THE NEXT GENERATION MULTI-MISSION U.S. SURVEILLANCE RADAR NETWORK*

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Initially submitted on: February 2007

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*This work was sponsored by the Federal Aviation Administration under Air Force Contract FA8721-05-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government.

ABSTRACT

The U.S. Government operates seven distinct radar networks providing weather and aircraft surveillance for public weather services, air traffic control and homeland defense. In this paper, we describe a next-generation, multi-mission phased array radar (MPAR) concept that could provide enhanced weather and aircraft surveillance services with potentially lower life-cycle costs than multiple single-function radar networks. We describe current U.S. national weather and aircraft surveillance radar networks and show that -- by reducing overlapping airspace coverage -- MPAR could reduce the total number of radars required by approximately one-third. A key finding is that weather surveillance requirements dictate the core parameters of a multi-mission radar – airspace coverage, aperture size, radiated power and angular resolution. Aircraft surveillance capability can be added to a phased array weather radar at low incremental cost since the agile, electronically steered beam would allow the radar to achieve the much more rapid scan update rates needed for aircraft volume search missions, and additionally to support track modes for individual aircraft targets. We describe an MPAR system design that includes multiple transmit/receive channels and a highly-digitized active phased array to generate independently steered beam clusters for weather, aircraft volume-search and aircraft track modes. For each of these modes, we discuss surveillance capability improvements that would be realized relative to today's radars. The Federal Aviation Administration (FAA) has initiated the development of an MPAR "pre-prototype" that will demonstrate critical subsystem technologies and multi-mission operational capabilities. Initial sub-system designs have provided a solid basis for estimating MPAR costs for comparison with existing, mechanically scanned operational surveillance radars.

Capsule Summary

A single network of multi-mission phased array radars can enhance United States weather and aircraft surveillance services, while potentially reducing the costs of ownership.

1. Introduction

Current U.S. weather and aircraft surveillance radar networks vary in age from 10 to more than 40 years. Ongoing sustainment and upgrade programs can keep these operating in the near to mid term, but the responsible agencies-National Weather Service, 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 multi-agency project demonstrating operational weather measurement capability enhancements that could be realized using electronically steered, phased array radars as a replacement for the current WSR-88D. FAA support for the NWRT and related efforts (Benner et al, 2007, Weber et al., 2007) address Air Traffic Control 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 multi-mission 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. A key finding is that weather surveillance requirements dictate the core parameters of a multi-mission radar – airspace coverage, aperture size, radiated power and angular resolution. Aircraft surveillance capability can be added to a phased array weather radar at low incremental cost since the agile, electronically steered beam would allow the radar to achieve the much more rapid scan update rates needed for aircraft volume search missions, and additionally to support track modes for individual aircraft targets. 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.

2. U.S. Operational Radar Networks

The Weather Service Radar 88-D (WSR-88D, or 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 μsec. 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 National Weather Service (NWS) personnel at Weather Forecast Offices (WFO), 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 non-attenuating 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 Corporation 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 generates a 0.5° pencil beam and transmits uncoded, 1 μsec, 250 kW pulses. Its sensitivity to volume-filling precipitation particles is very close to that of NEXRAD. TDWR is deployed operationally at forty-five 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 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 Air Traffic Control (ATC) services. Two-hundred thirty three Airport Surveillance Radars (ASR) 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) by 5° (elevation) cosecant-squared beam. Modern ASRs—the Westinghouse-manufactured ASR-9 and the Raytheon-manufactured ASR-11—provide parallel data processing chains that display to terminal controllers calibrated maps of the intensity of precipitation as sensed by their vertically integrating beams. Thirty-four ASR-9 radars are equipped with the Weather Systems Processor or WSP (Weber and Stone, 1995), which additionally detects low-altitude wind shear and provides zero-to-twenty-minute forecasts of thunderstorm future location.

One hundred one Air Route Surveillance Radars (ARSR) operate at 30cm 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 Departments of Defense (DoD) and the Department of Homeland Security (DHS) have recently assumed responsibility for operation, sustainment, 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 quantitative precipitation reflectivity estimates from these beams. The NWS is actively pursuing ingest 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 validated multi-agency 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 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 it’s agile beams can provide the rapid scan needed for these missions. The next section presents a multi-mission phased array radar (MPAR) concept that simultaneously satisfies all measurement capabilities listed in Table 1.

3. 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, path-length attenuation, and range-Doppler ambiguity challenges.

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

The overlapped sub-array beamformer 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 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 multi-channel TR modules and overlapped subarray beamformer to achieve necessary weather and aircraft surveillance timelines is discussed in Weber et al. (2005).

4. Transmit Peak Power and Pulse Compression

A key cost-containment strategy for MPAR is the use of low peak-power, commercially manufactured power amplifiers in the TR-modules. Point designs for 1 W and 8 W peak-power TR-modules have indicated that parts costs scale roughly linearly with peak-power. 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 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 usec respectively). It is assumed that pulse compression is used to maintain TDWR’s 150 m range resolution, and that corresponding-resolution 1 usec “fill pulses” are used to provide coverage at the short ranges eclipsed 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's 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 summarizes the MPAR trade space relative to TR-module peak power and long (compressed) pulse duration. The most stressing 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 sensitivity goal at long range is taken to be similar to that currently provided by 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 figure 4. The figure indicates that even a 2 W peak power TR-module, using 30 usec pulses can marginally meet both requirements. The requirements are easily met by 4 W or 8 W peak-power TR-modules, using long-pulse lengths between approximately 10 and 50 usec.

5. 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, 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 Figure 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^o 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 but would require duplication of receive electronics in the TR-modules, additional receiver channels, A/D converters and digital beamformer channels. We are currently assessing the trade-offs of an MPAR architecture supporting simultaneous versus sequential dual-polarization measurements.

Figure 5 illustrates a Lincoln-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 co-polarized pattern is relatively flat across the +/- 45^o steering angle range relevant for a four-faced array, and the cross-polarization rejection is 30 dB or greater. While this performance is acceptable, even better cross-pol isolation could be obtained using a balanced feed configuration to better control the antenna’s current patterns.

6. Airspace Coverage

Today, a total of 510 Government-owned weather and primary aircraft surveillance radars operate in the CONUS. To quantify the potential reduction in radar numbers, we developed a three-dimensional data base that defines the current airspace coverage of these networks. High-resolution digital terrain elevation data were used to account for terrain effects. An iterative siting procedure was used to delineate MPAR locations that at least duplicate current coverage. Figure 6 shows that 334 MPARs can replicate the airspace coverage provided by today's networks. Coverage above 5,000 ft AGL would be near seamless, replicating the national scale weather and aircraft coverage currently provided by the NEXRAD and ARSR networks. Approximately half of the MPARs are necessary to duplicate low-altitude coverage at airports that today is provided by TDWR and airport surveillance radars. The maximum-range requirement for these "Terminal MPARs" would be significantly reduced because they need only cover airspace beneath the radar horizon of the national-scale network. As discussed in Weber et al. (2005), Terminal MPAR would be a smaller-aperture, lower cost radar employing the same scalable technology as the full-sized MPAR.

7. Cost Model

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

Based on our concept development work, Herd et al. (2007) have commenced detailed design of a scaled "pre-prototype" MPAR array that incorporates the required technologies. This design work is providing technical and cost details for the MPAR concept. As an example, Table 3 is a complete list of parts required for the 8 Watt peak power TR-module that will be used for the pre-prototype MPAR. (Because the pre-prototype 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 pre-prototype designs have been developed for all of the MPAR sub-systems shown in Figure 2. Table 4 summarizes the resulting MPAR subsystem parts-cost estimates. The tabulated numbers are normalized to a per-TR-module basis. MPAR pre-prototype cost estimates in the left hand column are based on available technology, the higher peak power TR-modules required for the pre-prototype 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 to 5 years hence. Cost reductions result from the use of lower power (2 Watt)

TR-modules appropriate for the larger array, economies-of-scale, and new technologies expected to mature over the next three years (Herd et al. [2007]).

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

Clearly, the development of a comprehensive MPAR acquisition cost model will require that these preliminary parts cost estimates be integrated with corresponding costs for non-recurring engineering, sub-system 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.

8. 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.

8.1 Weather Surveillance

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

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

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

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

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

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

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

8.2 Non-Cooperative Aircraft Surveillance

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

MPAR's large vertical aperture can provide very useful measurement of target height. The digital array supports the use of monopulse (e.g., Sherman, 1984) which – for targets with moderate to high SNR --can improve angular resolution approximately 20-fold relative to its 1^0

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 feet or better are still very useful for non-cooperative 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. high PRF) (e.g., Bell and Grubbs, 1993). Figure 8 simulates a range-Doppler image of an aircraft exploiting high-range resolution and a large unambiguous Doppler interval to detect identifying signatures of the non-cooperative aircraft. One of MPAR's three frequency channels could be utilized to track a non-cooperative aircraft and illuminate it with special waveforms that support target characterization. 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.

8.3 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 multi-lateration using the aircraft "squitter" signals, and independent aircraft positioning estimates (e.g. from Loran or aircraft inertial navigation units).

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

9. Summary

We have described a concept for a next-generation multi-mission 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 strategy for current radar networks.

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 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 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.

10. References

Alexander, C. R., and J. Wurman, 2005: The 30 May 1998 Spencer, South Dakota, storm. Part I: The structural evolution and environment of the tornadoes. *Mon. Wea. Rev.*, **133**, 72-96.

Benner, W., G. Torok, M. Batista-Carver, and T. Lee, 2007: MPAR program overview and status. Preprints, *23rd Conf. on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology*, San Antonio, TX, Amer. Meteor. Soc., http://ams.confex.com/ams/pdfpapers/117051.pdf.

Bell, M. R., and R. A. Grubbs, 1993: JEM modeling and measurement for radar target identification. *IEEE Trans. Aerosp. Electron. Syst.*, **29**, 73-87.

Bluestein, H. B., C. C. Weiss, and A. L. Pazmany, 2003: Mobile Doppler radar observations of a tornado in a supercell near Bassett, Nebraska, on 5 June 1999. Part I: Tornado genesis. *Mon. Wea. Rev.*, **131**, 2954-2967.

Carbone, R. E., M. J. Carpenter, and C. D. Burghart, 1985: Doppler radar sampling limitations in convective storms. *J. Atmos. Oceanic Technol.*, **2**, 357-361.

Crook, A., 1994: Numerical simulations initialized with radar-derived winds. Part I: Simulated data experiments. *Mon. Wea. Rev.*, **122**, 1189-1203.

Crook, A., and J. D. Tuttle, 1994: Numerical simulations initialized with radar-derived winds. Part II: Forecasts of three gust-front cases. *Mon. Wea. Rev.*, **122**, 1204-1217.

Doviak, R. J., G. Zhang, and T.-Y. Yu, 2004: Crossbeam wind measurements with a phased array Doppler weather radar: Theory. *Proc. IEEE Radar Conf.*, Philadelphia, PA, IEEE, 312–316.

Evans, J., and D. Turnbull, 1989: Development of an automated windshear detection system using Doppler weather radar. *Proc. IEEE*, **77**, 1661-1673.

Forsyth, D. E., J. F. Kimpel, D. S. Zrnic, R. Ferek, J. F. Heimmer, T. McNellis, J. E. Crain, A. M. Shapiro, R. J. Vogt, and W. Benner, 2007: Update on the National Weather Radar Testbed (phased-array). Preprints, *23rd Conf. on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology*, San Antonio, TX, Amer. Meteor. Soc., http://ams.confex.com/ams/pdfpapers/119631.pdf.

Herd, J. S., S. M. Duffy, and H. Steyskal, 2005: Design considerations and results for an overlapped subarray radar antenna. *Proc. IEEE Aerospace Conf.*, Big Sky, MT., IEEE, 1–6.

Herd, J., S. Duffy, M. Vai, F. Willwerth, and L. Retherford, 2007: Preliminary multifunction phased array radar (MPAR) preprototype development. Preprint, *23rd Conf. on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology*, San Antonio, TX, Amer. Meteor. Soc.

Istok, M. J., P. Pickard, R. Okulski, R. E. Saffle, and B. Bumgarner, 2005: NWS use of FAA radar data—progress and plans. Preprints, *21rd Conf. on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology*, San Diego, CA, Amer. Meteor. Soc., http://ams.confex.com/ams/pdfpapers/85759.pdf.

Istok, M. J., M. A. Fresch, A. D. Stern, R. E. Saffle, B. R. Klein, N. Shen, D. J. Stein, III, Y. Song, and W. M. Blanchard, 2007: Future Terminal Doppler Weather Radar (TDWR) products for NWS operations. Preprints, *23rd Conf. on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology*, San Antonio, TX, Amer. Meteor. Soc., http://ams.confex.com/ams/pdfpapers/117743.pdf.

Mitchell, R. A., and J. J. Westerkamp, 1999: Robust statistical feature based aircraft identification. *IEEE Trans. Aerosp. Electron. Syst.*, **35**, 1077-1094.

O'Hora, F., and J. Bech, 2005: Operational use of pulse compression in weather radar. Preprints, *32nd Conf. on Radar Meteorology*, Albuquerque, NM, Amer. Meteor. Soc., http://ams.confex.com/ams/pdfpapers/96015.pdf.

Ryzhkov, A. V., T. J. Schuur, D. W. Burgess, P. L. Heinselman, S. E. Giangrande, and D. S. Zrnic, 2005: The Joint Polarization Experiment: Polarimetric rainfall measurements and hydrometeor classification. *Bull. Amer. Meteor. Soc.*, **86**, 809-824.

Saffle, R. E., M. J. Istok, G. S. Cate, 2006: NEXRAD product improvement—expanding science horizons. Preprint, *22nd Int. Conf. on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology*, Atlanta, GA, Amer. Meteor. Soc. http://ams.confex.com/ams/pdfpapers/104223.pdf.

Saffle, R. E., M. J. Istok, and G. Cate, 2007: NEXRAD product improvement—update 2007. Preprints, *23rd Conf. on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology*, San Antonio, TX, Amer. Meteor. Soc., http://ams.confex.com/ams/pdfpapers/117819.pdf.

Serafin, R. J., and J. W. Wilson, 2000: Operational weather radar in the United States: Progress and opportunity. *Bull. Amer. Meteor. Soc.*, **81**, 501-518.

Scardina, J., 2002: Overview of the FAA ADS-B link decision. Tech. Rep., FAA, Washington, DC, 14 pp., www.faa.gov/asd/ads-b/06-07-02_ADS-B-Overview.pdf.

Shapiro, A., P. Robinson, J. Wurman, and J. Gao, 2003: Single-Doppler velocity retrieval with rapid-scan radar data. *J. Atmos. Oceanic Technol.*, **20**, 1758-1775.

Sherman, S. M., 1984: *Monopulse Principles and Techniques*. Artech House, Norwood, MA, 363 pp.

Weber, M. E., and M. L. Stone, 1995: Low altitude wind shear detection using airport surveillance radars. *IEEE Aerosp. Electron. Syst. Mag.*, **10**, 3-9.

Weber, M., J. Cho, J. Flavin, J. Herd, and M. Vai, 2005: Multi-function phased array radar for U.S. civil-sector surveillance needs. Preprint, *32nd Conf. on Radar Meteorology*, Albuquerque, NM, Amer. Meteor. Soc. http://ams.confex.com/ams/pdfpapers/96905.pdf.

Weber, M., J. Cho, J. Herd, and J. Flavin, 2007: Multifunction Phased Array Radar: Technical synopsis, cost implications and operational capabilities. Preprints, *23rd Conf. on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology*, San Antonio, TX, Amer. Meteor. Soc., http://ams.confex.com/ams/pdfpapers/116588.pdf.

Wilson, J. W., R. D. Roberts, C. Kessinger, and J. McCarthy, 1984: Microburst wind structure and evaluation of Doppler radar for airport wind shear detection. *J. Climate Appl. Meteor.*, **23**, 898-915.

Yu, T.-Y., M. B. Orescanin, C. D. Curtis, D. S. Zrnic, and D. E. Forsyth, 2007: Optimization of weather update time and data quality using phased-array radar. Preprint, *23rd Conf. on Interactive Information Processing Systems for Meteorology, Oceanography, and Hydrology*, San Antonio, TX, Amer. Meteor. Soc., http://ams.confex.com/ams/pdfpapers/116982.pdf.

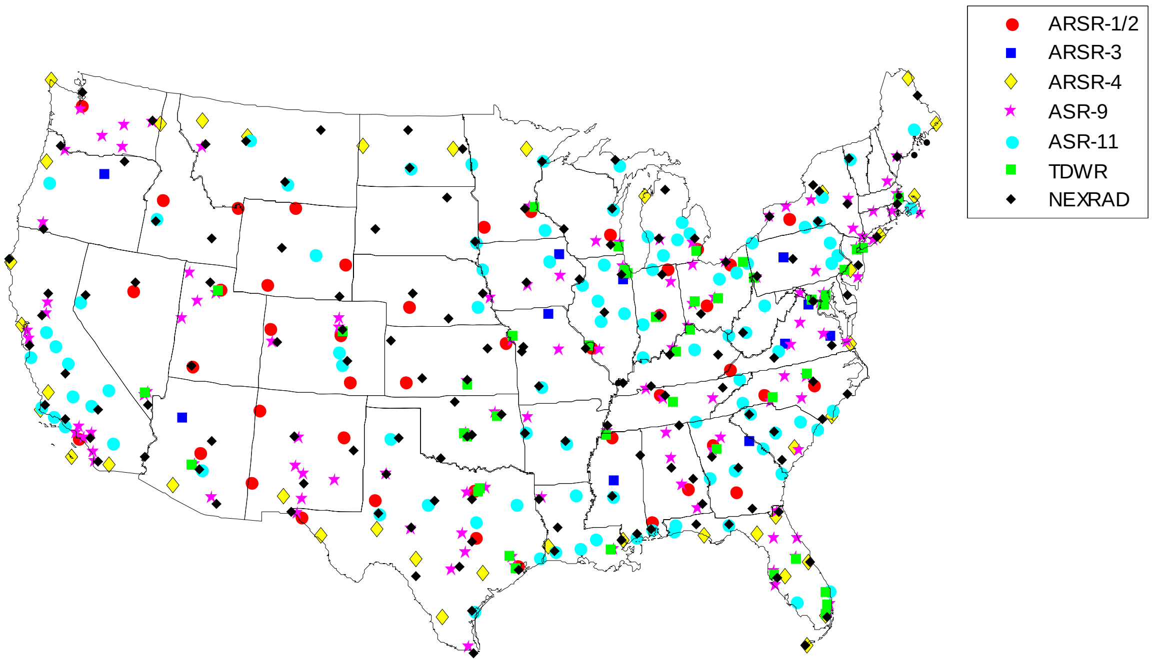


Figure 1: Locations of U.S. operational weather and air traffic control radars.

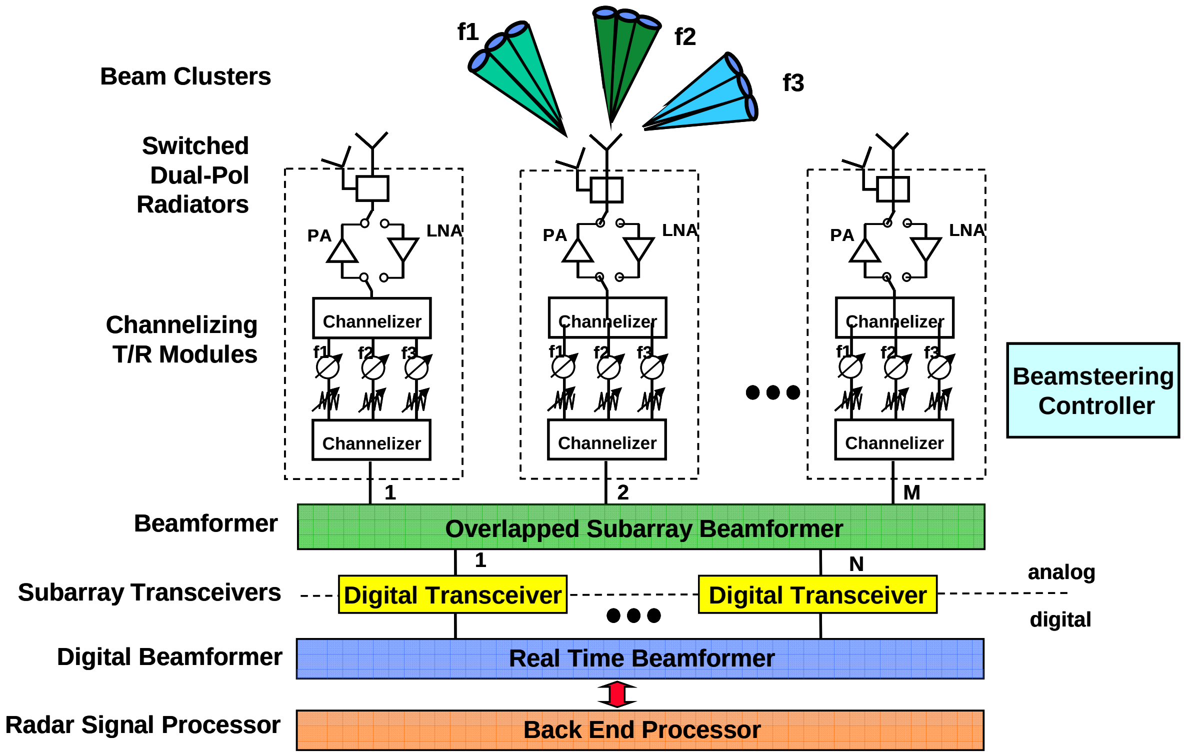


Figure 2. MPAR architecture overview.

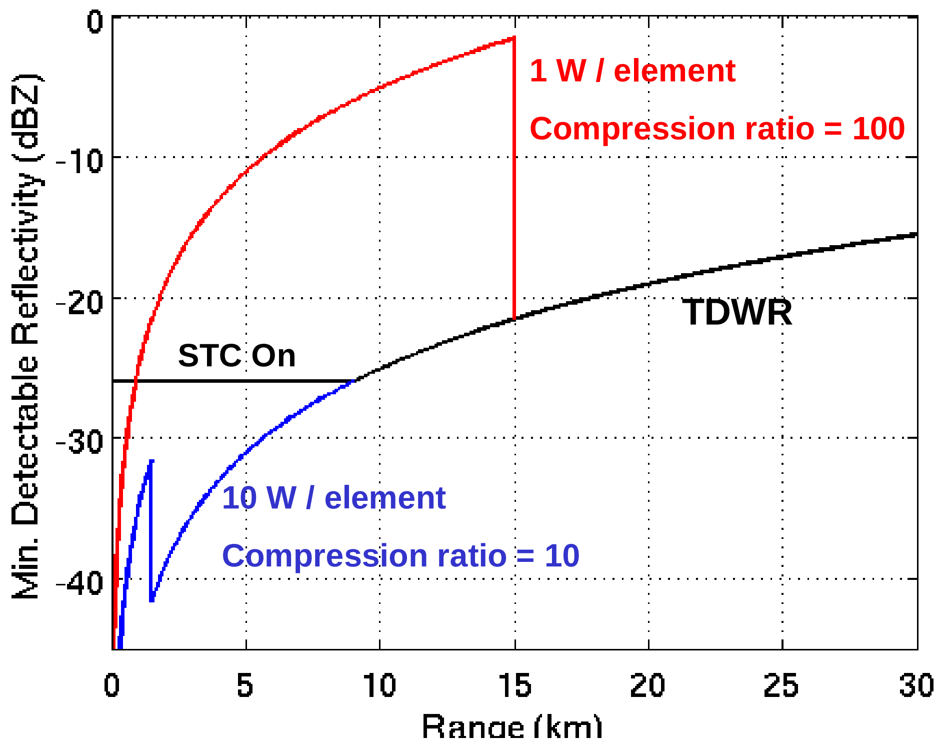


Figure 3. Minimum detectable weather reflectivity versus range for TDWR (black) and for MPAR using 1 W peak-power TR-modules and a 100 usec pulse length (red), and for MPAR using 10 W peak-power modules and a 10 usec pulse length (blue).

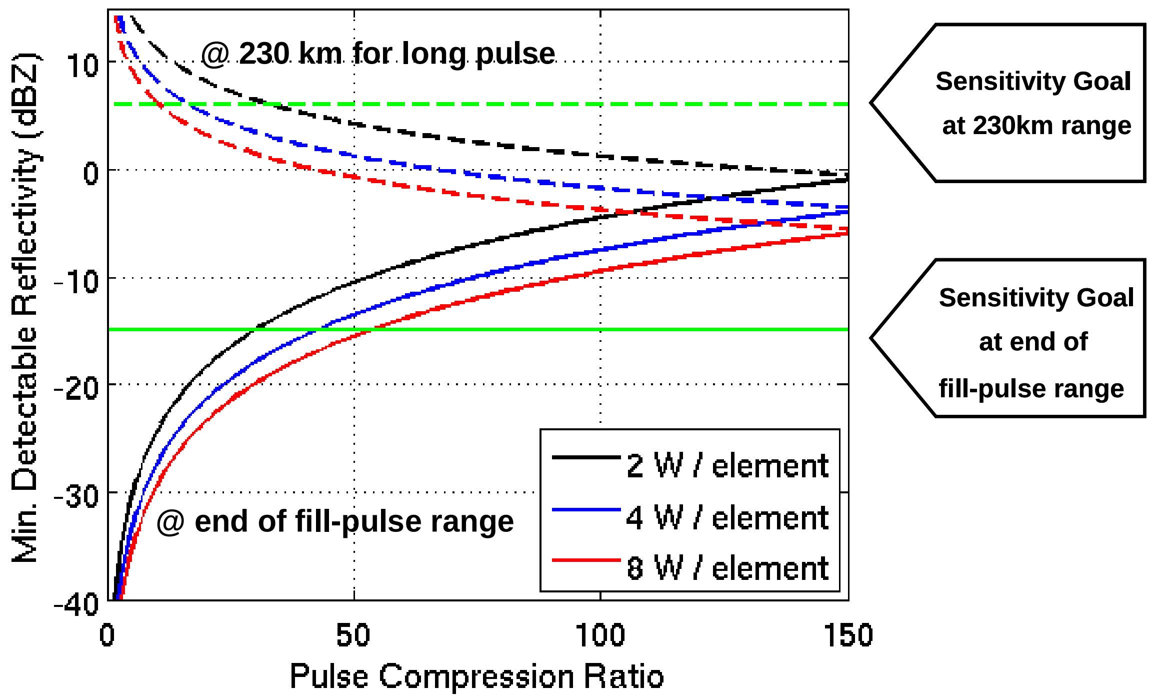
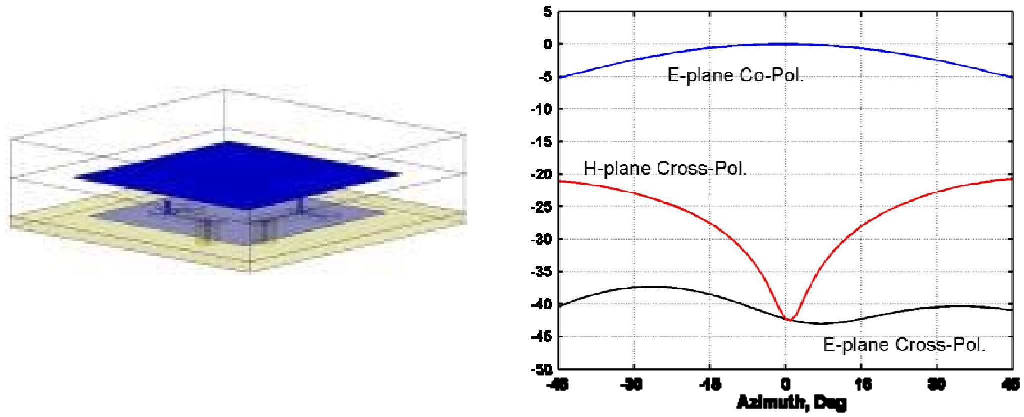


Figure 4. MPAR minimum detectible weather reflectivity versus pulse compression ratio at the short-long pulse transition range (lower curves) and at a range of 230 km (upper curves). For the assumed 1 usec compressed pulse length, pulse compression ratio is equivalent to long-pulse length.



Co- and Cross-Polarized Patterns

Figure 5. Dual polarized stacked patch antenna configuration and co- and cross-polarized patterns versus steering angle.

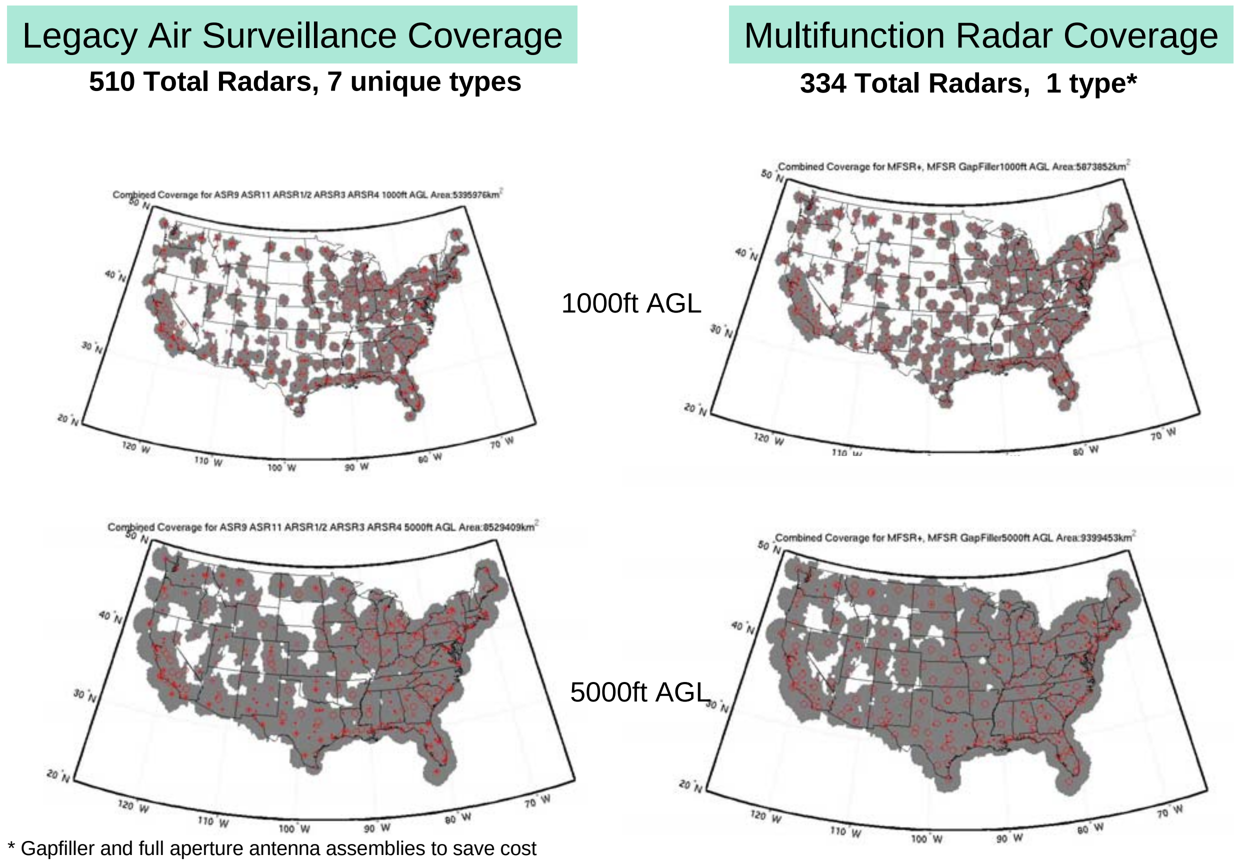


Figure 6: Airspace coverage comparison between current U.S. operational radar networks (ASR 9, ASR-11, ARSR-1/2, ARSR-3, ARSR-4, NEXRAD, TDWR) and a conceptual MPAR network.

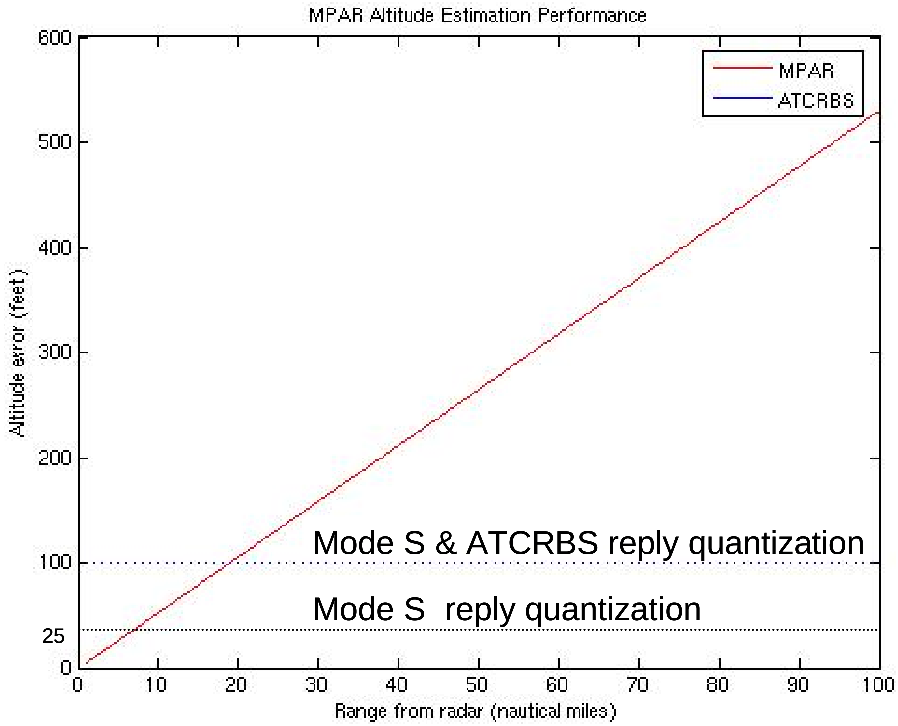


Figure 7. MPAR height measurement accuracy versus range. Twenty-to-one monopulse angle measurement improvement is assumed relative to the physical beamwidth.

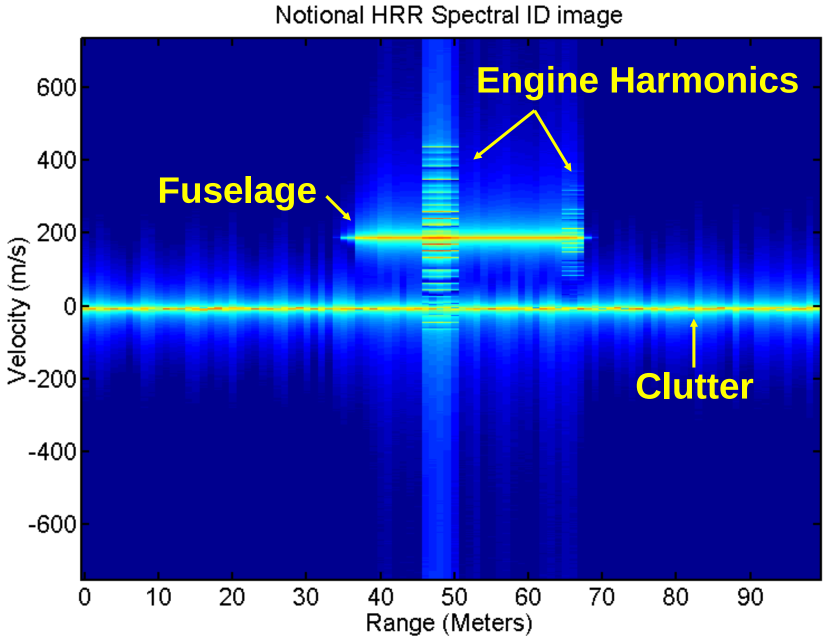


Figure 8: Notional Range Doppler image of an aircraft measured by a radar providing simultaneous high-range resolution and a large unambiguous Doppler interval.

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.

	Maximum Detection Range		Coverage		Angular Resolution		Waveform	Scan Period
	Aircraft 1 m^2	Weather 0 dBZ	Range	Altitude	Az.	El.		
Terminal Area Aircraft Surveillance (ASR-9/11)	60 nmi	12 nmi	60 nmi	20,000'	1.4°	5°	>18 pulses PRI ~0.001 sec	5 sec
En Route Aircraft Surveillance (ARSR-4)	205 nmi	5 nmi	250 nmi	60,000'	1.4°	2.0°	>10 pulses PRI ~0.001 sec	12 sec
Terminal Area Weather (TDWR)	195 nmi	100 nmi	60 nmi	20,000'	1°	0.5°	~50 pulses PRI ~0.001 sec	180 sec
En Route Weather (NEXRAD)	210 nmi	85 nmi	250 nmi	50,000'	1°	1°	~50 pulses PRI ~0.001 sec	>240 sec

Table 2. Concept MPAR parameters

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

Table 3: Parts costs for dual-channel MPAR pre-prototype 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	v$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 = $115.00

Table 4: MPAR subsystem parts-cost model, based on pre-prototype array designs.

	Equivalent Cost per Element	
Component	**Pre-Prototype**	**Full-Scale MPAR**
Antenna Element	**$1.25**	**$1.25**
T/R Module	**$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**