THE NEXT-GENERATION MULTIMISSION U.S. SURVEILLANCE RADAR NETWORK

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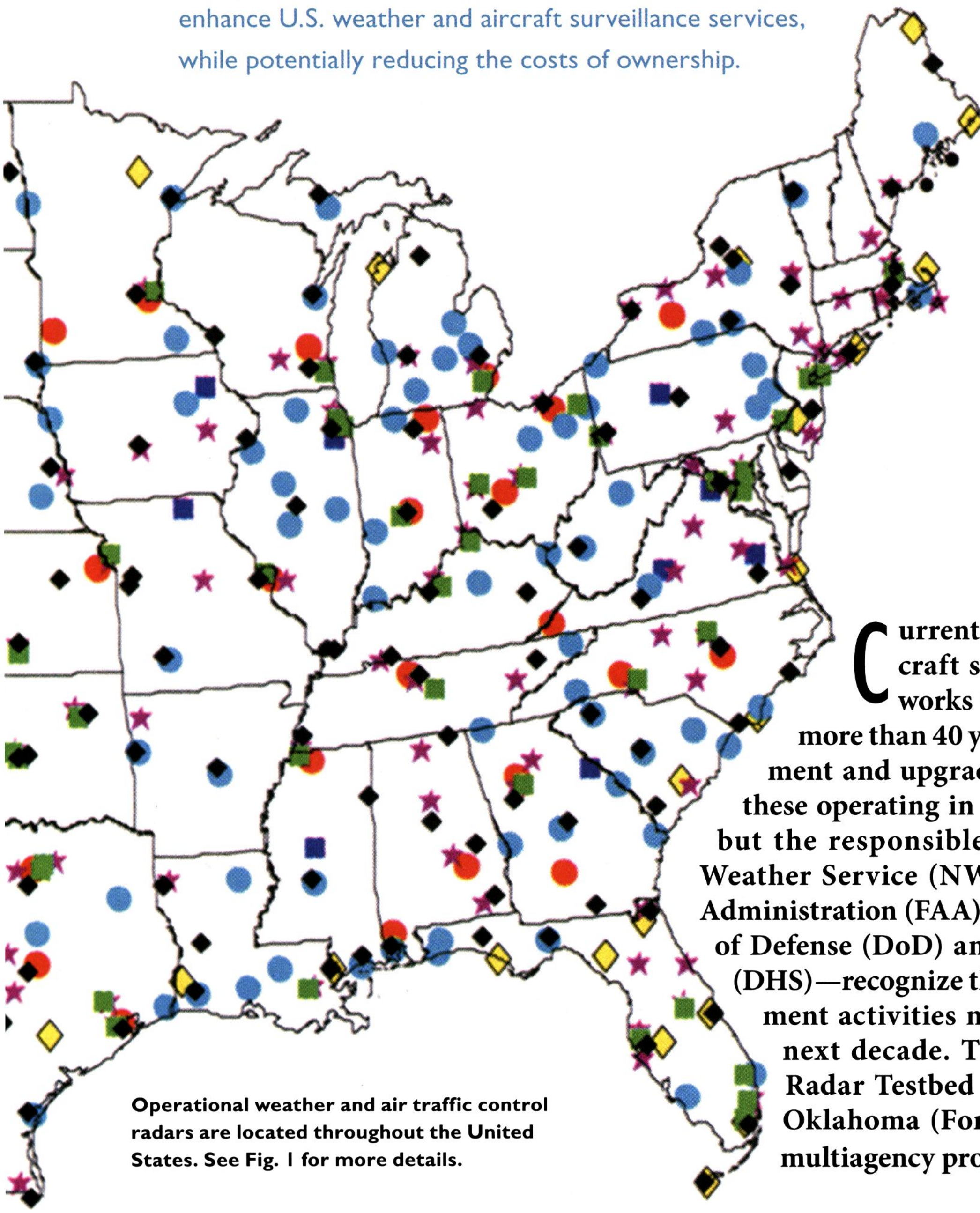
A single network of multimission phased-array radars can enhance U.S. weather and aircraft surveillance services, while potentially reducing the costs of ownership.



Operational weather and air traffic control radars are located throughout the United States. See Fig. 1 for more details.

Current U.S. weather and aircraft surveillance radar networks vary in age from 10 to more than 40 years. Ongoing sustainment and upgrade programs can keep these operating in the near to mid-term, but the responsible agencies—National Weather Service (NWS), Federal Aviation Administration (FAA), and the Departments of Defense (DoD) and Homeland Security (DHS)—recognize that large-scale replacement activities must begin during the next decade. The National Weather Radar Testbed (NWRT) in Norman, Oklahoma (Forsyth et al. 2007), is a multiagency project demonstrating ▶

operational weather measurements capability enhancements that could be realized using electronically steered phased-array radars as a replacement for the current Weather Surveillance Radar-1988 Doppler (WSR-88D). FAA support for the NWRT and related efforts (Benner et al. 2007; Weber et al. 2007) address air traffic control (ATC) and homeland defense surveillance missions that could be simultaneously accomplished using the agile-beam capability of a phased array weather radar network.

In this paper, we discuss technology issues, operational considerations, and cost trades associated with the concept of replacing current national surveillance radars with a single network of multimission phased-array radars (MPAR). We begin by describing the current U.S. national weather and aircraft surveillance radar networks and their technical parameters. The airspace coverage and surveillance capabilities of these existing radars provide a starting point for defining requirements for the next-generation airspace surveillance system. We next describe a conceptual MPAR high-level system design and our initial development and testing of critical subsystems. This work, in turn, has provided a solid basis for estimating MPAR costs for comparison with existing, mechanically scanned operational surveillance radars. To assess the numbers of MPARs that would need to be procured, we present a conceptual MPAR network configuration that duplicates airspace coverage provided by current operational radars. Finally, we discuss how the improved surveillance capabilities of MPAR could be utilized to more effectively meet the weather and aircraft surveillance needs of U.S. civil and military agencies.

U.S. OPERATIONAL RADAR NETWORKS.

The WSR-88D or Next-Generation Weather Radar (NEXRAD) was developed by Unisys Corporation in the 1980s, using technical specifications developed by scientists at the National Severe Storms Laboratory and other organizations (Serafin and Wilson 2000). The radar operates at 10-cm wavelength, utilizes a 1° transmit and receive beam, and transmits uncoded 750-kW pulses with selectable durations of 1.6 or 4.7 μs. NEXRAD is fully coherent to support ground-clutter suppression and weather Doppler spectrum moment estimation. One-hundred-fifty-six NEXRADs are deployed within the United States. NEXRAD data and derived products are disseminated to NWS personnel at Weather Forecast Offices (WFOs), the FAA, and a variety of private and media weather service providers. The NEXRAD network's key attributes include national-scale coverage, operation at a nonattenuating wavelength, and connectivity to essentially all operational weather personnel dealing with public and aviation weather services.

Terminal Doppler Weather Radar (TDWR) was developed in the late 1980s in response to a series of commercial aircraft accidents caused by low-altitude wind shear (Evans and Turnbull 1989). The radar was manufactured by Raytheon using technical specifications developed by the FAA, Lincoln Laboratory, and the National Center for Atmospheric Research (NCAR). Because spectrum availability at 10-cm wavelength was limited by in-place airport surveillance radars and NEXRAD, TDWR operates at 5 cm. TDWR employs a 0.5° pencil beam in order to reduce mainlobe illumination of ground targets as it scans for wind shear at low elevation angles. The radar transmits uncoded 1-μs, 250-kW pulses. Its sensitivity to volume-filling precipitation particles is very close to that of NEXRAD. TDWR is deployed operationally at 45 large U.S. airports. Because of TDWR's siting near major metropolitan areas, its twofold angular resolution improvement relative to NEXRAD, and its aggressive ground-clutter suppression algorithms, there is increasing interest in the use of its data for applications beyond the immediate airport vicinity. NWS has established a program to access data from all TDWRs and to process these data in the appropriate Weather Forecast Offices as an adjunct to NEXRAD (Istok et al. 2007).

In addition to these meteorological radars, the U.S. Government operates multiple surveillance radar networks for ATC services. Two-hundred-and-thirty-three airport surveillance radars (ASRs) operate at 10-cm wavelength and utilize a doubly curved reflector to detect aircraft returns in range–azimuth space by using a 1.4° (azimuth) × 5° (elevation) cosecant-squared beam. Modern ASRs—the Westinghouse-manufactured ASR-9 and the Raytheon-manufactured ASR-11—provide parallel data-processing chains that

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display calibrated maps of precipitation reflectivity as sensed by their vertically integrating beams. Thirty-four ASR-9 radars are equipped with the Weather Systems Processor (WSP; Weber and Stone 1995), which additionally detects low-altitude wind shear and provides 0–20-min forecasts of future thunderstorm locations.

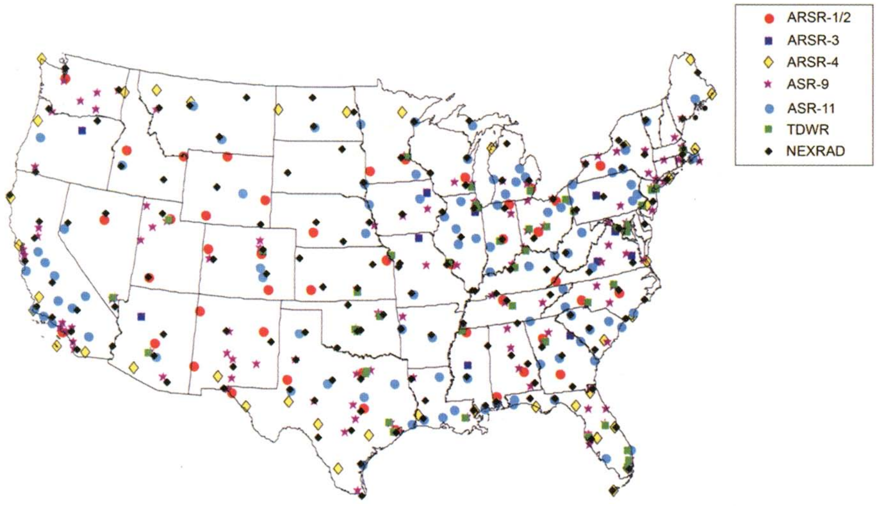

FIG. 1. Locations of U.S. operational weather and air traffic control radars.

One-hundred-one air-route surveillance radars (ARSRs) operate at 30-cm wavelength and provide national-scale primary aircraft surveillance. The ARSRs currently in operation date back to the ARSR-1 and ARSR-2 systems deployed in the 1960s. The DoD and DHS have recently assumed responsibility for operation, maintenance, and upgrades to the ARSR network, although technical support is still subcontracted to the FAA. The most modern ARSR (the Westinghouse-developed ARSR-4) employs a phased primary feed that supports the formation of an elevation receive stack of 2° pencil beams. A weather-processing channel derives precipitation reflectivity estimates from these beams. The NWS is actively pursuing the ingestion of both ASR and ARSR-4 weather data as a "gap filler" for the NEXRAD network (Istok et al. 2005).

Figure 1 shows the locations of the U.S. operational radars described above. TDWR and ASRs are deployed predominantly at commercial airports near medium- to large-sized U.S. cities. NEXRAD and the ARSR networks are designed to provide nationwide coverage, and as such are deployed on a more regular grid. In many cases however, NEXRAD and ARSR radars are located relatively close to TDWRs and/or ASRs.

Table 1 summarizes technical capabilities of the radar systems described above. In the absence of vali-

TABLE 1. Capabilities of current U.S. operational surveillance radars. Note that the wavelength dependence of maximum detection range is different for aircraft and weather targets. Note also that although TDWR employs a 0.5° physical pencil beam, its signal processor coherently integrates pulses acquired across 1° azimuth.

	Maximum detection range		Coverage		Angular resolution		Waveform	Scan period
	Aircraft 1 m²	Weather 0 dBZ	Range	Altitude	Azimuth	Elevation		
Terminal Area Aircraft Surveillance (ASR-9/11)	60 nmi	12 nmi	60 nmi	20,000 ft	1.4°	5.0°	>18 pulses PRI ~0.001 sec	5 s
En Route Aircraft Surveillance (ARSR-4)	205 nmi	5 nmi	250 nmi	60,000 ft	1.4°	2.0°	>10 pulses PRI ~0.001 sec	12 s
Terminal Area Weather (TDWR)	195 nmi	100 nmi	60 nmi	20,000 ft	1.0°	0.5°	~50 pulses PRI ~0.001 sec	180 s
En Route Weather (NEXRAD)	210 nmi	85 nmi	250 nmi	50,000 ft	1.0°	1.0°	~50 pulses PRI ~0.001 sec	>240 s

dated multiagency surveillance performance requirements, these serve as a starting point for defining capability requirements for a next-generation surveillance radar network. 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 that the sensitivity and angular resolution of the weather radars either equal or exceed that of both the terminal and long-range aircraft surveillance radars. A phased-array radar replicating the power-aperture product of current operational weather radars can support aircraft volume search and tracking modes "for free" if its agile beams can provide the rapid scan needed for these missions. The next section presents an MPAR concept that simultaneously satisfies all measurement capabilities listed in Table 1.

MPAR CONCEPTUAL DESIGN. A conceptual MPAR design was described by Weber et al. (2005). Figure 2 repeats the architectural overview presented there, and Table 2 details specific parameters of the radar. The 2.7–2.9-GHz operating band is a current NWS–FAA surveillance band and provides an excellent technical operating point with respect to wavelength dependencies for precipitation cross section, pathlength attenuation, and range-Doppler ambiguity challenges.

The radar is taken to consist of four planar active arrays, each of which scans a 90° quadrant. Each face contains 20,000 transmit–receive (TR) modules at half-wavelength spacing. These can form a 1° pencil beam (smaller at broadside), thus meeting[1] the angular resolution requirements of today's operational weather radars. As shown in Fig. 2, the transmit–receive modules utilize parallel bandpass filters to channel signals into three separated frequency channels within the 2.7–2.9-GHz band. Separate amplitude and phase weightings applied to these channels allow for the formation and steering of three simultaneous but independent beam clusters. Notionally, two of these channels would be devoted to volumetric weather and aircraft surveillance. The third channel could be employed to track and characterize features of special interest, such as unidentified aircraft targets or areas of severe weather.

The overlapped subarray beam former combines received signals from the TR modules such that its outputs can be digitized and processed to form a cluster of multiple, parallel receive beams for each frequency channel (Herd et al. 2005). In angular volumes, where the full sensitivity of the radar is not required, the transmit beam pattern can be spoiled (i.e., broadened in azimuth and/or elevation by changing the distribution of the amplitude and phase weights applied to the array) so as to illuminate multiple resolution volumes. The clusters of digitally formed full-resolution receive beams can thereby support more rapid scanning while maintaining the inherent angular resolution provided by the array. Use of the multichannel TR modules and overlapped subarray beam former to achieve

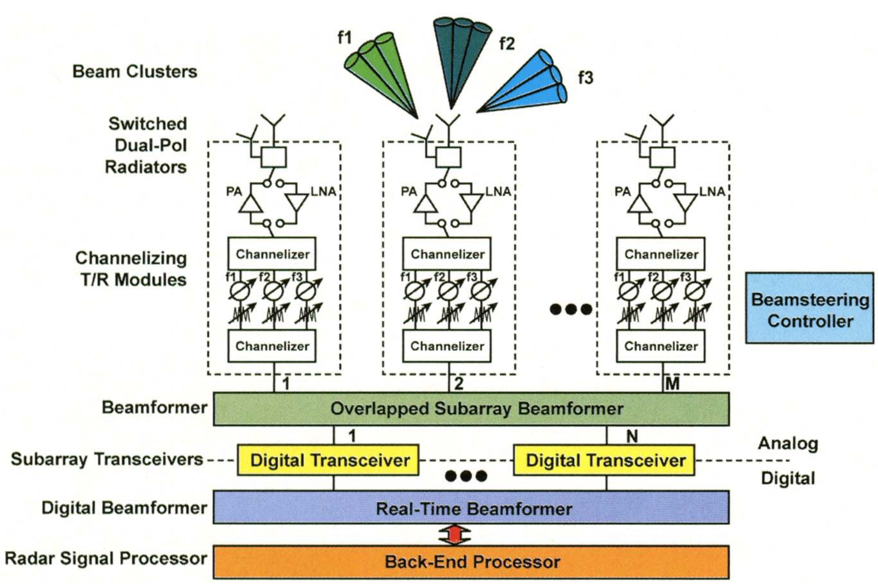

FIG. 2. MPAR architecture overview: "M" is the total number of TR modules (20,000) on each of four faces of the radar; "N" is the total number of digital transceivers (300–400).

[1] As noted previously, TDWR employs a 0.5° pencil beam to reduce ground clutter illumination during low-elevation-angle scanning. MPAR could achieve equivalent or better clutter suppression with a somewhat broader beam by adaptively steering above strong clutter sources and/or generating nulls in its elevation pattern directed at these sources.

Table 2. Concept MPAR parameters

Transmit–receive modules	Wavelength (frequency)	10 cm (2.7–2.9 GHz)
	TR-element peak power	1–10 W
	Bandwidth (per channel)	1 MHz
	Frequency channels	3
	Pulse length	1–100 μs
Active array (four-faced, planar)	Diameter	8 m
	TR-elements per face	20,000
	Beamwidth	
	• broadside	0.7°
	• @ 45°	1.0°
	Gain	>46 dB
Architecture	Overlapped subarray	
	• No. subarrays	300–400
	• Max No. concurrent beams	~160

necessary weather and aircraft surveillance timelines is discussed in Weber et al. (2005).

TRANSMIT PEAK POWER AND PULSE COMPRESSION. A key cost-containment strategy for MPAR is the use of low-peak-power, commercially manufactured power amplifiers in the TR modules. Designs for 1- and 8-W peak-power TR modules have indicated that parts costs scale roughly linearly with peak power. For a given aircraft or weather target size, the signal amplitude returned to an active array radar is proportional to the product $P_T L N^3$, where P_T is the peak radiated power for the TR modules, L is pulse length, and N is the number of TR modules. Given this dependency, required sensitivity can be achieved in a cost-effective manner by utilizing low-peak-power TR modules and by increasing, as necessary, the duration of the transmitted pulses (using pulse compression to maintain the required range resolution) and/or the number of TR modules in the array. Pulse compression is a well-established approach for achieving necessary energy on target for aircraft search radars, and has recently been demonstrated to be fully acceptable for weather radar (O'Hora and Bech 2005).

Figure 3 compares minimum detectable weather reflectivity versus range for the terminal Doppler weather radar and for an MPAR utilizing either 1- or 10-W peak-power TR modules and a pulse length necessary to match TDWR sensitivity (100 or 10 μs, respectively). It is assumed that pulse compression is used to maintain TDWR's 150-m range resolution, and that corresponding resolution 1-μs "fill pulses" are used to provide coverage at the short ranges eclipsed during transmission of the long pulse. The obvious drawback to the use of very low peak-power TR modules is the loss of sensitivity at ranges approaching the minimum range of the long-pulse-coverage annulus. As peak power is reduced, the required long pulse length is increased, correspondingly increasing the maximum coverage range for the low-energy fill pulse. Given weather's range^{-2} (or aircraft range^{-4}) echo strength dependence, this increase in required fill-pulse range coverage has a significant impact on worst-case sensitivity for the radar.

Figure 4 shows the dependence of minimum detectable weather reflectivity at two specific ranges on TR module peak power and long (compressed) pulse duration. The most stressful performance goal is for the relatively short-range airport wind shear detection function, which dictates the capability to detect "dry wind shear" phenomena (reflectivity factor as low as –15 dBZ; see Wilson et al. 1984) out to the range corresponding to short-to-long pulse transition. The

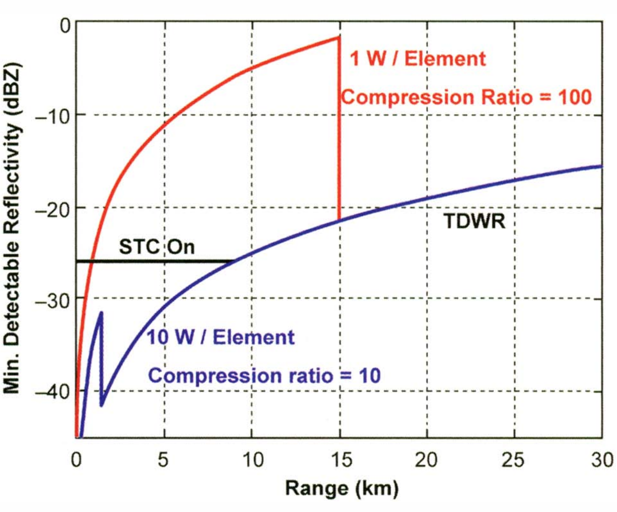

Fig. 3. Minimum detectable weather reflectivity versus range for TDWR (black) and MPAR using 1-W peak-power TR modules and a 100-μs pulse length (red), and for MPAR using 10-W peak-power modules and a 10-μs pulse length (blue). TDWR uses a range-varying attenuator [sensitivity time control (STC)] to prevent its receiver from saturating on returns from weather or ground clutter at very short ranges.

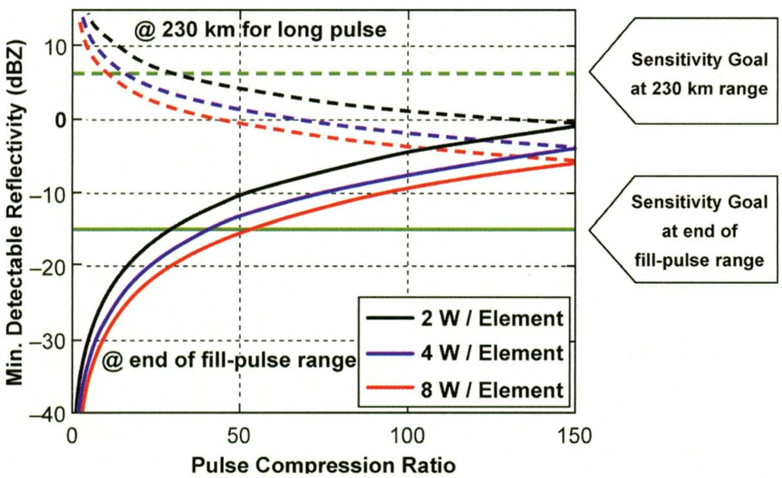

Fig. 4. MPAR minimum detectable weather reflectivity versus pulse compression ratio at the short–long pulse transition range (lower curves) and at a range of 230 km (upper curves). For the assumed 1-μs compressed pulse length, pulse compression ratio is equivalent to a long-pulse length.

sensitivity goal at long range is taken to be similar to that currently provided by either TDWR or NEXRAD. Given the MPAR aperture size and TR module peak power, these requirements dictate the minimum and maximum long-pulse durations as shown in Fig. 4. The figure indicates that even a 2-W peak-power TR module, using 30-μm pulses can marginally meet both requirements. The requirements are easily met by 4- or 8-W peak-power TR modules using long-pulse lengths between approximately 10 and 50 μs.

DUAL POLARIZATION. Improved capabilities for data quality control, quantitative precipitation measurement, and hydrometeor classification using dual-polarization weather radar have been well documented in the scientific literature (Ryzhkov et al. 2005). The WSR-88D network is being upgraded to include dual-polarization measurement capability (Saffle et al. 2007), and this must be taken as a requirement for any future national weather radar network. In addition, air traffic control radars currently allow for transmission of circularly polarized signals so as to increase the aircraft-to-precipitation clutter power ratio.

The MPAR architecture depicted in Fig. 2 includes a switch at the antenna element supporting linear horizontal or vertical signal transmission and reception. The two polarizations could be transmitted on alternating pulses and processed sequentially to generate a subset of the polarimetric parameters. Alternately, as will be done with the WSR-88D, the transmitted pulse could be at 45° from vertical with separate horizontal and vertical polarization receive paths provided for concurrent processing of both signal polarizations. The latter approach has advantages for dual-polarization product generation,[2] but would require duplication of receipt electronics in the TR modules, additional receiver channels, A/D converters, and digital beam former channels. We are currently assessing the trade-offs of an MPAR architecture supporting simultaneous versus sequential dual-polarization measurements.

Figure 5 illustrates a Lincoln Laboratory-designed, dual-polarized, stacked-patch antenna suitable for MPAR and measurements of its co- and cross-polarized patterns as a function of steering angle. The copolarized pattern is relatively flat across the ± 45° steering angle range, relevant for a four-faced array, and the cross-polarization rejection is 20 dB or

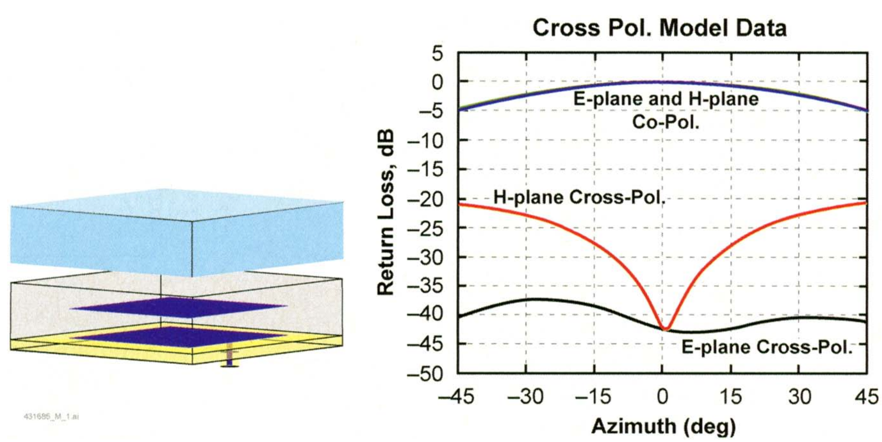

Fig. 5. Dual-polarized stacked-patch antenna configuration and co- and cross-polarized element radiation patterns versus steering angle. The E plane is the plane of polarization for the patch, and the H plane is perpendicular to the plane of polarization.

[2] These advantages would include the capability to transmit and receive circularly polarized signals for suppression of precipitation clutter in MPAR's aircraft surveillance modes. However, because MPAR would utilize narrow pencil beams for aircraft signal detection, precipitation clutter levels will already be significantly lower (~10 dB) than for today's aircraft surveillance radars.

greater. While this performance is acceptable, even better cross-polarized isolation could be obtained using a balanced-feed configuration. The balanced-feed configuration produces more symmetric current patterns in the antenna patch to better control the antenna's radiation patterns (Hanfling et al. 1989).

AIRSPACE COVERAGE. Today, a total of 510 government-owned weather and primary aircraft surveillance radars operate in the continental United States. To quantify the potential reduction in radar numbers, we developed a three-dimensional database that defines the current airspace coverage of these networks. High-resolution digital terrain elevation data were used to account for terrain effects. An iterative siting procedure was used to delineate MPAR locations that at least duplicate current coverage.

Figure 6 shows that a total of 334 MPARs can replicate the airspace coverage provided by today's networks. Approximately half (152) of these radars would be full-scale MPARs, as described in the preceding sections. These would provide both national-scale weather and aircraft surveillance (replacing the NEXRAD and ARSR networks), and wind shear protection services at large airports that today are provided by TDWR. The remaining 182 radars would be "terminal MPARs" ("T-MPAR"), needed to duplicate low-altitude airport surveillance radar coverage at smaller airports. The maximum-range requirement for T-MPAR would be significantly reduced because it would need to only cover the airspace beneath the radar horizon of the national-scale network. As discussed in Weber et al. (2005), T-MPAR would be a smaller-aperture, lower-cost radar employing the same scalable technology as the full-sized MPAR. It would provide both terminal aircraft surveillance and airport wind shear detection.[3]

[3] As noted in Weber et al. (2005) T-MPAR would not be as sensitive to low-reflectivity wind shear phenomena as is TDWR. T-MPAR would be deployed primarily at smaller airports where today, either wind shear protection services are not provided or are provided by the less capable ASR-9 Weather Systems Processor.

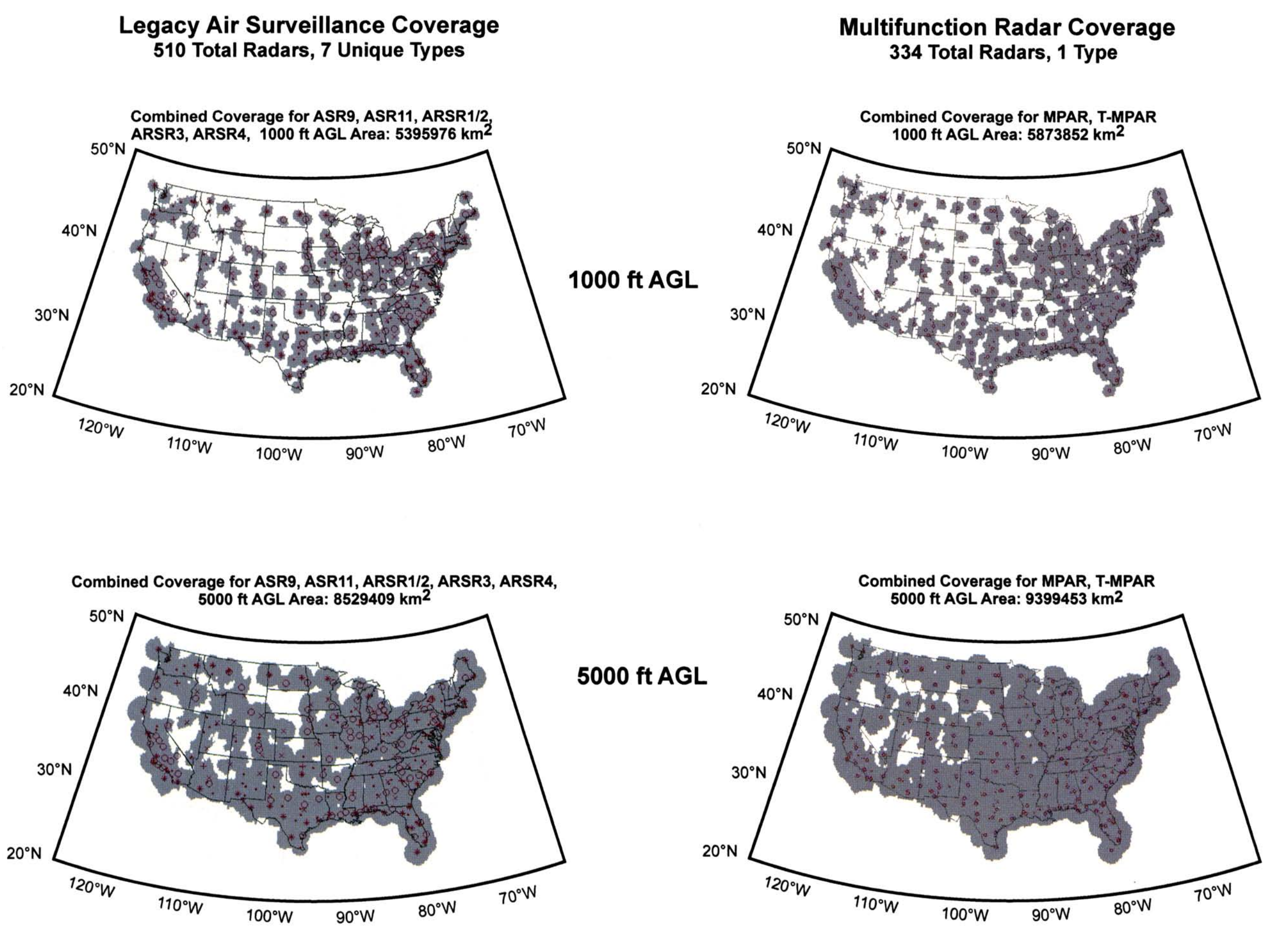

Fig. 6. Airspace coverage comparison between current U.S. operational radar networks (ASR-9, ASR-11, ARSR-1/2, ARSR-3, ARSR-4, NEXRAD, TDWR) and a conceptual MPAR network.

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

Based on our concept development work, Herd et al. (2007) have commenced detailed design of a scaled preprototype MPAR array that incorporates the required technologies. This design work is providing technical and cost details for the MPAR concept. As an example, Table 3 is a complete list of parts required for the 8-W peak-power TR module that will be used for the preprototype MPAR. (Because the preprototype array will have significantly fewer TR modules than an operational MPAR, higher-peak-power modules are being utilized in order to provide sufficient energy on target to demonstrate weather and aircraft surveillance functions.)

Similar preprototype designs have been developed for all of the MPAR subsystems shown in Fig. 2. Table 4 summarizes the resulting MPAR subsystem parts cost estimates. The tabulated numbers are normalized to a per-TR-module basis. MPAR preprototype cost estimates in the left-hand column are based on available technology, the higher-peak-power TR modules required for the preprototye, and small-quantity pricing for subsystem components. The costs in the right-hand column apply to a full-scale MPAR prototype that could be developed 3–5 yr hence. Cost reductions result from the use of lower-power (2 W) TR modules appropriate for the larger array, economies of scale, and new technologies expected to mature over the next 3 yr (Herd et al. 2007). Note that the cost estimates in Table 4 assume a switched polarization architecture. A simultaneous dual-polarized system will require twice the number of TR modules, transceivers, beam formers, and RF interconnects, effectively doubling the parts cost.

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

Clearly, the development of a comprehensive MPAR acquisition cost model will require that these preliminary parts costs estimates be integrated with corresponding costs for nonrecurring engineering, subsystem fabrication, system integration, and deployment. In the authors' opinion however, the favorable initial cost picture for MPAR based on current technology prices, coupled with expectations that essential components derived from the mass-market wireless and digital-processing industries will continue to decrease in price, indicate that active array multifunction radar technology is a promising option for next-generation U.S. weather and aircraft surveillance needs.

TABLE 3. Parts costs for dual-channel MPAR preprototype transmit–receive (TR) module.

Item	Quantity	Unit cost	Total cost
HPA	2	\$23.00	\$46.00
Bias	1	\$15.00	\$15.00
SP2T	3	\$4.00	\$12.00
LNA	1	\$1.69	\$1.69
BPF	1	\$3.00	\$3.00
Diplx	1	\$1.50	\$1.50
Vect Mod	3	\$2.14	\$6.42
Driver	1	\$2.50	\$2.50
Load	1	\$2.00	\$2.00
Board	1	\$25.00	\$25.00
			Total = \$115.11

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

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

1) simultaneous surveillance from each of the four antenna faces;
2) the ability to very rapidly cover higher-elevation angles by spoiling the transmit beam to cover a large angular volume in a single radar dwell period (Weber et al. 2005) (Angular resolution is maintained by digitally forming clusters of parallel pencil beams on receipt, using the overlapped subarray architecture. This approach exploits the fact that the maximum range to weather targets of interest at high elevation angles is small, thus reducing the energy on target requirement.);
3) agile beam capability, which enables "beam multiplexing" (Yu et al. 2007) and/or adaptive, rapid-update scanning of individual storm volumes of high operational significance.

Table 4. MPAR subsystem parts-cost model, based on preprototype array designs.

Component	Equivalent cost per element	
	Preprototype	Full-scale MPAR
Antenna element	$1.25	$1.25
T/R module	$115.00	$30.00
Power, timing, and control	$18.00	$18.00
Digital transceiver	$12.50	$6.25
Analog beamformer	$63.00	$15.00
Digital beamformer	$18.00	$8.00
Mechanical/packaging	$105.00	$25.00
RF Interconnects	$163.00	$40.00

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

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

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

Noncooperative aircraft surveillance. Today's operational ATC surveillance sensors do not measure altitude using the primary radar. Cooperative (beacon radar) techniques are used to obtain aircraft altitude and identification code. While cooperative surveillance is highly appropriate for ATC, it does not fully support airspace security needs. For this mission, the three-dimensional position and velocity of noncooperative targets must be accurately measured, and robust methods for determining target type (e.g., large or small airplane, birds, etc.) are needed.

MPAR's large vertical aperture can provide very useful measurement of target height. The digital array supports the use of a monopulse (e.g., Sherman 1984), which [for targets with a moderate-to-high signal-to-noise ratio (SNR)] can improve angular resolution approximately 20-fold relative to its 1° physical beam. Figure 7 compares MPAR's height measurement accuracy with that of existing ATC beacon radars. Although altitude accuracy is comparable with the beacon radars only at relatively short ranges (10–30 nmi), height estimates on the order of 1000 ft or better are still very useful for noncooperative target characterization. As seen from the figure, these are achievable over essentially the entire operational range of an MPAR.

Radar-based target identification is facilitated by high-range resolution (e.g., Mitchell and Westercamp 1999), that is, high bandwidth, and a large unambiguous Doppler interval [i.e., a high pulse-repetition frequency (PRF)] (e.g., Bell and Grubbs 1993). Figure 8 simulates a range-Doppler image of an aircraft exploiting high-range resolution and a large

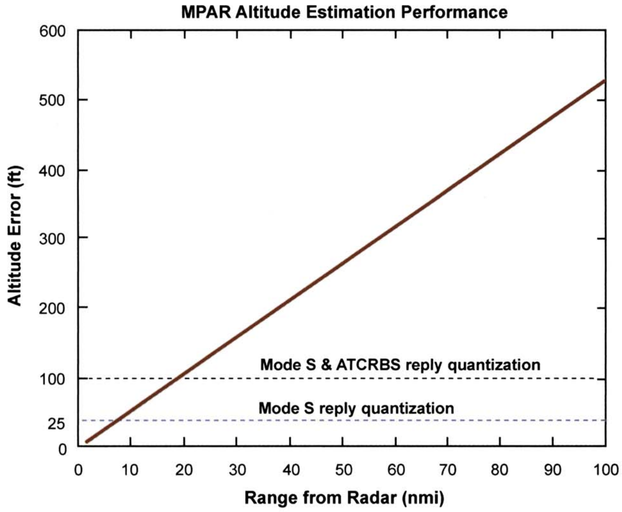

FIG. 7. MPAR height measurement accuracy vs. range. Twenty-to-one monopulse angle measurement improvement is assumed relative to the physical beamwidth. The horizontal lines show the accuracy provided using cooperative surveillance systems, such as the "Mode Select" and "ATC Radar Beacon System" ("ATCRBS") secondary radars. When interrogated by these radars, aircraft downlink their pressure altitude. The mode S message format supports a higher degree of precision than the older ATCRBS. ATCRBS is gradually to be phased out of use.

unambiguous Doppler interval to detect identifying signatures of the noncooperative aircraft. One of MPAR's three frequency channels could be utilized to track a noncooperative aircraft and illuminate it with special waveforms that support target characterization. Use of these wide-band and/or high-PRF waveforms might preclude simultaneous operation of MPAR's "standard" weather and aircraft surveillance modes. This would likely be operationally acceptable given that relatively short integration times would be needed to accomplish target identification, and the identification process would only need to be used intermittently.

Air traffic control. The FAA has stated that future ATC surveillance will be based on cooperative, high-accuracy aircraft position reports provided by the Automatic Dependent Surveillance Broadcast (ADS-B) system (Scardina 2002). Provision must be made, however, for the capability to verify that ADS-B position reports are valid and for ADS-B backup in the event of equipment failure. The FAA is evaluating various approaches to these needs, including maintaining existing primary or secondary radars, passive and active multilateration using the aircraft "squitter" signals, and independent aircraft-positioning estimates (e.g., from Loran or aircraft inertial navigation units).

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

MPAR and the Collaborative Adaptive Sensing of the Atmosphere concept. It is worth noting here the similarities and differences between MPAR and the Collaborative Adaptive Sensing of the Atmosphere (CASA) concept under investigation by McLaughlin et al. (2005). CASA envisions a dense network of small-aperture, low-cost weather radars that would significantly increase radar coverage in the lowest 3 km of the atmosphere (i.e., the planetary boundary layer). It is envisioned that, like MPAR, the CASA radars will use electronically scanned active array technology, and will minimize cost both by keeping transmitted peak power low and by exploiting wireless industry technology. As with MPAR, the CASA radars would be interconnected and thereby collaboratively scanned so as to optimize their utilization in fulfilling multiple operational missions.

Unlike MPAR, the CASA network concept involves a very large number of radars (more than 10,000 would be required to provide nationwide coverage down to 50-m altitude) and very small apertures to meet the per-radar cost goal of about \$0.5 million. The CASA radars would provide an approximately 2° beamwidth, a minimum detectable weather reflectivity goal of +15 dBZ, and surveillance to about 30-km range. This is roughly equivalent to the mean radar grid spacing.

The authors of this paper are engaged with the CASA development team and recognize the potentially significant operational advantages that could be realized with the dense radar network. (Indeed, the terminal MPAR concept described here recognizes the need for augmented low-altitude coverage in critical airspace.) As noted, substantial overlapping technology opportunities exist between the two concepts (e.g., ultra-low-cost TR modules, network-based collaborative scanning). We do not believe, however, that the CASA radar network could subsume all existing or future surveillance missions. For example, detection of some low-cross-sectional hazardous wind shear phenomena and mapping of

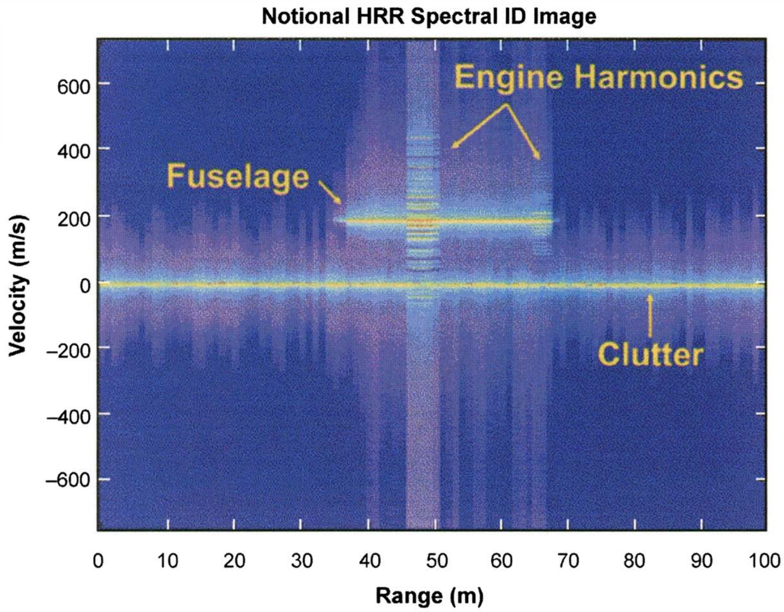

FIG. 8. Notional range Doppler image of an aircraft measured by a radar providing simultaneous high-range resolution and a large unambiguous Doppler interval.

"clear air" winds in the planetary boundary layer will be challenging for a very small aperture, low-peak-power radar, even at short ranges. Ongoing refinement of next-generation requirements for national weather and aircraft surveillance must continue, and radar and network design concepts must evolve to match these requirements.

SUMMARY. We have described a concept for a next-generation multimission 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 this paper will make MPAR a technically and economically effective replacement option for current radar networks.

To be fair, conventional weather and surveillance radar technology continues to improve. For example, O'Hora and Bech (2005) discuss the use of low-maintenance solid-state transmitters and pulse compression waveforms for weather surveillance; Torres et al. (2004) show how oversampling and whitening can increase scan rates and/or improve weather parameter estimates; and a number of vendors market "off the shelf" weather and surveillance radars whose performance capabilities compare favorably with the more expensive U.S. Government radars in use today. Thus, while the MPAR concept has many attractive features, its costs and benefits must be compared to other options.

A key consideration is the future role of primary radar aircraft surveillance in U.S. airspace. The air traffic control system is largely based on cooperative surveillance technologies (secondary or "beacon" radars today and GPS-based dependent surveillance in the future). It is likely, however, that there will always be a need for backup primary surveillance to handle the possibility of noncompliant 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 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 incremental cost. This fact should be considered in discussions about the future national surveillance architecture.

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