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Command and Control for Multifunction Phased Array Radar

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Abstract—We discuss the challenge of managing the Multifunction Phased Array Radar (MPAR) timeline to satisfy the requirements of its multiple missions, with particular focus on weather surveillance. This command and control (C2) function partitions the available scan time amongst these missions, exploits opportunities to service multiple missions simultaneously and utilizes techniques for increasing scan rate where feasible. After reviewing candidate MPAR architectures and relevant previous research, we describe a specific C2 framework that is consistent with a demonstrated active array architecture using overlapped sub-arrays to realize multiple, concurrent receive beams. Analysis of recently articulated requirements for near-airport and national scale aircraft surveillance indicate that, with this architecture, 40-60% of the MPAR scan timeline would be available for the high-fidelity weather observations currently provided by the Weather Service Radar (WSR-88D) network. We show that appropriate use of sub-array generated concurrent receive beams, in concert with previously documented, complementary techniques to increase the weather scan rate, could enable MPAR to perform full weather volume scans at a rate of 1 per minute. Published observing system simulation experiments, human-in-the-loop studies and radar-data assimilation experiments indicate that
high-quality weather radar observations at this rate may significantly improve the lead time and reliability of severe weather warnings relative to current observation capabilities.

I. Introduction

The National Oceanic and Atmospheric Administration (NOAA) and Federal Aviation Administration (FAA) are performing concept development and risk reduction for a next-generation Multifunction Phased Array Radar [1]. MPAR could subsume current national operational radar functions including surveillance for civil aviation, airport wind shear detection, severe weather observation and warning support, quantitative precipitation estimation and air-domain security. MPAR would exploit highly digital, active electronically scanned array technology to perform these missions.

A key MPAR challenge is the need to share radar resources in order to meet the surveillance requirements of these multiple missions. These requirements inevitably compete for radar resources. For example, operational weather radars have narrow main-beams, very low sidelobes and relatively long dwells for each pointing direction. These provide the spatial resolution and processing flexibility necessary for robust weather surveillance, but require a long-duration volume scan. In contrast, to achieve update rates necessary for aircraft tracking functions, operational air surveillance radars sacrifice angular resolution (for example, by employing broad elevation beams) and utilize much shorter dwell times.

This paper considers in depth the challenge of managing an MPAR’s timeline in order to fully satisfy the requirements of all users, with particular focus on the demanding weather surveillance mission. This “command and control” or “C2” function involves: (1) partitioning, as appropriate, the available scan time amongst the defined missions; (2) exploiting, where
feasible, opportunities to service multiple missions simultaneously; and (3) leveraging techniques for increasing the scan rate. Analysis of these C2 techniques unavoidably leads to consideration of associated performance issues such as detection and parameter-estimation, spatial resolution, and rejection of interference or clutter.

In sections II and III, we provide background information on the MPAR concept and discuss previous research on how phased array radar can increase surveillance efficiency. Section IV discusses an MPAR C2 framework for aircraft and weather surveillance, and establishes a plausible range for the fraction of MPAR scan-time that could be allocated to high-resolution weather surveillance. An adaptive weather surveillance strategy is presented in section V and simulations of its impact on the quality of weather variable estimates are discussed. Sections VI and VII discuss additional considerations and summarize our findings.

II. Background

NOAA research on potential benefits of phased array radar began in 2003, exploiting a SPY-1A passive phased array radar loaned to the National Severe Storms Laboratory (NSSL) by the US Navy. The radar was configured as a “National Weather Radar Testbed” [2] and has been used to support a variety of meteorological and operational studies. Efficient adaptive scanning strategies using the electronically steered beam have been developed and used to support high-temporal resolution studies of severe storm phenomena, demonstration of enhanced warning processes and multifunction operation. Of particular relevance here are observing system simulation experiments [3], NWRT-based radar data assimilation experiments [4] and human-in-the-loop studies [5]. Using different methodologies, all of these studies indicate that
the capability of a phased array radar to scan volumetrically at rates of approximately 1 scan/min may significantly improve the lead time and reliability of severe weather warnings.

Beginning in 2006, FAA partnered with NOAA to assess the feasibility of a joint-use phased array radar (subsequently designated MPAR) providing both operational aircraft and weather surveillance services [6] [7]. Operational motivation for FAA included decreased cost of ownership through facility consolidation [8] and improved weather advisory services, particularly in relation to low-altitude wind shear [9]. Through this partnership, a variety of efforts to refine the overall MPAR concept have been conducted, including detailed assessments of network siting strategy [10], spectrum utilization [11], preliminary functional requirements [12] and cost [13].

In 2016, the FAA, NOAA, Department of Defense (DoD), and Department of Homeland Security (DHS) initiated a feasibility study for a Spectrum Efficient National Surveillance Radar (SENSR). The goal is to assess approaches for vacating the 1.3 to 1.35 GHz radio frequency (RF) band currently allocated to FAA/DoD/DHS “Long Range Radars (LRR),” in order that this band could be auctioned for commercial use. The Government does not presuppose or necessarily prefer an MPAR-like solution for SENSR. The authors note, however, that its goal is consistent with the MPAR concept of consolidating the LRR mission with that of FAA’s airport surveillance radars (ASR-8, 9, and 11) and NOAA’s weather surveillance radars (WSR-88D), which operate in the 2.7-3.0 GHz band. The airport wind shear detection mission of the FAA’s 5.6-5.65 GHz Terminal Doppler Weather Radar (TDWR) would also be consolidated in this band under the MPAR concept. The participating agencies have developed SENSR “Preliminary Performance Requirements (PPR)” [14] to communicate consolidated technical requirements to the aerospace industry. These assume as a minimum the capabilities of legacy operational
radars, with several significant enhancements. For example, volumetric scan rate goals for both weather and aircraft surveillance are higher than current operational radars, height-finding capability for aircraft is required, and sensitivity requirements are more stringent. The PPR facilitates objective evaluation of proposed approaches to achieving SENSR goals.

III. Phased Array Radar Weather Scanning Strategies

In this section, we review previous research on arguably the most challenging MPAR C2 aspect, the desire for volumetric weather scanning at rates approaching 1 per minute. MPAR’s envisioned multifunction capability works against this, since a fraction of the radar’s timeline will need to be allocated to aircraft surveillance. Notional MPAR array geometries have involved four-faced planar configurations e.g. [1] or cylindrical configurations with four independent, commutating azimuth sectors [15]. The fourfold increase in scan-rate so realized—relative to a single-aperture, mechanically scanned radar utilizing the same number of beam positions and dwell-lengths—will be offset in proportion to the fraction of MPAR scan-time allocated to aircraft surveillance.

Fig. 1 depicts the time required for a four-faced MPAR to complete a specific convective weather volume scan, based on the fraction of the radar’s scan-time allocated to weather surveillance and a “speedup factor”—the increased scan rate achievable using a phased array radar relative to the scan rate of a mechanically scanned, single transmit/receive pencil beam weather radar. The scan pattern, based on an operational WSR-88D volume coverage pattern (VCP-12), is described further in section IV-D.

We show in section IV that a reasonable MPAR timeline fraction allocation for weather surveillance is 0.4 to 0.6. Thus speedup factors of 2 to 3 are needed to achieve volume scan
periods of 60 to 90 s. As discussed below, the necessary scan rate increase can be achieved by decreasing average dwell-time, adaptively reducing the number of pointing directions surveilled or servicing more than one pointing direction simultaneously. The available options will depend on the array architecture selected for MPAR.

A. Single-Channel Array Architecture

A single channel system, where received signals from all transmit-receive (TR) elements are routed through an analog beamformer, allows formation of one, electronically repositionable beam. This “steering agility” enables several techniques that increase scan rate to be employed. “Beam-multiplexing,” as described for example in [16], involves transmitting pairs of pulses successively in different directions and then revisiting each direction at time intervals longer than the decorrelation-time of the weather echo. Because weather variables would now be estimated by averaging independent, rather than correlated pulse-pairs, the total dwell time needed to achieve a given estimate variance at all the beam positions is reduced. Dwell-time decreases of two- to four-fold are achievable using this approach [16]. Note, however, that beam-multiplexing is not viable for pointing directions where long sequences of pulse-samples are required, for example to support Doppler filtering for clutter suppression or frequency-domain weather parameter estimation.

An adaptive scanning technique was tested using NSSL’s single-beam NWRT [17]. Beam directions without significant weather are not scanned on every volume scan, thus enabling faster completion of the scan, particularly when storms are isolated or small in scale. “Inactive” beams are selected based on the intensity, spatial extent and continuity of reflectivity measured during periodic complete volume scans (e.g. once every 5 minutes). The technique is not applied at low
elevation angles in order to assure continuous coverage of important phenomena in the planetary boundary layer. Reference [17] presents a case study where the adaptive scanning maintains an approximately 40% increase in scan rate while scanning an isolated supercell for more than one hour. An implication of this approach is that, because the achievable volume scan rate depends on the angular distribution of significant weather, a specified scan rate cannot be guaranteed. Further, a multi-faced planar MPAR might often require substantially different volume scan rates for its different faces and a cylindrical MPAR with synchronized, commuting sectors will be constrained by the scan-rate imposed by its most challenging sector. Thus during operationally important scenarios such as widespread severe weather, or severe weather very near to the radar, this approach may not significantly increase the volume scan rate.

Reference [18] describes a hybrid scan strategy that would allow a four-faced, single-beam phased array radar to complete a weather volume scan extending to 60° elevation in approximately 30 s. Separate short and long PRT waveforms, similar to those employed by the WSR-88D, are used at low elevation angles to provide robust clutter suppression and range/Doppler ambiguity resolution. Beam multiplexing is used to increase the scan rate at elevation angles of 1.3° and above. Broadening (in elevation) of the transmit and receive beams further increases the scan rate at 10° elevation and above where the reduced maximum range of interest obviates the need for full antenna gain. While effective for rapid update weather scanning, this approach does not appear capable of fully meeting the requirements of the SENSR PPR. A single-beam radar could not accomplish the aircraft surveillance mission with the remaining scan time, particularly given that broad transmit and/or receive beams are precluded by the azimuth and altitude resolution requirements. Additionally SENSR weather requirements do not allow for relaxation of angular resolution at high elevation angles. Finally, the use of
beam-multiplexing at relatively low elevation angles might not allow for acceptable clutter filtering performance.

B. Sub-Array Architecture

A more complex active phased array antenna architecture involves partitioning the array into sub-arrays. TR-element receiver outputs within each sub-array are combined through an analog beamformer to form sub-array patterns consistent with the size of the sub-array. These multiple sub-array outputs are digitized and combined in a digital beamformer (DBF) to form output beams from the full array. The DBF can form simultaneous receive beams in different pointing directions by applying different amplitude and phase weightings to the sub-array outputs. This effectively steers a beam with the resolution of the full array in a direction different from the steering direction of the subarrays. Angular aliases (so-called “grating lobes”) arise from the fact that the sub-array phase centers are separated by distances significantly greater than one-half the radar wavelength. The grating lobes are suppressed by the sub-array pattern, but will become severe if the phase weighting across the subarrays steers the beam too far from the subarray center, so that the first grating lobe also enters the subarray main beam. Therefore, the receive beams are configured as “clusters” around the center of the sub-array pattern. In order to provide large clusters, overlapped subarrays can be formed in which a given antenna element contributes to multiple subarrays (at the expense of increased antenna complexity). In this way, the sub-array phase centers can be moved closer together, pushing the grating lobes further from the desired main beam.

Reference [8] describes how the use of a broadened, or “spoiled,” transmit pattern, with matched clusters of receive pencil beams, could achieve necessary scan rates for MPAR’s
aircraft and weather surveillance missions. Their approach exploits the circumstance that targets of interest (either weather or aircraft) will not be present above 20-30 km in altitude, thus decreasing the maximum range of interest (and associated requirement for antenna gain) as elevation angle increases. The loss of two-way antenna gain associated with transmit beam spoiling is thereby offset. Reference [8] shows that, from a power management perspective, spoiling factors as high as 9 for weather surveillance and 60 for aircraft surveillance are plausible at elevation angles of approximately 20° or greater. This would result in corresponding scan rate increases for higher elevation tilts.

A drawback to this approach is the significant reduction in two-way antenna pattern suppression for weather or clutter returns that are outside the main-lobe of a receive beam but within the angular interval defined by the almost uniform-gain, spoiled transmit beam. These returns are reduced only by the one-way gain pattern of the receiving beam which will typically vary from -20 dB to -30 dB over the spoiled transmit beam. In circumstances where strong cross-range gradients in weather variables exist, the integrated effects of returns from these near-in sidelobes might significantly bias weather parameter estimates for a given receive beam. Reference [19] discusses the use of adaptive beamspace processing to mitigate this effect. In section V of this paper we analyze a complementary approach for minimizing the impact of the higher near-in sidelobes associated with the use of receive beam clusters.

C. All-Digital Array Architecture

The final array architecture we consider is an “all-digital” configuration where received signals from each TR-element are down-converted and digitized independently. This enables receive beams in any direction to be formed digitally and processed in parallel. Such an
architecture can be exploited to achieve more rapid weather scanning by using a “Multiple Beam Technique (MBT)” [20]. Back-to-back pulses are transmitted in three widely spaced directions, with simultaneous reception using corresponding digitally formed receive beams. The transmission directions would be chosen so as to minimize mainlobe-to-sidelobe coupling amongst the simultaneously active beams. This concept was extended with a method for combining the voltages received in the simultaneously active beams so as to reduce mainlobe-to-sidelobe coupling to negligible levels [21].

The MBT is attractive in that it could accelerate scan rate by a factor of three, in principle without increasing two-way sidelobe levels. It may however pose significant implementation challenges in that:

(a) costs, prime-power requirements, and manufacturing complexity of an all-digital active array may significantly exceed that of the simpler corporate beamformer or sub-array architectures described above;

(b) transmission of three equal back-to-back pulses triples the minimum reception range, average transmitted power, and duty factor compared to a single pulse. To support this mode without loss of sensitivity, the system needs to support an increased radar pulse width and duty cycle, as well as potentially provide a means for filling in the short range returns, or, the system needs to transmit short pulses with higher peak power. These limits may offset the apparent sensitivity advantage relative to transmit-beam spoiling since in the latter case only a single pulse is transmitted to illuminate the multiple receive beam volumes.

IV. An MPAR Command and Control Framework
In this section and the next, we discuss an MPAR C2 approach consistent with the sub-array architecture discussed above. We focus on this architecture since a single-beam system would not be able to meet the scan update requirements for concurrent weather and aircraft surveillance missions, and the feasibility of an all-digital architecture is as yet uncertain. Further, the specific MPAR configuration we assume is based on the low-cost, S-band active array panel [13] [22] developed by Lincoln Laboratory to replace the SPY-1A radar in NSSL’s National Weather Radar Testbed. Given this, the approach we describe is fully implementable with proven technology and can be experimentally tested using the “Advanced Technology Demonstrator” [1] that will be fielded at NSSL in 2018.

A. Key Performance Goals

Table I summarizes requirements for coverage, sensitivity, and volume scan update period for the mission areas defined in the SENSR PPR. “Near-range aircraft” requirements define surveillance needs for critical infrastructure, special events, urban areas, and maritime and land borders. As such, these needs may require dedicated radar assets outside the scope of the MPAR concept and will not be further considered here. “Short-” and “long-range aircraft” requirements are based respectively on capabilities of current terminal-area Airport Surveillance Radars (ASR) and national-scale Long Range Radars (Common Air Route Surveillance Radar (CARSR) and ARSR-4). There are significant differences, however. For example, the SENSR minimum detectable aircraft cross-section requirement is significantly smaller than that of current ASRs, which are designed for detection of 1-2 m² cross-section targets at full range. SENSR long- and short-range aircraft surveillance requirements also specify height-finding capability with accuracy of 3000 feet or better throughout the coverage region; today this capability is provided
only by the ARSR-4. Meeting these requirements will likely require a high-gain antenna consistent with the \(~1^\circ\) pencil beam specified for the “high-resolution weather” surveillance mission, which captures capabilities of the WSR-88D. “ATC weather” requirements reflect the capability of ASRs and ARSRs to provide rapid-update, coarse weather reflectivity information through parallel processing of data flowing to the aircraft target processor. MPAR would also acquire signals necessary for ATC Weather using the aircraft surveillance scans so there would be no impact on timeline. “Required” scan update periods for both aircraft and weather surveillance missions are similar to those of current operational radars, but “goals” are as much as 5 times shorter.

Other important performance requirements include detection in the presence of clutter or interference, maximum weather variable estimate bias and standard deviation, range and azimuth location accuracy, target capacity and processing latency. While we will not treat clutter/interference suppression and weather estimate variance requirements explicitly, our C2 analysis assumes dwell-times consistent with current state-of-the-art signal processing approaches for all missions. Thus the analysis should realistically account for pulse integration time necessary to satisfy these requirements. Section V analyzes trade-offs between weather scan-rate and weather-variable estimate error. Finally we will assume that the system has sufficient bandwidth and processing capacity to meet associated requirements for range accuracy, target capacity, and latency.

B. Antenna Configuration

Key considerations from the C2 perspective are antenna size, which sets beamwidth and number of pointing directions, the product \textit{transmitted pulse energy} \times \textit{two-way antenna gain}
which establishes sensitivity for aircraft surveillance, and the subarray architecture which determines the number of concurrent digital receive beams that can be formed. We assume that MPAR will be sized to provide 1° beamwidth, consistent with the WSR-88D.

Using the Lincoln Laboratory panel as the basis for a notional MPAR antenna, one possible configuration is shown in Fig. 2. The antenna is comprised of 376 panels, each of which is an 8x8 array of TR-elements spaced at approximately half-wavelength. There are thus a total of 24,064 elements in each array face, the antenna beamwidth at broadside is 0.9°, and the transmit gain (unspoiled) is 48 dB. The TR-elements and patch antennae support simultaneous transmission and reception of horizontally and vertically polarized radiation or circularly polarized signals. Peak power per element for each polarization channel is 6W. The maximum duty cycle is 5% if both polarizations are simultaneously transmitting, and 10% if only a single polarization at a time is used. We note that affordable, higher power TR-elements exploiting, for example, gallium-nitride (GaN) power modules on a silicon (Si) substrate [23] will likely be available by the time an operational MPAR would be deployed. This would only increase the applicability of C2 strategies described in this paper.

The array would be segmented into 159 overlapped, sub-arrays whose phase centers are indicated by red circles in Fig. 2. Each sub-array consists of eight panels (4x2) oriented so as to support beam clusters that are broader in azimuth than elevation. There would thus be 318 digital receivers to accommodate the two polarizations. An example cluster of 33 receive beams realizable with this array configuration is shown in Fig. 3. Note that the sub-array patterns reduce the receive beam response significantly at the edges of the cluster. This must be accounted for in the radar loss budget.
C. Sensitivity Considerations

Initially, considering only available energy, we can make a rough assessment of the amount of time required to search the coverage area for aircraft using the radar search equation. We will assume the long-range aircraft detection requirement from Table I—a radar cross section of 0.1 m² at a range of 92 nmi (~170 km). Furthermore, we assume that the required detection and false alarm probabilities are for a fluctuating target following Swerling 1 statistics. For simplicity, we will assume the same detection requirement over the required angular coverage region of 0° to 30° elevation, which will be conservative. The search equation (e.g. [24], equation 1.6), with the simplifying assumption, can be written

\[ t = \frac{4\pi k_B T_0 F \text{SNR} L \Omega R^4}{P_{\text{ave}} A \sigma}, \]  

(1)

where \( t \) is the search time, \( k_B \) is the Boltzmann’s constant, \( T_0 = 290 \) K is the standard reference temperature, \( F \) is the receiver noise figure, SNR is the signal-to-noise ratio, \( L \) is the sum of losses for aircraft search mode, \( \Omega \) is the solid angle searched, \( R \) is the range covered, \( P_{\text{ave}} \) is the average transmitted power, \( A \) is the effective antenna aperture area, and \( \sigma \) is the target radar cross section.

To achieve the required detection and false alarm probabilities considering coherent integration, the required SNR is 17.8 dB. Since the radar has four faces, each face must search a 90° azimuth sector from 0° to 30° elevation, or \( \Omega = 0.785 \) steradians. We will take the other notional radar parameters from Table II. Of note, the aircraft search losses include nominal atmospheric losses, a statistical rain model, antenna scan and beamshape losses, some signal processing losses (pulse compression, range straddling, Doppler processing, and constant false alarm rate (CFAR) processing), and a field degradation loss assuming that roughly 10% of the
antenna elements are failed (end-of-life). Using these estimates in the search equation (1), we calculate the search time could be as low as 1.93 seconds (or lower if we were to properly account for the reduced search requirements at higher elevation angles due to the 100,000 ft ceiling on required detection). However, we will see that for this radar, other considerations are going to be important for determining the search time.

Let us consider a single beam near the horizon. Using the radar equation,

\[
SNR = \frac{P G_T G_R \lambda^2 \sigma}{(4\pi)^3 k_B T_0 F L R^4},
\]

where \( P \) is the peak transmit power, \( G_T \) is the antenna gain on transmit, \( G_R \) is the antenna gain on receive, and \( \lambda \) is the radar wavelength, we can estimate the required pulse width, \( \tau \), to achieve the SNR specified above to be approximately 28 \( \mu \)s. At 5% duty cycle, this would be a dwell of 560 \( \mu \)s. This time scale is not consistent with the range delay to the required targets of interest. Near the horizon, we are required to detect targets out to an instrumented range of 250 nmi, which, even in the case of a single pulse with no required clutter or Doppler processing, would take at least ~3.1 ms. The radar is oversized for the aircraft mission, and will require some form of multiple-beam processing in order to use the radar energy efficiently—hence, the capability to form multiple receive beams in the notional architecture discussed in section IV-B.

For weather surveillance, the radar equation (adapted from [25]) is

\[
SNR = \frac{\pi^3 10^{-18} c P_t G_T G_R \theta |K_w|^2 Z_e}{1024 (\ln 2) \lambda^2 k_B T_0 F L R^2},
\]

where \( \theta \) is the antenna azimuth beamwidth, \( \phi \) is the antenna elevation beamwidth, \( |K_w| = 0.93 \) is the refractive index magnitude for liquid water, \( Z_e \) is the equivalent reflectivity in the customary
units of \( \text{mm}^6 \text{m}^{-3} \), \( B \) is the intermediate frequency (IF) receiver bandwidth, and \( L \) includes nominal atmospheric losses, maximum antenna scan loss appropriate for weather, pulse compression loss, and field degradation loss. The beamwidths are at broadside in units of radians. For the notional MPAR, the effective broadside beamwidth, taking into account the different gains on transmit and receive, is \( 0.9^\circ \) (0.016 rad) for both azimuth and elevation. We will assume a pulse length of 50 \( \mu \text{s} \), corresponding to the maximum 5% duty cycle at 1000-Hz pulse repetition frequency (PRF). Pulse compression processing would be used with \( B \approx 2 \text{ MHz} \).

With these assumptions, the single-pulse SNR is \(~6 \text{ dB} \) for the SENSR “precipitation mode” requirement of -9.5 dBZ (0.11 \( \text{mm}^6 \text{m}^{-3} \)) at a range of 27 nmi (50 km). This would again enable the use of transmit beam spoiling and receive beam clusters to increase the scan rate, even at the lowest elevation angles. We show through simulations in the next section of this paper, that the “spreading effect” of receive beam clusters for a distributed weather target precludes the use of cluster sizes larger than about 5, and in areas with significant weather, appropriate cluster sizes are 3 or less. Thus from a sensitivity perspective, there would be minimal constraints on the use of digitally formed receive beam clusters to increase the weather volume scan rate. The 9 dB more stringent SENSR “clear air mode” sensitivity requirement would preclude the use of receive beam clusters. However, in this case much longer scan update periods are appropriate, so this constraint is not an operational issue.

The use of a 50-\( \mu \text{s} \) transmit pulse inevitably leaves a near-range “blind zone” up to \(~7.5 \text{ km} \). A short “fill pulse” will be needed to cover this gap. If the long and short pulses are transmitted consecutively with a center-frequency shift to isolate their respective returns, then the scan timelines should not be adversely affected. However, with a short pulse (1 \( \mu \text{s} \)), there would be no SNR margin for meeting the SENSR “hazardous terminal weather” sensitivity.
requirement of -17 dBZ within 6 nmi of the airport, which would preclude transmit beam spoiling. The -17-dBZ threshold resulted from the need to detect dry microbursts. Thus, this is an issue that will need to be addressed for MPARs that would replace TDWRs at airports where dry microbursts are an issue (e.g., Denver, Las Vegas, Phoenix, and Salt Lake City). In this paper, we will not pursue this special case any further.

D. Default Aircraft Volume Search Patterns

In this section and the next we develop notional default scan strategies for meeting the long-range aircraft and high-resolution weather needs. For aircraft scans, if we add consideration of clutter suppression for the radar system, we must include some form of Doppler processing. The required dwell time for the radar system in clutter will be driven by the requirements to support the clutter processing rather than energy requirements. For example, if we desire to maintain an unambiguous Doppler space of approximately 50 m/s, at a frequency of 2.8 GHz ($\lambda = 0.107$ m) we need to maintain a PRF of approximately 950 Hz. A transmit waveform with a 950-Hz PRF will be range ambiguous, given the SENSR coverage requirements. To resolve the range and Doppler ambiguities, the radar will need to support multiple PRFs in a single dwell. This can be accomplished, for example, by introducing an $M$ out of $N$ binary integration scheme on the Doppler filter outputs from the $N$ different coherent processing intervals (CPIs), range unfolded to the instrumented range of interest. Each CPI needs to have sufficient pulses to support the required Doppler filtering and needs to include sufficient time to allow for range ambiguous targets and clutter. For example, for the 250 nmi coverage desired for long-range aircraft surveillance (3.1-ms range delay), if we desire 8 pulses for use in a Doppler filter bank at the average PRF above (1.05-ms ambiguity), we would need to
receive for the full 3.1 ms after the last pulse. However, our Doppler processing also needs to account for range ambiguous clutter, so instead we should transmit 10 pulses and process the returns from the last 8. In order to keep range ambiguous targets and clutter from the last two pulses from interfering with the next CPI, we can change frequency between CPIs.

Staying with this example, if we choose to include a 3-of-5 binary integration scheme in order to support range unfolding, a single dwell on the horizon would require 50 pulses at 950-Hz PRF, or about 52.6 ms of time. This is a much greater time than would be required by energy considerations alone. The timeline can be cut down if we can reduce the number of required dwells by introducing transmit beam spoiling and receive beam clusters, although spoiling the transmit beam on the horizon will increase the observed clutter because of the changes in the two-way antenna pattern.

Table III summarizes a volume search pattern obtained by extending the current example conservatively, assuming that Doppler processing waveforms are required everywhere and making use of beam spoiling in order to help improve the timeline. Receive beams are assumed to overlap at the 3-dB surfaces of the receive beam patterns. The number of pulses per CPI is allowed to decrease with elevation angle as the number of range ambiguities decreases, although we are still (somewhat arbitrarily) requiring 5 CPIs per dwell. The search could be executed in a total time of about 4.3 seconds, equivalent to 36% of the radar’s timeline given the requirement that search scans be repeated every 12 seconds. This should be an adequate estimate for the remainder of our discussion, although it should be kept in mind that an actual design could probably improve on these search times, especially if clutter processing waveforms are only used
when clutter is detected (clutter is more likely at low elevation angles and less likely at higher elevation angles).

To meet the SENSR short-range aircraft surveillance requirements, a separate full volume search scan to 30° elevation could exploit larger receive beam multiplicity at low elevation angles. A sensitivity analysis shows that the maximum transmit beam spoiling with 4 x 12 receive-beam clusters can be used at all elevations. Employing a transmission and processing scheme similar to the ASR-9 (i.e., two PRF sets with microstaggered pulse intervals), the short-range aircraft volume scan could be completed in ~0.76 s. Given the SENSR requirement for a 3 second update period for short-range terminal surveillance, this mission would utilize an additional 25% of the radar’s timeline. Note that this scheme does not explicitly account for range-ambiguous clutter. At a small number of airports where long-range clutter contamination is problematic, a mitigation technique such as fill-pulse transmission may need to be used, which can impact the scan time. We will not consider this special case further here.

E. Default High Resolution Weather Volume Scan Patterns

As with the current WSR-88D, an MPAR-based national surveillance radar network would utilize multiple volume scan patterns for weather surveillance, selected to meet environmental conditions and operational mission needs. The SENSR PPR specifies two basic patterns - “precipitation mode” and “clear air mode” – and within these we expect that multiple variants would be developed.

WSR-88D VCPs are carefully designed to provide coverage of dangerous weather phenomena (tornadoes, strong winds, microbursts, intense precipitation) near the surface, robust suppression of ground clutter, resolution of range- and Doppler velocity ambiguities and
acceptable weather variable estimate accuracies. In this paper, we conservatively assume that MPAR would employ identical VCPs, including the azimuth and elevation angles to be serviced, CPI lengths and pulse train structures, in order that the accuracy of the weather variable estimates would not be degraded relative to the WSR-88D. With this assumption, the most viable C2 strategy for performing the weather mission in the available timeline is to service multiple azimuth/elevation pointing angles concurrently. A technique accomplishing this is analyzed in Section V.

For specificity, Table IV summarizes the previously mentioned convective weather volume scan pattern based on the WSR-88D VCP number 12. It is comprised of 22 elevation tilts centered at elevation angles from 0.5° to 60°. The lowest elevations utilize dual-PRT (pulse repetition time) waveforms to facilitate unambiguous range-Doppler weather variable estimates over the full 250-nmi surveillance range, and thus involve significantly longer dwell times than the higher elevation angle tilts. Completion of this scan utilizing a single transmit/receive pencil beam pattern for each of the approximately 1770 pointing directions per face would require 73 s of scan time for a four-faced MPAR. As noted in Section III, achieving the SENSR volume scan rate goal of 1 minute for convective weather requires that 2 to 3 pointing angles be serviced simultaneously if a four-faced MPAR is employed and 40-60% of the radar’s timeline is devoted to aircraft surveillance.

*F. Scan Time Partitioning*

Approaches to partitioning scan time for MPAR will vary depending on the operational missions that each radar must service. The notional MPAR siting analysis [10] showed that approximately half of the large-aperture MPARs would service long-range aircraft surveillance
and high-resolution weather only. For these systems, the default volume scan patterns described above suggest partitioning the scan timeline into 12-s blocks, matching the SENSr scan update requirement for long-range aircraft surveillance. As indicated, this requirement could be fully met by allocating 4.3 s of this block for aircraft volume search. This would leave approximately 60% of the radar’s scan-timeline available for the high resolution weather mission.

Large-aperture MPARs situated near airports would additionally be required to meet short-range aircraft surveillance requirements and provide wind shear protection services. A plausible partitioning approach would again segment the timeline into 12-s blocks, allocate 4.3 s of the block to long-range aircraft surveillance and 3.04 s (0.76 s x 4) to short-range aircraft surveillance. This would leave ~40% of the radar’s scan-timeline available for high-resolution weather surveillance.

The MPAR siting study assumed that a scaled-down “Terminal MPAR” would be deployed at airports without the full-size MPAR to supply aircraft surveillance and weather information provided today by ASRs. The weather data provided by these radars would be supplementary to that provided by the large aperture MPARs that would replace the WSR-88D network. We assume therefore that weather scan update rate and/or elevation angle coverage would be adjusted to maximize operational value, given the available scan timeline, and that strict requirements for these parameters would not be imposed. We will not consider C2 for the Terminal MPAR variant further in this paper.

V. Adaptive Beam Cluster Allocation to Increase the Weather Volume Scan Rate

In the previous section, we established that meeting SENSr requirements for aircraft surveillance would utilize 40-60% of an MPAR’s scan timeline, depending on whether the radar
was tasked with short-range as well as long-range aircraft surveillance. Given this range, Fig. 1 indicates that “speedup” factors of 2 to 3 will be necessary to achieve the SENSIR high resolution weather mission goal of completing a volume scan every 60 s. Various techniques that could contribute to achieving this were discussed in Section III. Here we examine an attractive approach not previously considered, the use of adaptive receive beam cluster allocations and matched transmit beam spoiling to achieve the necessary speedup.

A. Approach

Our approach, summarized in Fig. 4, seeks to minimize weather estimate biases caused by the relatively high sidelobes within the angular interval defined by the spoiled transmit beam. The fraction of MPAR scan timeline allocated for high-resolution weather surveillance and the desired volume scan time determine the necessary speedup factor, which in turn establishes how many beam clusters may be allocated within the quadrant assigned to each array face. For example, if the volume scan pattern utilizes 1770 independent pointing angles per quadrant and a speedup-factor of 2 is needed, then “N” = 885 beam clusters of average size 2 would be allocated. Since the array structure we’ve assumed produces sub-array patterns that are broader and flatter in azimuth than in elevation (see Section IV-B), it is appropriate to consider beam clusters that extend only in the azimuth dimension: in this case, cluster allocation can be accomplished independently for each elevation tilt.

A small fraction of the scan-timeline available for high-resolution weather will be used to produce a frequently updated, single-pulse reflectivity map, synchronized in pointing directions to that in the operational volume scan pattern. PRI’s used to generate this map are selected to provide range-unambiguous measurement, and a single pencil transmit/receive pencil-beam
pattern is used. From this map the spatial distribution of “bias” in reflectivity that would occur using spoiled transmit patterns and matched receive beam clusters of size 2 through 5 is estimated using equation (3) below.

Cluster sizes are allocated as a function of azimuth within each elevation tilt so as to minimize the number of gates with “bias” exceeding a threshold, subject to the constraint that no more than “N” clusters may be allocated within the quadrant assigned to each array face. This process is repeated for all elevation tilts. All weather variables (reflectivity, Doppler moments, and polarimetric variables) are then estimated using this beam cluster allocation.

Fig. 5 is an example of beam cluster allocation for a speedup factor of 2.0. The input reflectivity map for a single tilt is shown on range, azimuth angle axes and the beam cluster allocation versus azimuth is depicted by the horizontal ribbon half way down the image. The allocation is performed within array-face quadrants (assumed 0-90°, 91-180°, etc). In the first and second quadrants, larger cluster sizes are allocated to the “quiet region” between 45° and 145° azimuth whereas cluster sizes are more uniform in the third and fourth quadrants which have active weather at all azimuths.

Note that since the allocation is performed independently for each elevation tilt, different speedup factors may be used on different tilts to achieve the desired volume scan time. For example if 50% of an MPAR’s total scan time is allocated to high resolution weather, the scan pattern in Table IV could be performed in 60 s by specifying a speedup factor of 1.5 for the 3 lowest elevation angle tilts, and a speedup of 3 for the remaining tilts. This would assure that receive cluster-induced biases for the operationally important low elevation tilts are minimal.

We note that other approaches for increasing the weather scan rate described in section II can be integrated with the adaptive beam allocation approach to achieve the necessary speedup
factor. For example, reducing dwell time by a factor of two using beam multiplexing could be combined with a 1.5x speedup through beam-cluster allocation to achieve a net scan-rate increase of 3x.

B. Evaluation

To assess impacts of the above C2 approach on weather variable estimate quality, we performed simulations using WSR-88D “level 2” archives as input. Level 2 data are “raw” weather variable estimates, stored in radial format with the native radar spatial quantization of 250 m in range by 1° in azimuth. The simulation processing and output was performed on this input grid: thus beam-broadening that would occur as an array is steered off-broadside was not simulated. We also did not adjust the output images to account for reduction in sensitivity that would occur due to transmit beam spoiling. As discussed in section IV, the assumed array has sufficient power-aperture to meet the sensitivity requirement for the spoiling factors considered here.

The model for transmit/receive beam two-way sidelobes is shown in Fig. 6, in this case for the largest cluster size we considered. The flat, -20 dB value across the cluster is a conservative approximation to the average of the actual two-way pattern across the cluster. Given plausible amplitude tapers in generating the receive beams, their mainlobes will cross the -20 dB level at 1.5° from their center and would reach -40 dB at 2.5° from beam center.

For this initial evaluation, we considered three of the measured weather variables: reflectivity measured with horizontal polarization ($Z_H$), radial velocity ($V_R$) and differential reflectivity ($Z_{DR}$). We simulated the output of the $k^{th}$ receive beam of a cluster of length M as:
\[
Z_H^o(k) = \sum_{n=1}^{M} w(n)Z_H^i(n) / \sum_{n=1}^{M} w(n) 
\]

\[
V_R^o(k) = (V_N/\pi)\arg\{\sum_{n=1}^{M} w(n)R_1^i(n)\} 
\]

\[
Z_{DR}^o(k) = \sum_{n=1}^{M} w(n)Z_{DR}^i(n) / \sum_{n=1}^{M} w(n)Z_{DR}^i(n)/Z_{DR}^o(n) 
\]

where \(w(n) = 1.0\) if \(n = k\) and 0.01 (-20 dB) otherwise. The variable \(R_1^i(n)\) in equation (4) is an estimate for the “lag 1” complex autocorrelation function of the weather echo, derived using the archived reflectivity, radial velocity, and spectrum width fields, and knowledge of the Nyquist velocity, \(V_N\). Note that received-power related quantities such as reflectivity must be expressed in linear units in these equations, rather than the customary decibel units. From (3)-(5) it is apparent that strong intra-cluster gradients in one or more of these variables must exist for significant biases to result.

Our evaluation does not simulate statistical fluctuations of the complex weather signal (i.e. voltage returns) and the associated processing to generate weather variable estimates. This is appropriate as we have conservatively assumed that the MPAR’s coherent processing interval (CPI) structure (see Table IV) and signal processing algorithms are identical at all elevation angles to those employed for the input WSR-88D data. Hence related factors affecting the accuracy of the simulated weather variable estimates (e.g. estimate standard deviation, biases due to ground clutter residue, unresolved range and Doppler velocity ambiguities) are accurately reflected by our methods at all elevation angles. “Cross terms” between signals in the different beams within a cluster would arise if equations (3)-(5) were modified to use complex voltages in place of power-related variables (e.g. \(Z_H\)). We have verified through Monte-Carlo simulations that these cross-terms would not substantively affect our simulations of weather variable estimates generated using the assumed CPIs. The mean of the cross terms is zero, and the
normalized standard deviation of the differences between simulations using complex voltages versus equations (3)-(5) was typically 0.2 dB for power related variables.

To simulate the reflectivity map used to dynamically allocate beam cluster sizes (see Fig. 4), we multiply the reflectivity estimates in each input WSR-88D resolution cell by an exponentially distributed random number with unit variance. This approximates the variance that would be present in a rapid update reflectivity map generated using only a single pulse per resolution cell.

For this initial assessment, we examined four WSR-88D volume scans from the KTLX radar near Oklahoma City, chosen so as to “stress” the cluster allocation approach. Two were from a quasi-linear convective system that moved across the Oklahoma City metro area on 26 April 2016. One of these scans was taken as the highly convective line approached the radar, and a second as it moved off to the east and began to transition to a more stratiform system. This case was chosen owing to the large angular extent of the quasi-linear convective system (QLCS). The third volume scan, during the Moore, OK tornado impact on 20 September 2013, features very high gradients in reflectivity and other weather variables, particularly near the tornado. A fourth case, a discrete supercell to the southwest of Norman on 29 April 2016 also featured strong gradients in the weather variables. Fig. 7 shows the input WSR-88D reflectivity, radial velocity and differential reflectivity fields for the inbound QLCS, and corresponding simulations of MPAR output using dynamically allocated receive beam clusters with the indicated “speedup factors.” KTLX is at the center of the images which extend 200 km east-west and north-south. With higher quality images than can be reproduced here, it is possible to see subtle spreading effects that become more prominent as the speedup factor increases. These occur for example, on the perimeter of the very small discrete cell 50 km to the southwest of KTLX, and in front of
the leading edge of the line 75 km to the west. These are both areas of strong gradient in reflectivity and – along the line’s leading edge - radial velocity. However, these do not appear to be of sufficient magnitude to adversely affect operational use of the data.

Fig. 8 shows input data and MPAR simulations for the 20 September, 2013 tornado vortex signature. The image is in radial format: range increases top to bottom from 0 to 50 km, and azimuth varies from 200° to 260° along the horizontal axis. Beam cluster induced spreading effects are more noticeable here owing to the higher resolution of the images and the very large gradients in reflectivity and radial velocity present in the vicinity of the vortex. Even so, the effects are minor and again would not appear to have an impact on interpretation of the data.

Histograms of spreading-induced biases in each of the weather variable fields are shown in Fig. 9. These were computed across all of the elevation tilts for the four storm volume scans described above. For a speedup factor of 3, the distribution of reflectivity bias is plotted in Fig. 9(a). This is calculated by comparing the simulated MPAR output with the input reflectivity field for each radar resolution cell. In the vast majority of these resolution cells, the bias is less than 0.5 dB. Only 1.6x10⁵ of the approximately 4x10⁶ resolution cells were biased between 0.5 and 1.5 dB and the count decreases rapidly with greater biases. Similar distributions were observed for the other simulated variables, consistent with the visual comparisons in Fig. 7 and 8 that indicate a very small number of resolution cells are substantively affected using the adaptive beam-cluster allocation approach.

As a function of the speedup factor, Fig. 9(b), (c), and (d) plot the percent of resolution cells where simulated beam-cluster induced spreading biases exceed the SENSR maximum bias requirements for reflectivity, radial velocity, and differential reflectivity, respectively. Note that the velocity error simulated via equation (4) is not a bias as its distribution is zero-mean and
symmetric about 0. Thus we use the SENSR maximum velocity estimate standard deviation requirement as the basis for Figure 9(c). For the targeted speedup factor range of 2 to 3, the percent of resolution cells with biases exceeding the SENSR requirement are 2% or less for reflectivity and radial velocity, and 10% or less for differential reflectivity. The larger “biased cell” percentage for $Z_{DR}$ reflects the higher variance of this variable which impacts our pixel-by-pixel bias accounting approach. The SENSR requirement for $Z_{DR}$ standard deviation is 0.4 dB, four times higher than the “goal” bias requirement. Note also that the SENSR $Z_{DR}$ preliminary bias requirement has been recently relaxed to 0.2 dB which would approximately halve the number of “biased” gates depicted in each histogram bin in Figure 9(d).

In Fig. 10, for a speedup factor of 3, we plot the percentage of resolutions cells with reflectivity bias greater than 1 dB as a function of elevation angle. As indicated, the separate lines correspond to the four volume scans we analyzed. In general, the fraction of resolution cells with significant bias decreases with increasing elevation angle, and there is a larger percentage of biased cells in the more highly convective cases. This likely reflects higher likelihood of strong gradients in the weather variable fields within intense convective storms.

VI. Discussion

Our analysis assumes a non-rotating, multi-faced active array with a highly digital receive architecture. SENSR requirements for fine angular resolution, high sensitivity, and rapid volumetric updates for both aircraft and weather drive these assumptions. As shown, the large number of angular positions requires that multiple antenna faces transmit and receive simultaneously, and that each face process multiple, concurrent receive beams. SENSR requirements might alternately be met using separate, single-function radars for the different
missions defined in Table I, in which case other radar architectures might be appropriate. Ongoing analyses and interactions with industry will evaluate operational and cost tradeoffs between an integrated (i.e. MPAR) approach to meeting SENSR requirements, versus a “system-of-systems” approach.

An important aspect of the C2 approach described herein is that pulse transmissions on the different faces of the radar would be synchronous, owing to the quasi-deterministic schedule for the aircraft and weather volume scans. This obviates the need for extreme signal isolation between the faces, since one face will not be receiving while another transmits. Dedicated aircraft track modes and/or highly adaptive weather scanning concepts might increase efficiency but would likely prevent synchronous transmission on all faces, thus requiring that greater levels of signal isolation be provided with associated increases in cost and/or radio-frequency spectrum utilization.

Plausible MPAR national network configurations would likely result in significant coverage overlap near operationally significant population centers and high-density commercial airspace [10]. Cooperative multi-radar scanning in such airspace could potentially increase the efficiency with which aircraft and weather surveillance missions are performed. While not considered in this paper, such concepts are at the core of the Collaborative and Adaptive Sensing of the Atmosphere (CASA) concept [26], and should be evaluated in the context of any SENSR C2 solution.

Further research is needed to refine and validate the aircraft search patterns proposed here, and to evaluate complementary tracking techniques that may relieve requirements for scanning the full coverage volume at the required track update rates. One strategy might be to adaptively update targets already under track, while conducting much less frequent search scans to detect
new aircraft entering the surveillance volume. However, if the full number of aircraft defined by
the SENSR target-capacity requirements must be updated at the rates indicated in Table I, this
approach would not be time-effective. If only non-cooperative aircraft need be tracked at the
required rates, however, this approach may result in significant scan time savings. Simulation
and data collection (for example using the ATD when it is fielded) are also needed to evaluate
the extent to which the large beam multiplicities assumed do not degrade aircraft detection
performance, particularly in the presence of ground or precipitation clutter.

Stringent antenna sidelobe requirements for SENSR’s high-resolution weather mission are
based on the capabilities of the WSR-88D [27]. Achieving these using a phased array antenna is
possible, but will require rigorous array calibration and continuous monitoring. From a C2
perspective, antenna sidelobe requirements are coupled to the array architecture choice. As
shown in this paper, multiple concurrent receive beams are necessary to meet volume search
timelines, but achieving these using sub-array sampling introduces spurs in the sidelobe pattern
which must be mitigated through careful antenna design and/or post-processing. An all-digital
array architecture eliminates this issue at the cost of greater hardware complexity.

Finally, MPAR C2 approaches must be consistent with the need for high-quality estimates
of dual-polarization weather variables using an array antenna. These observations require
careful matching of resolution volumes for horizontally (H) and vertically (V) polarized signals,
and corrections for geometrically induced biases [28]. Achieving required accuracy may require
longer CPIs, owing for example to the need for alternating H and V transmissions for some scan
angles [29]. Impacts of transmit beam-spoiling and concurrent digital receive beams must be
understood, and if necessary compensation techniques developed.
VII. Summary

We have shown that, from a C2 perspective, the MPAR concept is consistent with SENSR requirements provided that the antenna array architecture supports a high degree of receive beam multiplicity, using multiple faces (or cylindrical array sectors) and digital sampling across each array face. Analysis and simulation of a specific MPAR configuration - realizable using demonstrated, relatively low-cost array technology - show that specified aircraft and weather sensitivity can be achieved while satisfying dwell-time and angular resolution necessary for clutter suppression, target/weather localization and parameter estimation. Ongoing research will refine and validate these conclusions using higher-fidelity simulations, analysis and field measurement.

The authors believe that significant operational and financial benefits may result from an integrated solution for SENSR requirements such as MPAR. Overlapping coverage of systems capable of servicing all operational missions will enhance surveillance quality. Faster updates, expanded low-altitude coverage and multi-aspect target viewing (supporting, for example, vector wind field retrievals) are examples of surveillance benefits. Consolidation of operational systems would likely reduce acquisition and life cycle costs through economies of scale and through streamlining of maintenance, logistics and second-level engineering service organizations. Finally, spectrum utilization, a key driver for the SENSR program may benefit from an integrated solution since the total number of radars deployed would be reduced and by definition, scanning for the different SENSR missions would be accomplished in a coordinated and non-interfering fashion.

Acknowledgment
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References


Figure Captions

Fig. 1. MPAR volume scan time versus weather surveillance timeline fraction allocation and speedup factor as defined in the text.

Fig. 2. Notional MPAR array-face.

Fig. 3. Receive beam cluster amplitude response for notional MPAR array.

Fig. 4. Framework for adaptive allocation of beam cluster size as a function of pointing direction.

Fig. 5. Example beam cluster size adaptive allocation versus azimuth as described in text.

Fig. 6. Two-way sidelobe approximation for a spoiled transmit beam and the second of a cluster of five adjacent-in-azimuth simultaneous receive beams. The numbers are the relative two-way gains.

Fig. 7. Input WSR-88D reflectivity ($Z_H$), radial velocity ($V_R$) and differential reflectivity ($Z_{DR}$) and corresponding MPAR simulations. 27 April 2016 00:35 UTC (KTLX WSR-88D)

Fig. 8. Input WSR-88D reflectivity ($Z_H$), radial velocity ($V_R$) and differential reflectivity ($Z_{DR}$) and corresponding MPAR simulations. 20 Sept 2013 20:06 UTC (KTLX WSR-88D)

Fig. 9. (a) Histogram of beam-cluster induced reflectivity bias. A total of $4 \times 10^6$ resolution cells with valid data are included. (b) Percent of cells with reflectivity bias exceeding the SENSIR requirement (1.0 dB) versus speedup factor. (c) As in (b) but for radial velocity standard deviation. (d) As in (b) but for differential reflectivity.

Fig 10. Percentage of resolutions cells with reflectivity bias greater than 1 dB as a function of elevation angle (speedup factor is 3). The separate lines correspond to the four volume scans we analyzed.
Fig. 1
Fig. 2
Fig. 4
Fig. 5
Fig. 7
Fig. 8
Fig. 9
Fig. 10
Table Captions

Table I. Notional C2 Performance Goals Derived from SENSR Preliminary Performance Requirements (PPR) Document

Table II. Notional MPAR Parameters

Table III. Default Long-Range Aircraft Volume Search Pattern

Table IV. Default “Precipitation Mode” High Resolution Weather Volume Scan Pattern
### Table I

<table>
<thead>
<tr>
<th>Mission Area</th>
<th>Coverage Envelope</th>
<th>Sensitivity</th>
<th>Update Period (Required)</th>
<th>Update Period (Goal)</th>
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<td>Near-Range Non-Cooperative Aircraft</td>
<td>0.25-20 nmi range 0-24,000 ft alt.</td>
<td>$0.25 \text{ m}^2 @ 20 \text{ nmi}$ $P_d = 0.95$, $P_{fa} = 10^{-6}$</td>
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<td>Not Specified</td>
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<td>Short-Range Non-Cooperative Aircraft</td>
<td>0.25-60 nmi range 0-24,000 ft alt.</td>
<td>$0.1 \text{ m}^2 @ 60 \text{ nmi}$ $P_d = 0.90$, $P_{fa} = 10^{-6}$</td>
<td>3 s</td>
<td>1 s</td>
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<td>Long-Range Non-Cooperative Aircraft</td>
<td>5-250 nmi range 0-100,000 ft alt.</td>
<td>$0.1 \text{ m}^2 @ 92 \text{ nmi}$ $P_d = 0.80$, $P_{fa} = 10^{-6}$</td>
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<td>12 s</td>
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## Table II

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<th>Quantity</th>
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<td>Receive Antenna Gain</td>
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<td>Effective Antenna Area (from 2-way beam)</td>
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<td>Losses</td>
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<tr>
<td>Elevation Angle (°)</td>
<td>Rx Beams to Cover 90° Sector</td>
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<td>-----------------------------</td>
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<td>27.6-30.6</td>
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<td>Number of Tilts</td>
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| 0.5 – 1.3           | 3               | • Long PRT scan for range-unambiguous surveillance  
                              • Short PRT scan for Doppler velocity                                        | 7.7                         |
| 1.8 – 6.4           | 6               | • Interleaved long PRT surveillance and short PRT Doppler pulses                | 3.2                         |
| 8.0 – 19.5          | 5               | • Short PRT for Doppler and reflectivity                                        | 3.0                         |
| 24.5 – 60.0         | 8               | • Short PRT for Doppler and reflectivity                                        | 2.0                         |
| Totals              | 22              |                                                                                  | 73.3                        |