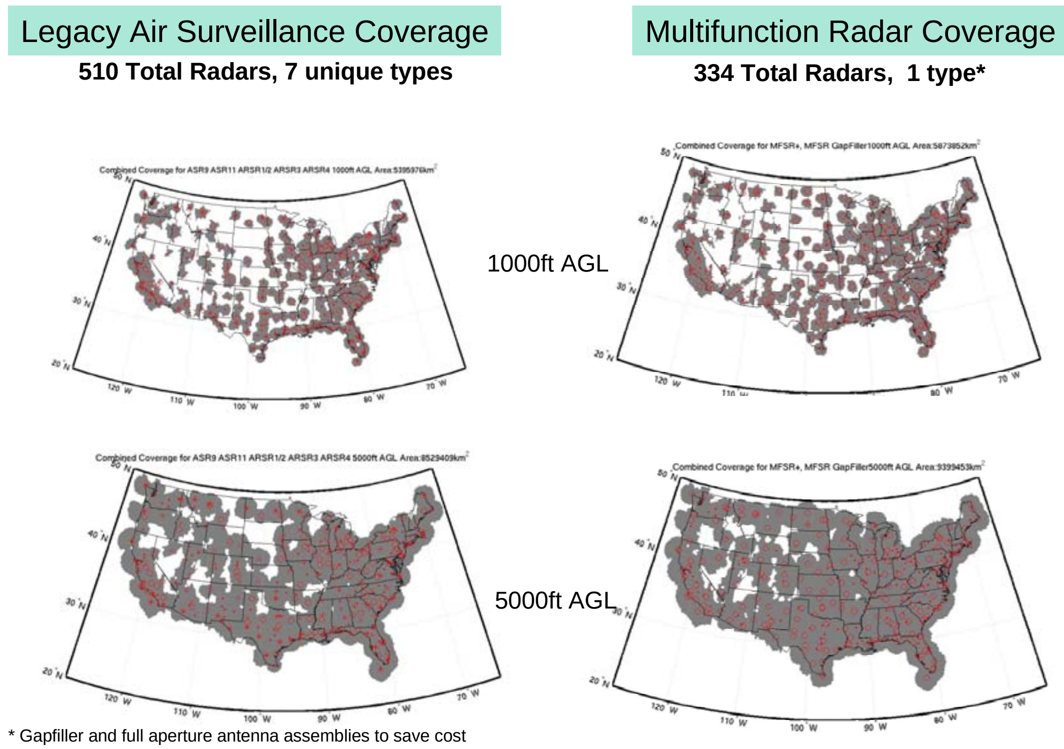

Figure 4: Airspace coverage comparison between current U.S. operational radar networks (ASR 9, ASR-11, ARSR-1/2, ARSR-3, ARSR-4, NEXRAD, TDWR) and a conceptual MPAR network.

Table 2: MPAR subsystem parts-cost model, based on pre-prototype array designs.

	Equivalent Cost per Element	
Component	**Pre-Prototype**	**Full-Scale MPAR**
Antenna Element	**$1.25**	**$1.25**
T/R Module	**$30.00**	**$30.00**
Power, Timing and Control	**$18.00**	**$18.00**
Digital Transceiver	**$12.50**	**$6.25**
Analog Beamformer	**$63.00**	**$15.00**
Digital Beamformer	**$18.00**	**$8.00**
Mechanical/Packaging	**$105.00**	**$25.00**
RF Interconnects	**$163.00**	**$40.00**

Figure 5 provides a very preliminary comparison of national radar network costs for two scenarios: one where current radar networks are maintained until their plausible end-of-life (2012-2025 -- depending on the age of the individual network) and then replaced with the same number of single-function radars; and a second where the current networks are maintained until end-of-life and then replaced by smaller number of MPARs. Per radar replacement cost estimates for the legacy radars are based on actual costs in previous procurements. For MPAR, we have set the full aperture system cost at $15M and the smaller terminal area MPAR cost at $5 M. Recall that approximately equal numbers of these two sized MPARS are needed to efficiently duplicate today's airspace coverage.

Based on the Laboratory's long-term involvement with the TDWR, NEXRAD and ASR-9 life-cycle support and enhancement programs, we have estimated the yearly, per radar operations and maintenance (O&M) costs of the legacy radars as $ 0.5 M per year. This figure considers the numbers of personnel in the associated Government program offices, engineering support facilities and operational facilities, as well as the agency's yearly budget allocations for these systems. By consolidating today's 7 separate operational radar networks into one, per-radar expenditures for non-recurring engineering and hardware developments (e.g. processor refreshes, transmitter upgrades) could be substantially reduced since these tasks would no longer be performed independently on multiple systems.

We estimate that approximately one-half of the Government's O&M costs for the legacy radar networks fall into this non-recurring category. Based on this argument, we have estimated that the 7-to-1 system support consolidation associated would MPAR could reduce per radar O&M costs to approximately $0.3 M. We view this as conservative since MPAR may also reduce recurring O&M costs by eliminating single point-of-failure scenarios associated with the legacy radars' transmitters and mechanical drive sub-systems.

As seen from Figure 5, for the twenty year period considered the MPAR implementation scenario reduces total costs by approximately $2.4 B relative to a "sustain and replace" strategy. The majority of this saving accrues from reduced O&M costs associated with the smaller number of radars required and our assumption that a consolidated national radar network can substantially reduce non-recurring engineering costs. Clearly, our acquisition and O&M cost models must be refined and validated. In the authors' opinion however, the favorable overall cost-picture for MPAR based on current-technology prices, coupled with expectations that essential components derived from the mass-market wireless and digital processing industries will continue to decrease in price, indicate that active-array, multifunction radar technology is a promising option for next generation U.S. weather and aircraft surveillance needs.

6. CAPABILITY IMPROVEMENTS

The improved and expanded hazardous weather detection, weather forecasting and aircraft surveillance capabilities of an MPAR network could potentially benefit security, safety and air traffic control efficiency beyond that provided by the legacy radar networks it replaces. We conclude this paper with a brief discussion of capability improvement opportunities.

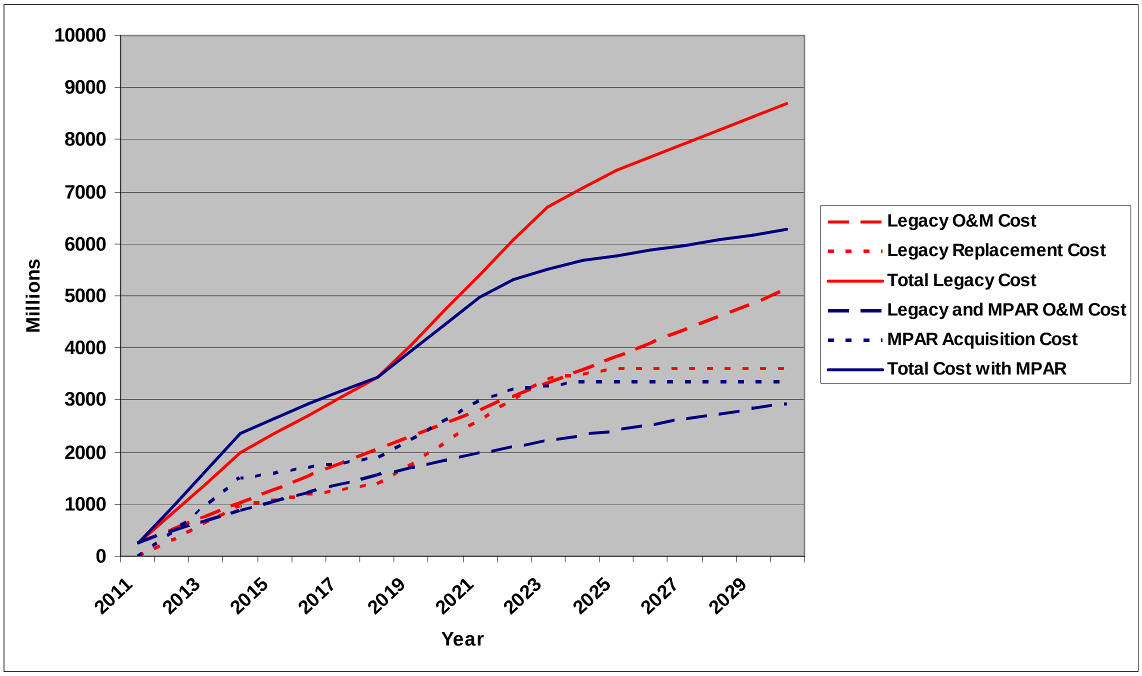

Figure 5: Comparison of cumulative costs for a "sustain and replace legacy radars" strategy (red) versus "replace with MPAR when needed" strategy (blue).

6.1 Weather Surveillance

MPAR's volumetric scan period for weather surveillance will be substantially shorter than provided by today's pencil beam, mechanically scanned weather radars. The factors supporting rapid scanning include:

(1) simultaneous surveillance from each of the four antenna faces;

(2) the ability to very rapidly cover higher elevation angles by spoiling the transmit beam to cover a large angular volume in a single radar dwell period (Weber et al [2005]). Angular resolution is maintained by digitally forming clusters of parallel pencil beams on receive, using the overlapped sub-array architecture. This approach exploits the fact that maximum range to weather targets of interest at high elevation angle is small, thus reducing the energy on target requirement;

(3) agile beam capability which enables "beam multiplexing" (Yu et al, 2007) and/or adaptive, rapid-update scanning of individual storm volumes of high operational significance.

In combination, these factors can readily reduce scan update periods to 1 minute or less. Rapid scanning can enhance the ability to track variations in the structure and dynamics of severe storms (Carbone et al, 1985; Alexander and Wurman, 2005; Bluestein et al, 2003), and will improve wind retrievals (Shapiro et al, 2003) and NWP model initializations (Crook, 1994; Crook and Tuttle, 1994).

The flexible beam shaping and pointing supported by MPAR's active, electronically scanned array can improve the quality of meteorological measurements. Low elevation angle beam tilts can be adjusted in relation to the local horizon in order to reduce beam blockage and main-lobe illumination of ground clutter. Where necessary the array element amplitude and phase weights can be programmed to form nulls on areas of extreme ground clutter or non-stationary clutter (e.g. roadways) that are not readily suppressed by Doppler filters. MPAR will be fully polarimetric, thereby supporting associated capabilities for clutter discrimination, hydrometer classification and quantitative precipitation estimation (Ryzhkov et al., 2005).

Finally, MPAR's digital array architecture will support estimates of the non-radial component of the wind (Doviak et al., 2004). This may improve the identification of weather hazards, as well as facilitating wind retrievals and NWP initializations.

6.2 Non-Cooperative Aircraft Surveillance

Today's operational ATC surveillance sensors do not measure altitude using the primary radar. Cooperative (beacon radar) techniques are used to obtain aircraft altitude and identification code. While cooperative surveillance is highly appropriate for ATC, it does not fully support airspace security needs. For this mission, the three-dimensional position and velocity of non-cooperative targets must be accurately measured, and robust methods for determining target type (e.g. large or small airplane, birds, etc.) are needed. As noted, the Enhanced Situational Awareness System deployed in the NCR uses special radars and cameras to realize these capabilities.

MPAR's large vertical aperture can provide very useful measurement of target height. The digital array supports the use of monopulse which – for targets with moderate to high SNR --can improve angular resolution approximately 20-fold relative to its 1^0 physical beam. Figure 6 compares MPAR's height measurement accuracy with that of existing secondary radars. Although altitude accuracy is comparable with the secondary radars only at relatively short ranges (10-30 nmi), height estimates on the order of 1000 feet or better are still very useful for non-cooperative target characterization. As seen from the figure, these are achievable over essentially the entire coverage volume of an MPAR.

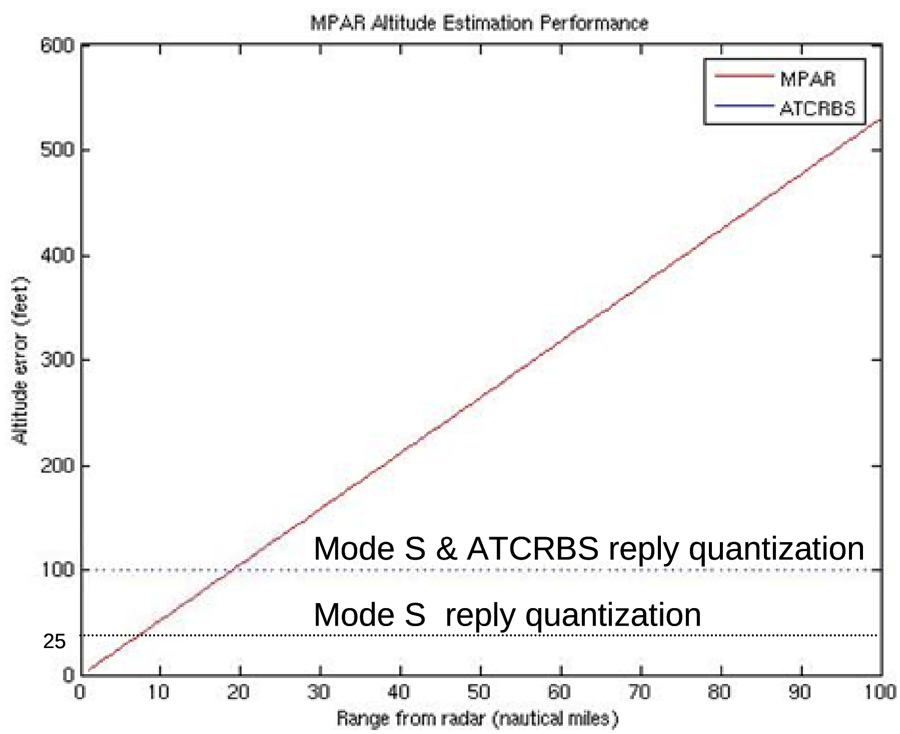

Figure 6. MPAR height measurement accuracy versus range. Twenty-to-one monopulse angle measurement improvement is assumed relative to the physical beamwidth.

Radar-based target identification is facilitated by high-range resolution -- that is, high bandwidth -- and a large unambiguous Doppler interval (i.e. high PRF). Figure 7 simulates a range-Doppler image of an aircraft exploiting high-range resolution and a large unambiguous Doppler interval to detect identifying signatures of a non-cooperative aircraft.

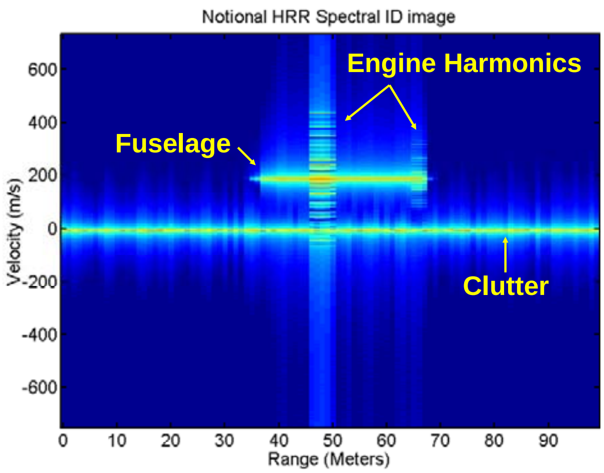

Figure 7: Notional Range Doppler image of an aircraft measured by a radar providing simultaneous high-range resolution and a large unambiguous Doppler interval.

One of MPAR's three frequency channels could be utilized to track a non-cooperative aircraft and illuminate it with special waveforms that support target characterization. Table 3 shows notional parameters for MPAR operating modes providing (1) Wide Area Surveillance (WAS), (2) High Doppler Velocity Measurement (HDVM), (3) High Range Resolution (HRR) and (4) combinations of these modes. The HDVM, HRR and HRR/HDVM modes would preclude simultaneous operation of MPAR's "standard" weather and aircraft surveillance modes due to the high PRF's and/or high-bandwidths they require. This would likely be operationally acceptable given that relatively short integration times would be needed to accomplish target identification, and the identification process would only need to be used intermittently. A lower bandwidth HRR waveform (80 MHz or 2 m range resolution) could be utilized to enable simultaneous HRR and WAS.

Table 3. Notional parameters for MPAR operating modes supporting non-cooperative target identification.

Mode	PRF (kHZ)	Bandwidth (MHZ)	Range Resolution (m)	Doppler Resolution (Hz)	Integration Time (msec)
Wide Area Surveillance (WAS)	1	2	100	10	100
High Doppler Velocity Measurement (HDVM)	15	2	100	2	500
High Range Resolution (HRR)	1	200	1	10	100
HRR / HDVM	15	200	1	2	500
Simultaneous HRR /WAS	1	80, 2	2.5 , 100	10	100

6.3 Air Traffic Control

High precision cooperative surveillance provided by ADS-B is a key concept for the Next Generation Air Transportation System (NGATS). Provision must be made, however for the capability to verify that ADS-B position reports are valid and for ADS-B backup in the event of equipment failure. The FAA is evaluating various approaches to these needs including maintaining existing primary or secondary radars, passive and active multilateration using the aircraft "squitter" signals, and independent aircraft positioning estimates (e.g. from Loran or aircraft inertial navigation units).

MPAR would not be a cost-effective system if considered only as an ADS-B backup/verification system. However, if deployed to meet the nation's weather and non-cooperative target surveillance needs, MPAR could also provide an effective complement to ADS-B for next-generation Air Traffic Control. By reducing the need for additional complexity in ADS-B ground stations or on-board avionics, MPAR might in fact reduce the costs of ADS-B implementation.

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