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MULTI-FUNCTION PHASED ARRAY RADAR FOR U.S. CIVIL-SECTOR SURVEILLANCE NEEDS

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1. INTRODUCTION

This paper is a concept study for possible future utilization of active electronically scanned radars to provide weather and aircraft surveillance functions in U.S. airspace. If critical technology costs decrease sufficiently, multi-function phased array radars might prove to be a cost effective alternative to current surveillance radars, since the number of required radars would be reduced, and maintenance and logistics infrastructure would be consolidated. A radar configuration that provides terminal-area and long-range aircraft surveillance and weather measurement capability is described and a radar network design that replicates or exceeds current airspace coverage is presented. Key technology issues are examined, including transmit-receive elements, overlapped sub-arrays, the digital beamformer, and weather and aircraft post-processing algorithms. We conclude by discussing implications relative to future national weather and non-cooperative aircraft target surveillance needs.

The U.S. Government currently operates four separate ground based surveillance radar networks supporting public and aviation-specific weather warnings and advisories, and primary or “skin paint” aircraft surveillance. The separate networks are:

(i) The 10-cm wavelength NEXRAD or WSR88-D (Serafin and Wilson, 2000) national-scale weather radar network. This is managed jointly by the National Weather Service (NWS), the Federal Aviation Administration (FAA), and the Department of Defense (DoD).
(ii) The 5-cm wavelength Terminal Doppler Weather Radars (TDWR) (Evans and Turnbull, 1989) deployed at large airports to detect low-altitude wind-shear phenomena.
(iii) The 10-cm wavelength Airport Surveillance Radars (ASR-9 and ASR-11) (Taylor and Brunins, 1985) providing terminal area primary aircraft surveillance and vertically averaged precipitation reflectivity measurements[1].
(iv) The 30-cm wavelength Air Route Surveillance Radars (ARSR-1, 2, 3 and 4) (Weber, 2005) that provide national-scale primary aircraft surveillance.

The latter three networks are managed primarily by the FAA, although the DoD operates a limited number of ASRs and has partial responsibility for maintenance of the ARSR network. In total there are 513 of these radars in the contiguous United States (CONUS), Alaska, and Hawaii.

The agencies that maintain these radars conduct various “life extension” activities that are projected to extend their operational life to approximately 2020. At this time, there are no defined programs to acquire replacement radars.

The NWS and FAA have recently begun exploratory research on the capabilities and technology issues related to the use of multi-function phased array radar (MPAR) as a possible replacement approach. A key concept is that the MPAR network could provide both weather and primary aircraft surveillance, thereby reducing the total number of ground-based radars. In addition, MPAR surveillance capabilities would likely exceed those of current operational radars, for example, by providing more frequent weather volume scans and by providing vertical resolution and height estimates for primary aircraft targets.

Table 1 summarizes the capabilities of current U.S. surveillance radars. These are approximations and do not fully capture variations in capability as a function, for example, of range or operating mode. A key observation is that significant variation in update rates between the aircraft and weather surveillance functions are currently achieved by using fundamentally different antenna patterns—low-gain vertical “fan beams” for aircraft surveillance that are scanned in azimuth only, versus high-gain weather radar “pencil beams” that are scanned volumetrically at much lower update rates. Note also that, if expressed in consistent units, the power-aperture products of the weather radars significantly exceed those of the ASRs and ARSRs.

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[1] A limited number of ASR-9 are equipped with the Weather Systems Processor (Lay et al., 1990), which additionally provides a capability for low-altitude wind-shear detection.

	Sensitivity	Coverage		Angular Resolution		Waveform	Update Rate
		Range	Altitude	Az	El		
Terminal Aircraft Surveillance	1 m^2	60 nm	20,000'	1.4°	5.0°	>18 pulses PRI ~ 1 ms	5 s
En Route Aircraft Surveillance	2.2 m^2	250 nm	60,000'	1.4°	2.0°	>10 pulses PRI ~ 3 ms	12 s
Terminal Area Weather	-20 to -5 dBz	60 nmi	15,000'	1°	1°	>50 pulses PRI ~ 1 ms	60 s
National Scale Weather	-20 to -5 dBz	250 nmi	60,000'	1°	1°	~50 pulses PRI ~ 1 ms	300 s

Table 1. Summary of current U.S. surveillance radar capabilities.

In the next section, we present a concept design for MPAR and demonstrate that it can simultaneously provide the measurement capabilities summarized in Table 1. In Section 3 we present an MPAR network concept that duplicates the airspace coverage provided by the current multiple radar networks. Section 4 discusses technology issues and associated cost considerations. We conclude in Section 5 by discussing implications relative to future national weather and non-cooperative aircraft target surveillance needs.

2. RADAR DESIGN CONCEPT

2.1 *Antenna Configuration and Scan Patterns*

Four antenna faces are assumed so that azimuth scanning of ±45° is required. The angular resolution and power-aperture requirements of the weather function drive the size of each face. To compensate for beam squinting, a broadside beam-width of 0.7° is needed. Roughly 20,000 elements per face would be required and, at S-band, an 8-m diameter circular aperture (50 m^2). Antenna gain would be 46 dB or greater depending on scan angle. We assume each transmit-receive (TR) module can provide 10-W peak power, thus providing 200 kW total for the array.

Three different surveillance functions (terminal aircraft, en route aircraft, and weather) are assigned to separate frequency channels. These frequencies are within the same band, but are separated sufficiently that pulse transmission, reception, and processing can be accomplished independently. Pulse transmissions for the three functions will not be synchronized. Thus, isolated "dead gates" will be introduced into the coverage volumes of each function when energy is transmitted for one of the other functions. It is assumed that these blanked gates will shift around on successive volume updates so as to minimize operational impact. Figure 1 illustrates the pulse transmission sequence.

We show below that transmission of 5 μs, 200-kW peak-power pulses provides sufficient energy on target to realize the weather and en route aircraft surveillance functions. Five-to-one pulse compression is assumed to maintain the ~150-m range resolution of current surveillance radars. For the terminal aircraft surveillance function, a 1-μs uncoded pulse provides sufficient energy on target. This pulse can also be used as a "fill pulse" to measure weather at very short ranges.

The separate frequency channels allow for the formation of independent transmit beams and receive beam clusters separately for the different functions. High angular resolution can be maintained for all surveillance functions by using the full aperture for receive beam formation. Where needed, rapid volume scanning can be achieved by dynamically widening the transmit beam pattern so as to illuminate multiple resolution volumes concurrently.

Figure 2 depicts notional transmit and receive beam patterns appropriate for the various surveillance modes. Digital control and processing of the TR-elements is needed to generate these independent beams. Since, at any one time, the receive beams are clustered in relatively small angular intervals, an overlapped sub-array beamforming architecture (Herd et al., 2005) with digitization at the sub-array level can be used. As seen from Figure 2, the maximum number of concurrent beams in our concept is approximately 200, which sets a lower limit on the number of sub-arrays. For specificity, we will assume that 400 sub-array channels will be digitized to support synthesis of low-sidelobe (< 40 dB) receive beam patterns.

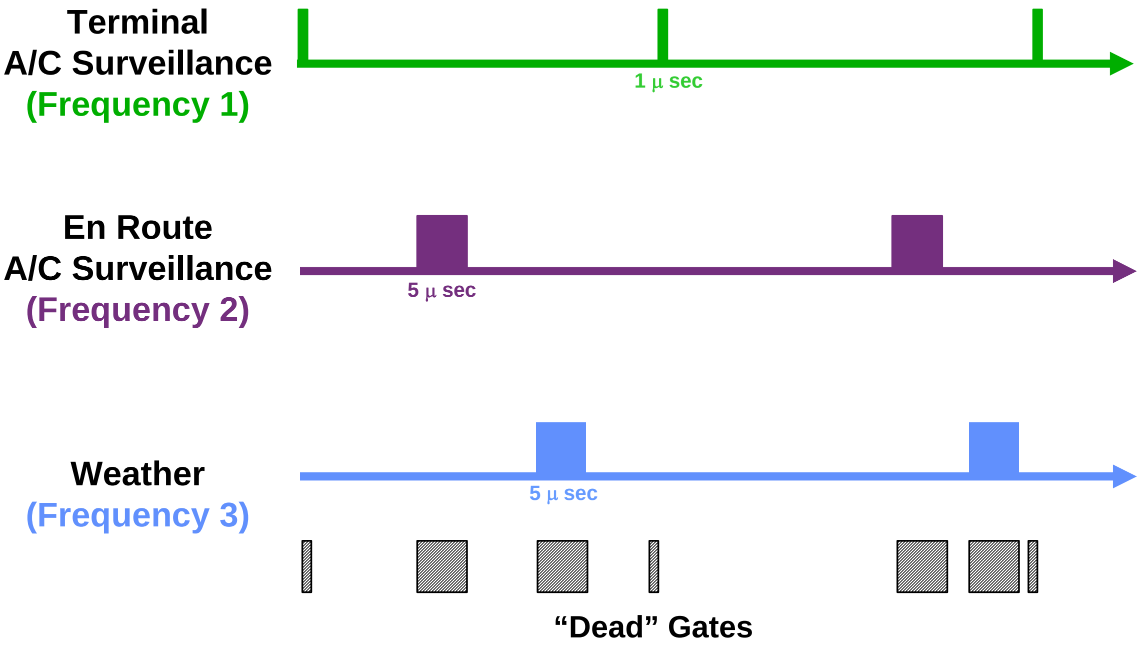


Figure 1. Pulse scheduling for MPAR.

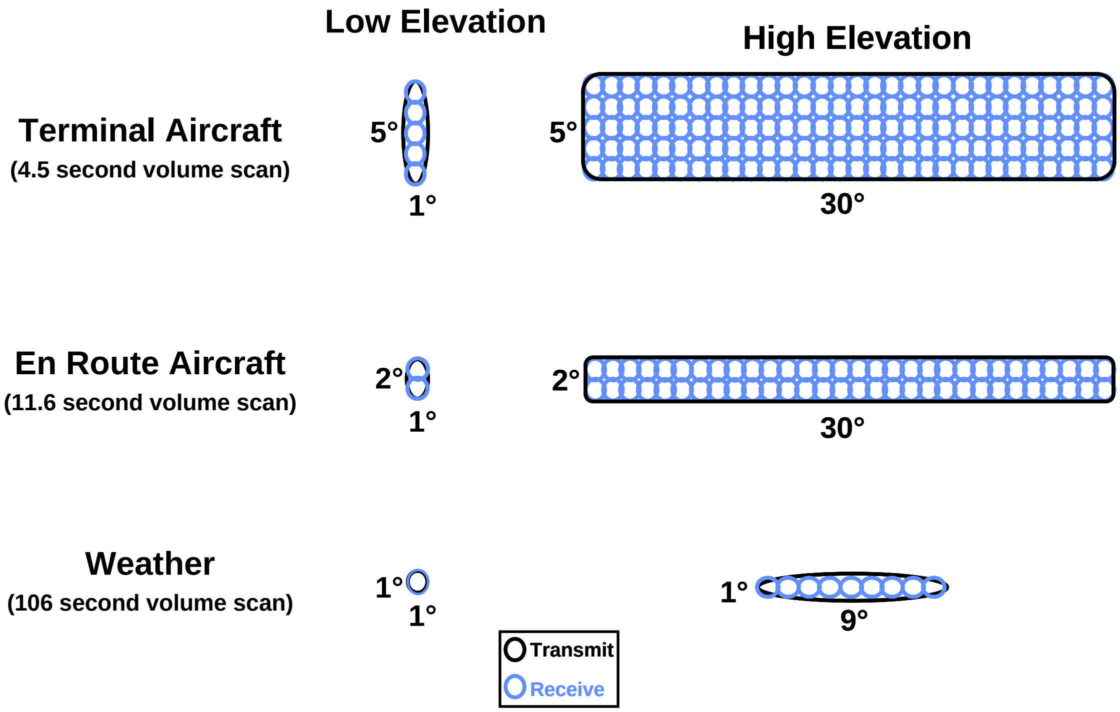


Figure 2. Notional beam patterns for multifunction radar surveillance modes.

Elevation Angle	Number of Dwells	CPI	PRI (s)	Time (s)	Number of Concurrent Azimuth Beams
0	90	18	0.001	1.62	1
5	90	18	0.001	1.61	1
10	89	18	0.001	0.80	2
15	87	18	0.001	0.12	13
20	85	18	0.001	0.05	30
25	82	18	0.001	0.05	30
30	78	18	0.001	0.05	30
35	74	18	0.001	0.04	30
40	69	18	0.001	0.04	30
45	64	18	0.001	0.04	30
50	58	18	0.001	0.03	30
				Total=4.46	

Table 2. MPAR scan timeline for terminal area aircraft surveillance.

To clarify the scanning concept, Table 2 presents an explicit timeline for the terminal aircraft surveillance function. We assume transmission using a 1^o (azimuth) by 5^o (elevation) beam, and reception using "stacked" 1^o x 1^o pencil beams. The first column ("Angle") is the lower edge of the 5^o transmit beam and "Number of Dwells" is the associated number of 1º azimuth dwells required. For each dwell, the ASR-9 transmitted waveform is assumed so that the coherent processing interval (CPI) utilizes 18 samples at an average pulse repetition interval (PRI) of 1 ms.

At higher elevation angles, it is possible to increase the scan rate by further spoiling the transmit beam pattern, since, for a fixed altitude ceiling, the maximum range requirement falls off as the cosecant of the elevation angle. The column "Number of Concurrent Azimuth Beams" shows the number of simultaneous 1^o azimuth beams across which the transmit energy can be spread while maintaining sufficient energy on target. This number has been capped at 30 to limit the number of beams that must be processed simultaneously. For this calculation, a maximum aircraft surveillance height of 15,000 m (49 kft) is assumed. The column labeled "Time" gives the scan time per 5^o elevation wedge and sums to 4.5 s for the entire volume. Thus, relative to the ASR-9, the MPAR terminal aircraft surveillance function would maintain update rate while providing significant capability benefits associated with 1^o elevation angle resolution. Total volume scan times derived from similar analysis for the en route aircraft and weather surveillance functions are shown in Figure 2.

2.2 *Power-Aperture Comparison*

Table 3 compares relevant power-aperture products between the concept MPAR and current surveillance radars. Note that the calculations are for worst-case antenna gain corresponding to a scan angle for the multi-function radar of 45^o. At broadside, the values would be 4 dB higher than listed. Overall, the concept multi-function radar provides essentially the same target sensitivity as current operational weather and en route surveillance radars with reasonable assumptions for element peak-power levels and duty cycle. Its power-aperture would be significantly greater than current ASRs, suggesting that a scaled-down "gap filler" could be used to provide additional low altitude surveillance where needed.

2.3 *Gap-Filler Radars*

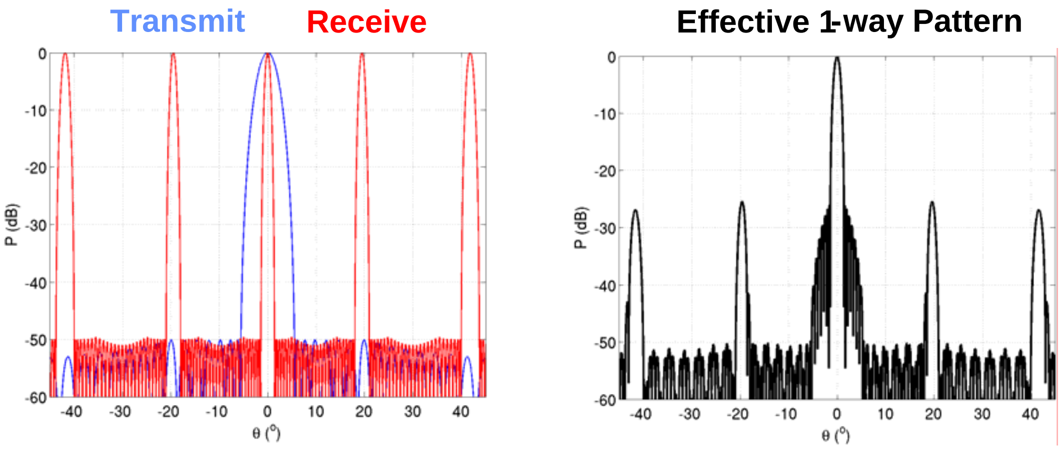
The siting analysis described in Section 3 indicates that half of the total number of radars required to replicate current airspace coverage would be devoted to surveillance below 10,000' altitude at relatively short ranges. For this, it would be inefficient to use the large aperture radar described above. A down-scaled MPAR, or "gap-filler", could provide aircraft surveillance out to about 30 nmi as well as weather surveillance and wind shear protection services at the airport.

Necessary power on target to detect a 1-m^2 aircraft at 30 nmi dictates an aperture consisting of approximately 2000 TR elements per face, a factor of 10 less than the system described above. If deployed as a filled circular array, however, this number of elements would result in a 2.2^o x 2.2^o beam, which is insufficient resolution for the surveillance functions under consideration. Monopulse techniques could be used to sharpen aircraft angular resolution, but these are problematic in the presence of multiple closely spaced targets and ground clutter. Furthermore, monopulse is not suitable for detection of distributed weather targets.

An alternate approach to achieving high angular resolution with a smaller number of array elements is to employ a dual-density array: a dense inner array at about half-wavelength spacing embedded within a much larger (in physical dimensions) sparse array at several wavelength spacing. The dense inner array is used on transmit to form a moderate-width beam with very low sidelobes. The sparse array is used to form much narrower receive beams. There are grating lobes on receive, but these are in the low-sidelobe region of the transmit beam. The resulting two-way

Function	Radar	Point Target $P_T G_T G_R \lambda^2$ (dB)	Weather Target $\frac{P_T G_T G_R \Delta\vartheta\Delta\phi}{\lambda^2}$ (dB)
Terminal Aircraft Surveillance	**ASR- 9**	**108**	
	MF RADAR	**120**	
En Route Aircraft Surveillance	**ARSR – 4**	**132**	
	MF RADAR	**129**	
Weather	**NEXRAD**		**171**
	TDWR		**173**
	MF RADAR		**170**

Table 3. Comparison of relevant power-aperture products.



- **66 x 66 elements total**
  Inner array: 44 x 44
- **Inner array spacing = λ/2**
- **Sparse array spacing = 3λ**
- **Aperture size = 8.7 m**

- **Beamwidth = 1.2°**
- **Effective Gain = 33 dB**
- **dBZ $_{min}$ (10 km) = 11 dBZ***
- **A/C RCS $_{min}$ (30 nmi) = 5 dBsm***

***10 W per element on average**

Figure 3: Example beam patterns and sensitivity for a dual-density active array.

beam pattern is dramatically narrower than the corresponding two-way pattern for the inner array alone, with only a modest increase in the number of elements.

Figure 3 shows a specific example where approximately 2000 elements are used in the inner array and an additional 2400 receive-only elements comprise the thinned outer array. The total aperture is 8.7 m in diameter. The resulting antenna pattern has a 1.2° main lobe and very acceptable -25-dB effective one-way sidelobes. The limitation to this approach is, of course, that relative to a filled aperture configuration, transmitted power is substantially lower as is effective two-way antenna gain. Sensitivity with 10-W peak power for the transmit elements (on average) and a 5-µs pulse is equivalent to 11 dBZ for weather targets at a range of 10 km. Although possibly adequate for precipitation mapping and many

Doppler measurement applications, this gap-filler configuration would be substantially less sensitive at short range than are current TDWR or NEXRAD systems.

3. MPAR NETWORK AIRSPACE COVERAGE

A second aspect of our study was to determine how many multi-function radars would be required to replicate airspace coverage provided by the current operational radar networks. To accomplish this, we developed a three-dimensional (3D) CONUS data base that defines current coverage capabilities for each of the surveillance functions we are considering: en route aircraft, terminal aircraft, national-scale weather, and terminal weather. For each grid point we determined whether an appropriate radar provides coverage and, if so, what available sensitivity and spatial resolution are provided. High-resolution digital terrain elevation data (DTED) were used to account for terrain effects in this analysis.

We used current NEXRAD locations as the initial site choice for the full-aperture MPAR described in Section 2. For radars located within approximately 50 km of large airports currently equipped with TDWR and/or ASR-9, we adjusted the MPAR site to be close enough to the airport to meet current siting criteria for the terminal radars. A total of 145 full-aperture MPARs so sited would provide near-seamless airspace coverage above 10,000 ft AGL, replicating the national scale coverage currently provided by the NEXRAD and ARSR networks. In addition, the terminal area weather and aircraft surveillance functions provided by TDWR and ASR would be duplicated at many airports. An additional 144 gap-filler MPARs as described in Section 2 could provide terminal-area weather and aircraft surveillance at remaining U.S. airports.

Figure 4 compares airspace coverage at 1000 ft AGL between current operational radar networks and the concept MPAR network. Differences are minimal and within the coverage areas, MPAR would meet or exceed current radar measurement capabilities—horizontal and vertical resolution, minimum detectable target cross section, and update rate—with one exception. As noted, the gap-filler MPAR would not have the sensitivity for very low cross-section wind-shear phenomena that is currently provided by the TDWR.

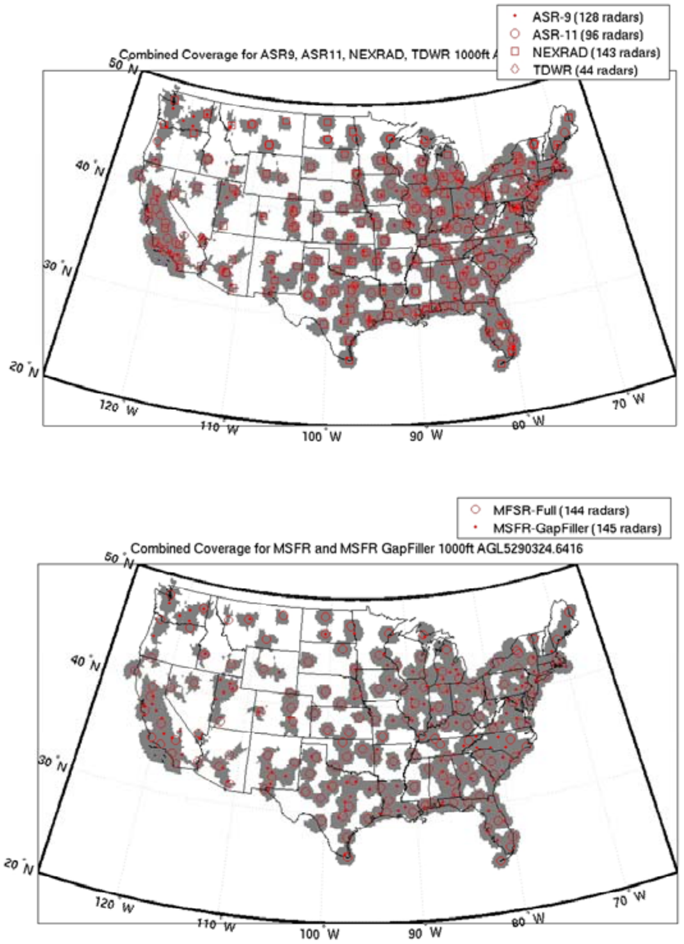


Figure 4. Airspace coverage at 1000 ft AGL provided by current U.S. surveillance radar networks (top) and conceptual MPAR network (bottom).

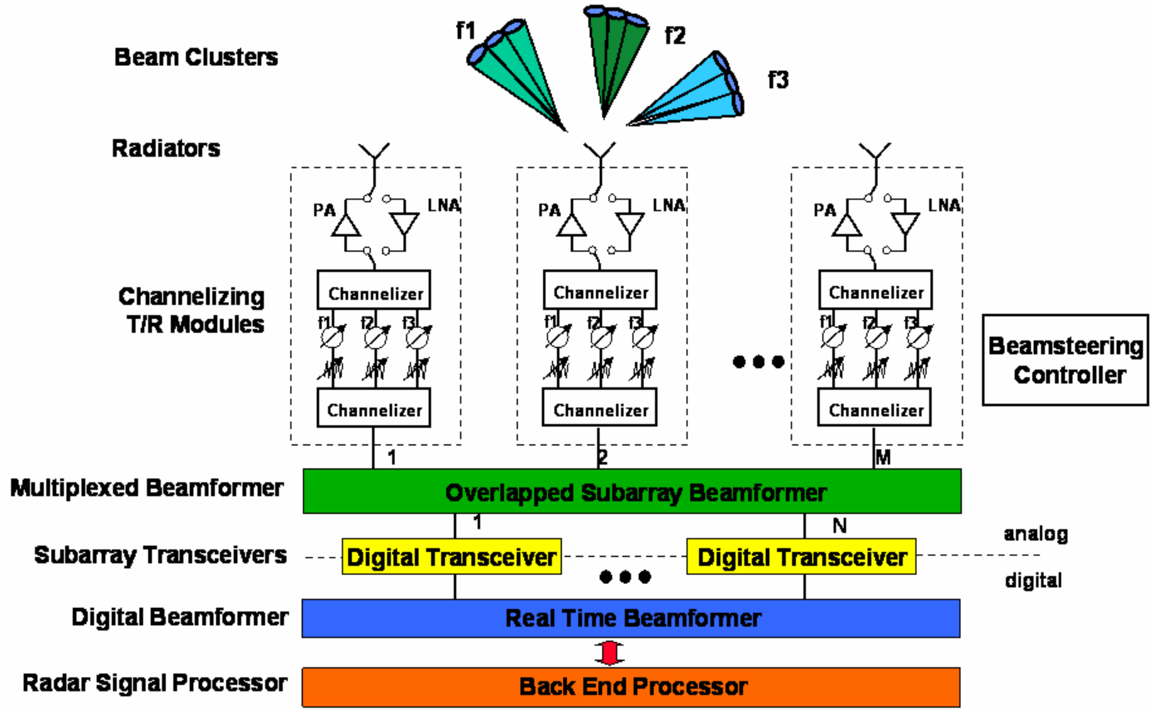


Figure 5. High-level MPAR architecture.

This analysis does not attempt to fully capture the considerations that go into actual site choices for operational radars. It is however, sufficient to support the contention that a significant reduction in the total number of radars needed to provide necessary weather and aircraft surveillance capabilities is possible. Services currently provided by over 500 radars could be duplicated using less than 300 MPARs. In addition, replacement of today's multiple, dissimilar radar types with a single architecture should considerably reduce logistics and maintenance costs.

4. TECHNOLOGY CONSIDERATIONS

Figure 5 depicts the major sub-systems of the requisite multi-function radar. The active array of TR elements is partitioned into "sub-arrays," which are controlled by analog circuitry. A digital input/output port for each sub-array allows the full array aperture to be employed in generating appropriate transmit patterns and clusters of narrow receiving beams. Each receive beam is post-processed through appropriate Doppler filters, parameter estimation algorithms, and target tracking algorithms.

4.1 *Transmit-Receive Elements*

A major cost driver in an active phased array system is the large number of TR modules. Each element of an active array has a TR module with a phase shifter, a low-noise receive amplifier (LNA), and a high-power transmit amplifier (HPA). In addition, the modules have DC power circuits and beam-steering control functions. In a multifunction radar system, there are additional components in every TR module to support the multiple modes. For example, a multiple beam system will require separate phase shifters for each independent pointing direction. This will further impact the cost, size, power consumption, thermal management, and control of the modules.

A key benefit at S band (2600-3950 MHz) is the availability of inexpensive RF components (phase shifters, LNAs, HPAs) due to the wireless market. The rapid proliferation of digital cellular telephones, digital communication systems, personal communication systems, wireless data, WiFI, and WiMAX systems has served to reduce critical component costs by an order of magnitude. As a result, the acquisition cost of a phased array is becoming a viable alternative to mechanically steered reflector antennas.

4.2 *Overlapped Sub-Array Beamformer*

Maximum flexibility for active-array antenna beam-forming is provided if each element is digitized. However, element-level digitization for a large array is unnecessary for most applications. A more effective approach is to partition the aperture into overlapping sub-arrays, whose elements are controlled via analog circuitry, combined and digitized to allow simultaneous beams to be formed digitally at the sub-array combination level. The spacing of the sub-arrays is significantly greater than one-half wavelength, resulting in grating lobes. Analog manifolds control the sub-array elements to produce a flat-topped pattern whose width is less than the spacing of the grating lobes. Thus the composite pattern provides concurrent, digitally formed clusters of narrow beams as illustrated in Figure 6.

4.3 *Digital Beamforming (DBF)*

Whether digitization takes place at the element level, the sub-array level, or after some amount of analog beamforming, the resulting digital output presents a sizeable processing task for beamforming. The concepts discussed in Section 2 dictate approximately 400 digital sub-arrays (50 TR-elements each) that are processed to form up to 220 simultaneous digital receive beams. Figure 7 shows a possible DBF design, in which all beams are computed concurrently. For each sub-array output, an analog-to-digital converter (ADC) samples the signal into a sequence of digital samples. A three-channel digital receiver recovers F1, F2, and F3 into three separate digital complex signal streams. Using the weights provided by the control host computer, the processor computes the requisite beams for each surveillance function.

For reasonable assumptions as to the bandwidth and spacing of the three frequency channels, we estimate the computational throughput of this DBF approach to be about 1 tera (10^{12}) operations per second. This is a significant challenge to an implementation that uses general-purpose programmable processors (e.g., microprocessors and digital signal processors (DSPs)), but would be tractable using field programmable gate arrays (FPGAs) and/or application-specific integrated circuits (ASICs). The 1200-channel interface between the digital receivers and beamforming units will be complex. The use of a bit-serial communication format will significantly reduce the connectivity at this interface. Lastly, the 220-beam output requires a communication bandwidth exceeding 1 gigabytes per second (GBPS). A wide communication channel will be essential to keep the clock frequency within a practical range.

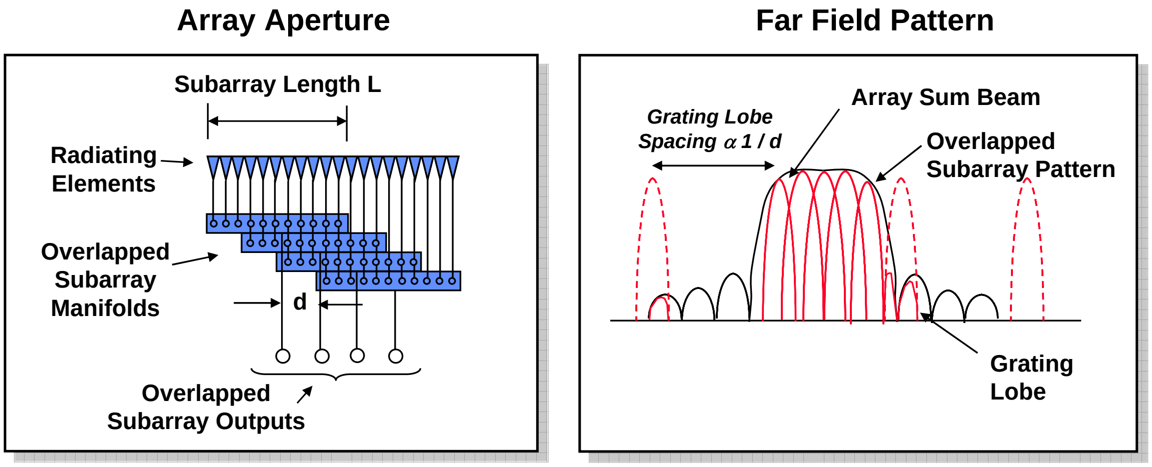


Figure 6. Overlapped sub-array concept.

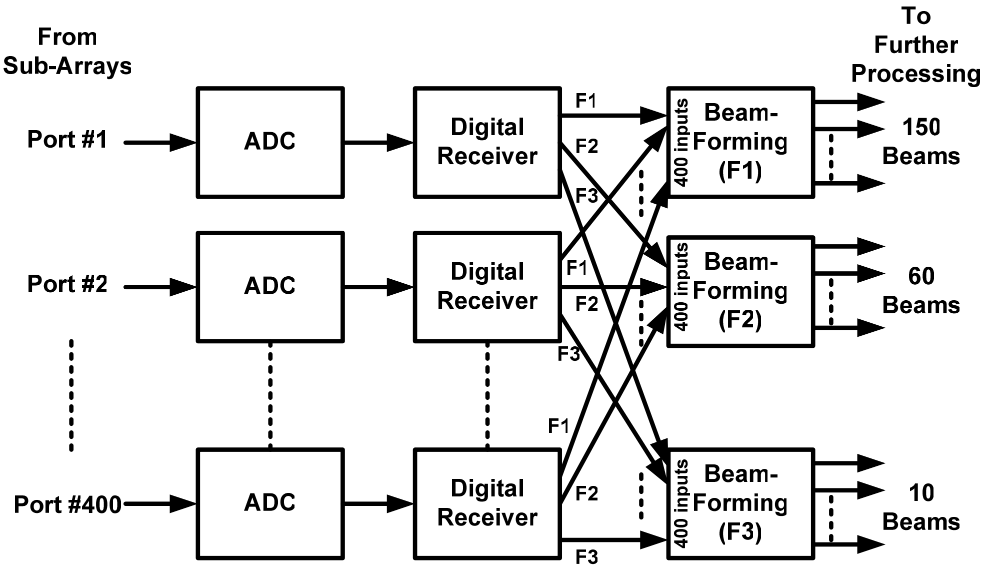


Figure 7: Block diagram of a fully parallel DBF design.

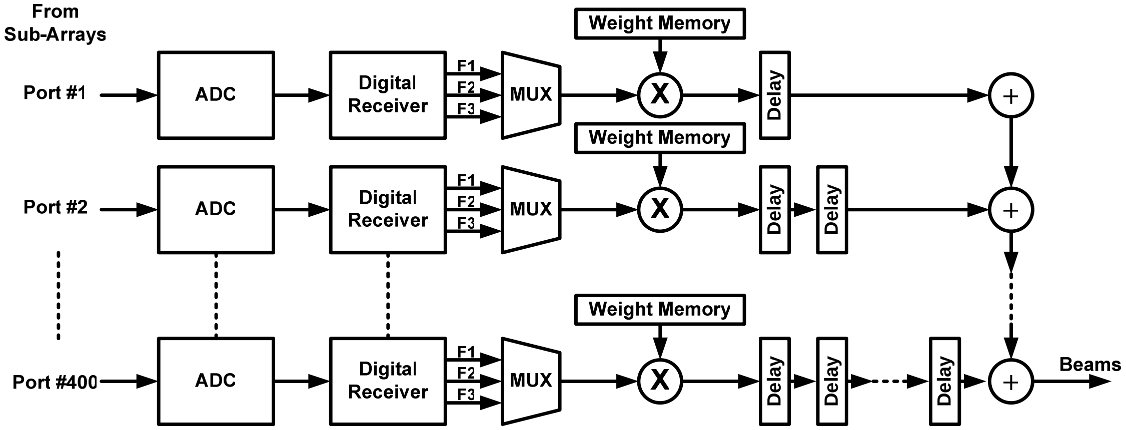


Figure 8: Block diagram of a systolic DBF design.

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The high computational throughput can be mitigated by reducing the parallelism of operations. Instead of computing each beam in an individual beamforming unit, a group of beams can be sequentially computed in the same unit. Figure 8 illustrates a systolic design that embodies this concept to the extreme, in which all the beams are computed sequentially. In addition to a much simplified interconnection requirement, the beam output bandwidth is also significantly reduced, since only one beam is produced at a time.

In this approach, the three signals (F1, F2, and F3) coming out of each digital receiver are sequentially multiplied with corresponding weights to form partial beams. Each partial beam is delayed with an amount according to its position in the summing chain. A 400 sub-array implementation will require a maximum of 400-cycle delay. The multiplication, delay, and addition can be readily implemented with FPGA technology.

4.4 *Aircraft Post Processing*

MPAR would support more selective antenna patterns and flexible scan strategies than current operational radars, thus potentially improving the quality of aircraft surveillance. However, the radar front end will incur a significant transformation in the flow and content of the data provided to the post-processing algorithms as depicted in Figure 9. New post-processing techniques will need to be developed to meet or exceed the performance of the legacy Moving Target Detection (MTD) (Karp and Anderson, 1981) air traffic control search radars. Examples are:

(i) The use of multiple beam clusters significantly expands the amount of data to be processed. An efficient and affordable open architecture must be defined that reduces acquisition cost by making appropriate use of commercial off-the-shelf solutions. This architecture must also enable technology refresh and the future insertion of new technology and algorithms.

(ii) Target detections will occur in multiple beams within each beam cluster requiring a new algorithm for correlation and interpolation to the single centroided target report needed for input to existing Air Traffic Control display systems. Also, since the merging of primary and beacon radar target reports cannot depend upon the azimuth and range registration advantages of collocated antennas, modified reinforcement algorithms will also need to be developed.

(iii) A selective elevation pattern will allow the altitude of detected targets to be estimated, motivating the development of a new highly simplified clutter elimination algorithm.

(iv) Automatic Dependent Surveillance Broadcast (ADS-B) will replace beacon radars in some regions. Efficient scan strategies should be developed to allow phased arrays radars to confirm and augment ADS-B reports.

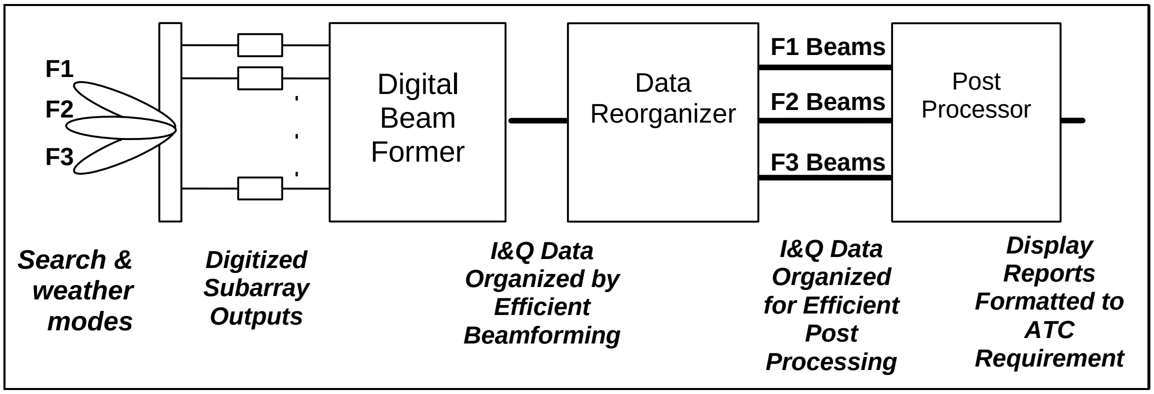

Figure 9: Aircraft detection post-processing block diagram for MPAR.

4.5 *Weather Post Processing*

As with the aircraft surveillance functions, the weather scan strategies and data processing algorithms should be optimized to exploit the capabilities of a phased-array radar. Significant optimization of scan time can be realized by:

(i) Removing the requirement for 360° coverage from a single aperture.
(ii) Exploiting the ability to form concurrent receiving beams along radials where either signal-to-noise ratio is uniformly high or maximum range coverage is limited.
(iii) Utilization of "decorrelated pulse-pairs" for radials where long CPIs are not required for clutter suppression or spectral-domain weather echo processing.

Such techniques can significantly increase the volume scan update rate and/or improve data quality by allowing for longer dwell time along "high value radials" (e.g., low-elevation tilts for boundary layer wind mapping).

Spaced aperture techniques can be applied by separately processing received signals from halves or quadrants of the full aperture. Such techniques can potentially be used to estimate the cross-range wind component and 3D turbulence fields. Meteorological surveillance requirements for high power-aperture, angular resolution, and long dwell times are likely to have a significant influence on system architecture and cost. It is essential that significant effort go into the evaluation and demonstration of efficient phased-array radar designs and processing approaches for this application.

5. SUMMARY AND DISCUSSION

We have described a concept for a next-generation multifunction phased array radar (MPAR) network that could provide high-quality weather and primary aircraft surveillance capabilities. The authors are optimistic that continuing advances in the critical technology areas described in Section 4 will make MPAR a technically and economically effective replacement strategy for current radar networks.

A key operational consideration is the future role of primary radar aircraft surveillance in U.S. airspace. The Air Traffic Control system is increasingly moving towards cooperative surveillance technologies (secondary or "beacon" radars and/or GPS-based dependent surveillance). It is likely, however, that there will always be a need for backup primary surveillance to handle the possibility of non-compliant intruders in controlled airspace. DoD and DHS currently rely on FAA primary radars as a major input to their airspace monitoring activities; it seems highly likely that an equivalent capability will be needed for the foreseeable future.

In any scenario, an operational weather radar network remains a critical observing system for the nation. We noted that the power-aperture and angular resolution requirements for weather surveillance significantly exceed corresponding requirements for aircraft surveillance. Thus MPAR will allow the future weather radar network to additionally provide high quality aircraft surveillance services at modest cost. This fact should be considered in discussions about future national surveillance architectures.

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