Comparisons of Weather and Aircraft Surveillance Radar Requirements

to Determine Key Features for a 10-cm Multi-function Phased Array Radar

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Abstract—Surveillance capabilities of the ARSR-4 and ASR-9/11 for aircraft detection and tracking, and the TDWR and the WSR-88D for weather surveillance are reviewed to determine requirements for a 10-cm wavelength polarimetric Multi-function Phased Array Radar (MPAR) that can match present day performance. Low sidelobes, polarimetric purity, and well matched H and V radiation patterns required for the weather radar surveillance mission are among those issues that place stringent requirements on the MPAR. Attenuation of 10-cm radiation to meet the ARSR-4 performance is addressed. Matching the angular resolution requirements of the WSR-88D and the ARSR-4 sets the size of the MPAR. To match the height resolution of the TDWR for the detection of low altitude wind shear along the approach and departure corridors of an airport and also to serve the ASR-9/11 function, the MPAR needs to be located on the airport at or near the present site of the ASR-9/11. Time multiplexing of the surveillance functions allows independent control of each function, while offering the potential of freeing spectral space. It is concluded that a network of 10-cm wavelength MPARs could meet the present day requirements of airport and long range surveillance of aircraft, and provide faster weather surveillance without compromising data quality.

Keywords—Multi-function Phased Array Radar; Weather Surveillance; Aircraft Surveillance; Polarization Radar

I. INTRODUCTION

The present surveillance of weather and aircraft is achieved with four different radars. These are:

- 1.) The Federal Aviation Administration's (FAA) Airport Surveillance Radar (ASR-9/11); operates in the 10-cm band.
- 2.) The FAA's Terminal Doppler Weather Radar (TDWR); operates in the 5-cm band.
- 3.) The National Weather Service's (NWS) Weather Surveillance Radar-1988 Doppler (WSR-88D); operates in the 10-cm band.
- 4.) The Air Route Surveillance Radar (Common ARSR or CARSR, and ARSR-4); operate in the 20-cm band. These radars are operated and maintained by the FAA, but serve the missions of both the Department

of Homeland Security (DHS), and the Department of Defense (DOD).

The National Severe Storms Laboratory (NSSL) and the Advanced Radar Research Center (ARRC) at the University of Oklahoma are testing various design concepts of polarimetric phased array radar (PPAR) operating within the single 10-cm wavelength band that can accomplish the mission of the four radars [1, 2]. One important objective is to determine if all radar functions can share common frequencies, but within the bandwidth allowed by the National Telecommunication and Information Administration's RSEC (Radar Spectrum Engineering Criteria; [3]) thus freeing valuable spectral allocations. A scaled-down Planar PPAR (PPPAR) and a Cylindrical PPAR (CPPAR) have been developed to provide engineering information that can reduce the risks of building a full size polarimetric MPAR. Results of engineering and meteorological tests will provide valuable data to determine whether MPAR can fulfill the requirements of all four agencies (NWS, FAA, DOD, and the DHS).

It is most important that the 10-cm MPAR at least meet present day aircraft and weather surveillance performance levels. Furthermore, the MPAR needs to comply with the National Telecommunications and Information Administration's (NTIA) criteria established for radars operating in the 2.7 to 2.9 GHz band [3]. The MPAR should operate within the frequency bands presently allocated for the ASR and WSR functions.

II. COMPARISON OF THE CHARACTERISTICS FOR WEATHER AND AIRCRAFT SURVEILLANCE RADAR

The characteristics of today's radars used to survey and track weather and aircraft locations, are compared in Table I. The entries are, wherever possible, based on measurements. These parameter values and detection capabilities should not be compromised by MPAR.

Note that two radars (i.e., the TDWR and the ARSR-4) presently operate outside the 10-cm wavelength band.

TABLE I. PRESENT CAPABILITIES FOR WEATHER AND AIRCRAFT SURVEILLANCE¹

Parameters	FAA's TDWR	FAA's ASR-9/11	DoD/DHS's ARSR-4	NOAA's WSR-88D
Frequency (GHz) ⁽¹⁾	5.5 $\rightarrow$ 5.65	2.7 $\rightarrow$ 2.9	1.2 $\rightarrow$ 1.4	2.7 $\rightarrow$ 3.0
Peak power P_t (MW) ⁽²⁾	0.250	1.1	6.4	0.475
Pulse width τ (μ s)	1.1	1.0	1	1.57
2-way beamwidth ⁽³⁾ θ_6 ($^\circ$)	0.55	1.4 (Az) $\approx$ 5 (El)	1.4 (Az) 2 (El on rec.)	0.95 $\rightarrow$ 0.85 ⁽⁴⁾
Antenna Gain (dB) ⁽⁵⁾	50	34	35(T.); 40(R)	45.36 $\rightarrow$ 46.32
Range resol.; r_6 ^(6a) (m) Elevation resol. ΔE ^(6b) : Azimuth resol. ΔA ^(6c) :	150 0.55 $^\circ$ 1.0 $^\circ$	230 1.5 $^\circ$	115 0.12 $^\circ$ 1.9 $^\circ$	235 1.0 $^\circ$ 1.0 $^\circ$
Coverage ⁽⁷⁾ ; r (km) Z/ac r (km) for v, σ_v Elevation span ($^\circ$) ⁽⁸⁾ Max Height (km)	? $\rightarrow$ 111 ? $\rightarrow$ 111 0.25 $\rightarrow$ 60 6.1	0.9 $\rightarrow$ 111 NA _p 0 $\rightarrow$ 30 7.3	9 $\rightarrow$ 460 NA _p $\approx$ -7 $\rightarrow$ 30 30	2 $\rightarrow$ 460 2 $\rightarrow$ 300 0.5 $\rightarrow$ 20 20
Sys. Noise Temp. T _{sy} (K)	NA _v	NA _v	NA _v	730 ⁽⁹⁾
Detection ^(10a) Z ₁₀ (dBZ): RCS(m ²) at 460 km w/o precip ^(10b) : with precip ^(10c,10d) :	-25.6 0.6 NA _p	-6 35 NA _v	0 0.14 0.30 ^(10d)	-21.8 $\rightarrow$ -23.65 0.15 $\rightarrow$ 0.12 0.23 $\rightarrow$ 0.18 ^(10d)
Polarization	Linear H	Cir. or Lin	Cir. or Lin	Dual linear H,V
Polarization data mode ⁽¹¹⁾ On-axis copolar/Xpol (dB) Patt. Match: at -20 dB ⁽¹²⁾	NA _p NA _v NA _p	NA _p NA _v NA _p	NA _p >17 NA _p	STSR >40 dB < 0.5 dB
Sidelobe levels (two-way; dB) ⁽¹³⁾	-54; 1 st -80; $\theta > 5^\circ$	<-48	EL: < -60; AZ: < -70	-66; 1 st @ 2 $^\circ$ <-100; $\theta > 10^\circ$
Volume update rate ⁽¹⁴⁾ (s)	60 lower 3 min. upper	4.8	12	$\approx$ 5 min.

¹ The numerals in parentheses refer to annotations listed in Appendix 1 of [4] where explanations are given for Table 1 entries. "NA_p": Non Applicable; "NA_v": Not Available.

The MPAR should only operate in the 10-cm band. A downside of decreasing the wavelength for the ARSR-4 function is the increased attenuation principally due to precipitation. Attenuation due to precipitation can be significant when moving the ARSR-4 functions to the 10-cm band as shown by annotation² (10) and Appendix 2 in [4].

The TDWR has an angular resolution of 0.5°. Because the MPAR has about the same aperture area as the TDWR, increasing wavelength from 5 to 10 cm will degrade the angular resolution. The prime purpose of the TDWR is for the detection of low altitude wind shear along the aircraft's approach and departure corridors. Presently the TDWRs are located many kilometers from the airport with concomitant degradation of performance to detect low altitude wind shear. If the MPAR with its 1° circular beam (i.e., for the CPPAR/MPAR for the weather surveillance function) can be located on airports where presently the ASR-9/11 is located, MPAR should also meet the low-altitude wind shear detection requirements presently provided by the TDWR. An advantage of off-airport siting for TDWR is the capability to efficiently scan mid-level storm features that are predictive of surface wind shear (e.g. descending reflectivity cores). MPAR would realize this capability using data from other nearby radars in the network – where possible – and by adaptively programming high elevation angle scans. Increase in ground clutter to weather signal ratio is expected with a 10-cm wavelength MPAR, but clutter spectra will be narrower [5], especially for stationary objects and thus increase clutter might be sufficiently suppressed.

Table I lists the present day operating characteristics of radar used for weather and aircraft surveillance. In preparing Table I, an effort has been made to substantiate all entries by citing the source and or providing information as to how the entries were obtained. These substantiations are given in [4]. Entries in Table I are the minimum capability that the MPAR must provide. Documents that list additional requirements the MPAR needs to match or exceed are provided by the FAA and NWS documents [6], [7], and [8]. Although most of the requirements listed in the documents are met with present day radar capabilities, there are some that exceed these capabilities (e.g., weather surveillance updates every minute) and some that are worse (e.g., sidelobe levels). Note that to maintain consistency for the table entries, peak power and pulse width values for current solid state transmitter radars (the ASR-11 and ARSR-4) include the effect of energy gained using long, frequency-modulated transmissions and compressive receivers.

An examination of Table I shows that the parameter values of the various radar functions cannot be met using existing mechanically scanned reflector technologies or even single-agile-beam electronically scanned radars. True multifunction capability will require the use of next generation array

technology to simultaneously form multiple, independent beams supporting these different functions.

An example of such a MPAR is one proposed by [9]. There it is shown multi-functionality does not require beam agility but four orthogonal beams synchronized in azimuthal scanning and simultaneous collecting data. It is shown that if each of the functions (i.e., WS, AS, and ARS) time share the antenna, aircraft surveillance can be obtained at present update rates, but weather surveillance can be twice as frequent (i.e., about every 3 minutes). To obtain the desired 1 minute weather updates requires 3 beams per 90° azimuth sector using a Multiple Beam Technique in which three pulses are sequentially transmitted nearly simultaneously and echoes are simultaneously received and coherently processed to suppress contamination from mainlobe-to-sidelobe coupled echoes [10]. Alternatively, to speed up weather data acquisition, is the possibility of transmitting at different center frequencies on multiple beams and yet be within the spectral band allocated by the NTIA to the operation of a WSR-88D [11]. On the other hand, the agile beam capability of the MPAR might produce sufficiently fast volumetric surveillance by implementing approaches other than the MBT (e.g., [12], [13]).

III. SOME KEY MPAR REQUIREMENTS

A. *Average Transmitted Power*

Matching the performance of the CARSR/ARSR-4 and ASR-9/11 for aircraft detection and tracking, and the WSR-88D for weather surveillance with a 10-cm wavelength MPAR (either using a 4-face Planar Polarimetric PAR or a 4-sector Cylindrical Polarimetric PAR) requires at least 12 kW (3 kW per face or 90° sector) of average transmitted power as shown by annotation (15) in [4]; 6 kW of the 12 kW is required for weather observations to be updated about once a minute if the MBT approach is used to obtain faster weather data updates.

If the ARSR-4 precipitation model specified by Appendix A. section 3.3 in [14] for tropical storm systems is used in computing propagation loss as done in annotation (10d) in [4], about 5 kW of transmitted power is required³ to overcome increased attenuation for the ARSR function with the 10-cm instead of 20-cm wavelength radiation. There can be more demanding precipitation conditions typical of lines of storms containing rain and mixtures of rain and hail. Attenuation for these conditions has been computed by annotation (10c) and Appendix 2 in [4]. But these are relatively rare events that typically occur over central USA—higher average power would be required during these events if availability requirements are to be met. However, increased power might not be necessary if all MPARS have the ARSR functionality because the MPAR coverage would blanket the continental US and other MPARS would detect aircraft if

² All annotations henceforth referenced are in Appendix 1 of [4].

³ Thanks to William W. Shrader of Shrader Associates, Inc. for spotting an error in computing ARSR-4 average power requirements.

echoes from one MPAR are not detected. The agencies responsible for non-cooperative aircraft surveillance within US airspace would need determine the pertinent requirements and determine if higher average power is warranted to deal with this issue.

B. *Size*

Matching the 0.95° beamwidth of the WSR-88D, operating at a frequency of 2.7 GHz, sets the size of the MPAR (12.1 m diameter by 8.54 m tall for the CPPAR, and 4 faces each having an elliptical aperture 12.1 by 8.54 m for the PPPAR). The total 325 m^2 active aperture area is the same for the 4-sector CPPAR and 4-face PPPAR. Although the total number of elements is the same for the CPPAR and PPPAR (i.e., to satisfy the 1° beamwidth requirement for the PPPAR beam directed 45° in azimuth from the broadside direction), the CPPAR inherently has array elements that can be utilized for sidelobe blanking and pattern synthesis [15].

C. *Cross-polar radiation*

Cross-polar radiation along the copolar beam is the most important contributor to bias of polarimetric parameters (annotation 11 in [4]). For example, differential reflectivity bias needs to be less than 0.1 dB for radar rainfall rate estimates to be accurate to within 15% [16]. If on-axis cross-polar radiation cannot be guaranteed to be 45 dB below the copolar peak, precise measurements of the amplitude and phase of the cross-polar field must be made for each of the electronically steered beam directions so that corrections can be made to remove Z_{DR} bias [17] and [18]. However, if the cross-polar radiation is in phase or in counter phase with the copolar radiation (as it is for the geometrically induced cross-polar radiation of a MPAR with planar arrays [19]), the level of acceptable cross-polar radiation in a beam coaxial with the copolar beam is increased to -26 dB without Z_{DR} bias being larger than 0.1 dB [11].

Alternatively, polarimetric data collection could be made in the Alternate Transmit and Simultaneous Receive (ATSR) mode. This mode relaxes significantly the acceptable levels of on-axis cross-polar fields, but would impact severely on the performance of the polarimetric measurements [11]. Therefore the recommended mode of operation remains Simultaneous Transmit and Simultaneous Receive (STSR).

D. *Pattern matching*

To maintain Z_{DR} bias below acceptable levels (i.e., $< 0.1 \text{ dB}$), radiation patterns of the antenna need to be well matched for all beam directions. Pattern measurements show the -10 dB beamwidths of the WSR-88D to be circular within $\pm 0.02^\circ$ (annotation 12 in [4]). If patterns are circularly symmetric and Gaussian shaped to about the -20 to -25 dB level below the peak gain (as are the patterns of the WSR-

88D) but the beamwidths are not perfectly matched (i.e., directive gains are not matched), the Z_{DR} bias is given by [20].

$$Z_{\text{DR}}(\text{bias}) = \mp 10 \frac{\Delta}{L} \log_{10}(e)$$

where Δ (dB) is the difference in the H and V patterns at a level $-L$ (dB) below the pattern peak. Thus to have $Z_{\text{DR}}(\text{bias}) < 0.1 \text{ dB}$ (i.e., the specified bias limit), the H and V patterns should be within 0.5 dB of each other at the -20 dB level.

E. *Sidelobes*

Setting and meeting the requirements for two-way sidelobe levels of MPAR to monitor weather is most challenging because sidelobe levels for weather surveillance need to be much lower than for aircraft surveillance [7]. Weather reflectivities span a large angular space and thus encompass hundreds of sidelobes. That is, unwanted power integrated over relatively low sidelobe levels, but over large angular space, can cause unacceptable levels of power that competes with the power from the main lobe needed to make quantitative measurements of weather. Moreover, weather reflectivity factors of interest span an 85 dB range (i.e., -25 dBZ for Bragg scatter from perturbations in the atmosphere's refractive index, Rayleigh scatter from clouds, etc., to more than 60 dBZ in hail storms).

Although weather data artifacts due to sidelobes have been reported by [21], it appears that the WSR-88D operates at an acceptable level of tolerance against these artifacts. Thus it behooves us to examine the sidelobe levels of the WSR-88D to determine the conditions that could be placed on MPAR's two-way sidelobe levels. Fig.1 from [22] shows the theoretical or ideal one-way sidelobe level (i.e., that attained without scatter and blockage of reflector's radiation due to the feed horn struts, and radome) of the WSR-88D. The dashed-dotted line is the envelope of the peak side lobes (without radome) measured along the 30° cut that avoids ridges of enhanced sidelobes due to struts. These measurements agree reasonably well with the ideal pattern.

The solid line is the specified maximum allowed sidelobe levels without a radome. One might be tempted to apply these specifications to the MPAR. However, the WSR-88D antenna exceeds these specifications by a wide margin [7], and the NWS is unlikely to accept an MPAR not meeting present performance of the WSR-88D. Thus the MPAR specifications will lie below the specified level but above the ideal curve.

Fig. 1 KOUN's ($\lambda = 11.09\text{ cm}$) one-way theoretical copolar H radiation pattern (solid wavy line) is compared with measurements along two cuts and specifications for WSR-88D sidelobe levels without radome.

The dashed line in Fig.1 is the envelope of the NSSL measured sidelobes along a 0° cut through a ridge of heightened sidelobes due to strut blockage of radiation from the WSR-88D (KOUN) antenna with radome. Analysis of other data collected on a better antenna range using the antenna without radome indicates six sidelobe ridges due to strut blockage of the fielded WSR-88Ds are likely near -33 dB at 2° , and drops linearly to -50 dB at about 15° as suggested by annotation [18] in [4]. Because there are three struts spaced 120° in azimuth, there are six sidelobe ridges spaced 60° in azimuth

There are additional sidelobe ridges but they are due to scatter from the struts. Similar ridges of sidelobes are seen in other pattern measurements of center fed parabolic reflector antennas [23]. The ridges of sidelobes due to scatter lie in the planes common to the struts and the reflector's axis, but appear only on the side opposite the strut. Thus there are in all, 9 sidelobe ridges intersecting the beam and displayed in a 2D pattern format as shown by annotation (13) in [4]. From an analysis of data collected by Andrew Canada it is concluded the one-way three sidelobe ridges due to strut scatter in the fielded WSR-88Ds are likely near -28 dB at 2° , and drop linearly to -45 dB at about 10° .

Although MPAR's first sidelobe can be higher than the ideal one of -35 dB , it is recommended in annotation (13) of [4] that the specified close-in sidelobe level be that associated with the ridges of sidelobes due to strut blockage. That is, specified MPAR two-way sidelobe level should be below the level of -66 dB at 2° decreasing to about -100 dB at about 15° . Any increase in the sidelobe levels of the MPAR over what is effectively attained with the WSR-88D would likely increase the incidence of data corrupted by sidelobe coupled power.

Even though the WSR-88D's two-way sidelobe level beyond 15° is nearly everywhere 100 dB or more below the peak gain of the beam, artifacts due to these sidelobes are often seen above severe storms as shown in Fig. 3 of [4]. Thus if the MPAR aperture distribution is set so the MPAR close-in sidelobes do not exceed those WSR-88D side lobes levels determined by strut blockage of aperture radiation, there remains the question whether the far out sidelobes can be raised above the -100 dB level. Raising the far-out sidelobe levels above -100 dB requires a rigorous assessment of the impacts on meteorological interpretation of weather radar data.

IV. CONCLUSIONS

A network of 10-cm wavelength MPARs could meet the present day requirements of airport and long range surveillance of aircraft with a modest increase of average transmitted power. However, extensive testing of prototype MPARs is required. If time multiplexing of the four surveillance functions proves practical, spectrum utilization might be decreased from that presently allocated for the four independently operated surveillance radars [4, annotation 16].

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