COVERAGE COMPARISON OF SHORT RANGE RADAR NETWORKS VS. CONVENTIONAL WEATHER RADARS: CASE STUDY IN THE NORTHWESTERN UNITED STATES

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ABSTRACT

The West Coast of Washington and the NE and SW corners of Wyoming are regions of the contiguous United States where NEXRAD coverage is incomplete. One approach to addressing these gaps is to install additional NEXRAD-class radars. Another potential approach is to install small radar networks of the type being investigated in the CASA project. This paper compares these two approaches. We provide a meteorological and user-need assessment of present radar coverage in these regions (based on a recent feasibility study led by J. Brotzge [1]) as well as an objective assessment of the radar-coverage that would be achieved using the large radar and small radar approaches. For this evaluation we consider two classes of radar: long-range radars having similar attributes to the WSR-88D (i.e., 10 cm wavelength, >250 km maximum range, 1 degree beamwidth, ~500 kW peak power); and short-range radars having attributes similar to those operating in CASA's Oklahoma prototype network (i.e., 3 cm wavelength, 40 km maximum range, 2 degree beamwidth). We first establish the number of both types of radar that would be needed to provide coverage over a given rectangular ground-domain. Next, we quantify the coverage-versus-altitude for both weather-event detection and precipitation estimation over these regions, considering the blockage caused by both the curved earth and the local terrain.

Index Terms—*Radar, CASA, NEXRAD, Radar coverage*

1. INTRODUCTION

The Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) was established by the National Science Foundation in 2003 to develop the concepts and technologies to enable future deployment of large numbers of low-cost, low-power radars as a means to provide improved radar coverage of the lower atmosphere. The CASA concept is to deploy thousands of small radars on rooftops and telecommunication towers as a way to complement or potentially replace the large radars in use today [2]. Numerous issues related to the hardware and software system design, as well as the radar reliability, cost, and cost/benefit relative to the use of large radars need to be investigated as a prerequisite to any such deployment.

This paper analyzes the coverage that would be obtained in the radar gap areas of Wyoming and western Washington by installing large radars and networks of small radars. Section 2 summarizes the radar performance of physically large, high-power S-band and physically small, low-power X-band radar technologies. C-band radars, which tend to be intermediate in size between X and S band systems, are a third alternative used by some countries but are not discussed in this paper. We discuss S-band radars owing to the substantial U.S. experience with installing and operating these radars as part of the NEXRAD program. We discuss X-band radars owing to the potential for improved low-level coverage provided by these radars as reflected in the ongoing research in the Collaborative Adaptive Sensing of the Atmosphere (CASA) NSF Engineering Research. Section 3 explores example network configurations of short-range and long-range radars in the domains of Wyoming (Domains A and B in Figure 1) and western Washington (Domain C in Figure 2). In addition to assessing the technical performance and coverage of new radars, section 4 discusses issues such as cost, radar sitting, installation and integration of new observational data into weather service operations.

2. LONG-RANGE VS. SHORT-RANGE RADAR DEPLOYMENTS

Radars designed to operate over long ranges (e.g., >230 km), operating at wavelengths of ~ 10 cm, need large antennas (8.5 m diameter antenna for the WSR-88D/NEXRAD system) and high power transmitters (peak power of 750 kW for the WSR-88D) and they require dedicated land and substantial physical support infrastructure. The CASA NSF Engineering Research Center is pursuing a concept in which networks of small, short-range radars overcome the earth curvature and terrain blockage problems faced by long-range radars. Such radars have the potential to be deployed in any number of location in the nation – as a supplement or replacement to the large radars in use today – or in a "gap fill" mode, addressing gaps such as those in Wyoming and Washington State. The short-range (~ 40 km) radars being considered by the CASA project operate at X-band (Figure 6.1 of [2]) and require substantially smaller antenna (~1 m diameter) and lower radiated power (average power ~ 10s of Watts) than the long-range S-band radars in the national network. The CASA project has deployed 4 of these radars in a research test bed in Oklahoma, an average 25 km apart [3]. The short-wavelength of the CASA-type radars requires that careful attention be paid in the design to the effects of attenuation due to rainfall. Dual-polarization and overlapping beam coverage provide two methods for real-time correction of attenuation [4]. Overlapping beam coverage also provides the additional benefit of having dual-Doppler coverage available across much of the network domain, which allows for the derivation of three-dimensional wind information and alternative coverage in cases of complete attenuation from one radar's viewing

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angle [5]. CASA radars also provide adaptive scanning capabilities through Distributed Collaborative Adaptive Sensing, or DCAS [6]. Additional capabilities provided by CASA radars include automated range-height indicator scans (RHIs) and possibly differential refractivity, a promising technique for quantifying low-level moisture [7]. A summary of the specifications of CASA and WSR-88D radars are presented in Table 1.

Table 1: Technical specifications for CASA and WSR-88D radars

	CASA	WSR-88D
Operating frequency	9.41 GHz	2.7 – 3.0 GHz
Wavelength	3 cm	10.0 cm
Antenna diameter	1.20 m	8.53 m
Antenna gain	38 dB	45.5 dB
Antenna beamwidth	1.8º	1.0º
Range gate spacing	100 m	250 m
Maximum rotation rate	35 deg s-1	36 deg s-1
Acceleration rate	50 deg s-2	15 deg s-2
Average transmitter power	9 W/pol	1.56 kW
Peak transmitter power	7.5 kW/pol	750 kW
Min. Detect. Reflect. (10 km)	-2 dBZ	-23 dBZ
Pulse repetition frequency	1.6, 2.4 kHz	318-452 318-1304 pulses/sec
Pulse width	660 nsec	1.6, 4.5-5.0 µ sec
Dual-polarization	Yes	For 2010-2012

3. POSSIBLE RADAR SOLUTIONS

This section explores example network configurations of short-range and long-range radars in the domains of Wyoming (Domains A and B in Figure 1) and western Washington (Domain C in Figure 2). These domains were selected to address the needs outlined in Section 2 of the recent feasibility study [1].

3.1. Idealized radar calculations (smooth-earth, equilateral grid). The idealized calculations, which assume no terrain blockage and a regular grid (equilateral triangular with 35km spacing), provide theoretical understanding of the value of long-range vs. short range radar systems. Figure 3a shows the number of short-range radars (blue) and long-range radars (red) that would be required to provide coverage across a given-size domain. Figure 3b shows the percentage coverage of the atmosphere as a function of altitude, independent of domain, for long-range radars (red) and short-range radars (blue) systems. Figure 3b shows networks of short-range radars provide similar coverage at 2 km AGL and, superior coverage below 1.5 km. At 1 km AGL, long-range radars give only 40% of the 100% coverage that the networks of small radar provide. Of course, these estimates are valid only over land areas and do not apply to areas over open water, such as in Domain C of Figure 2.

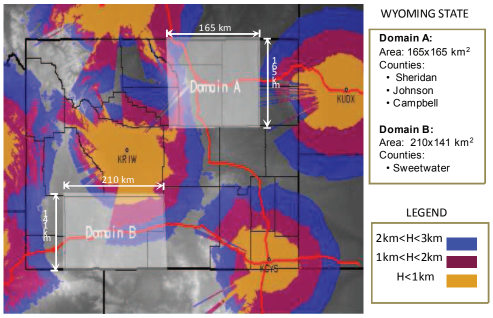

Figure 1: Wyoming radar gap-coverage analysis Domains A and B.

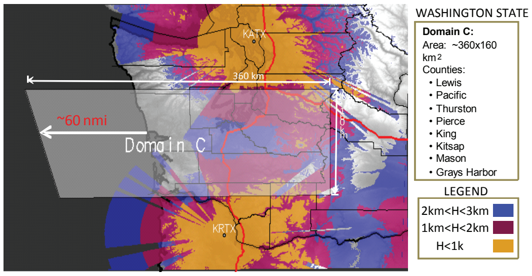

Figure 2: Western Washington radar gap-coverage analysis domain C.

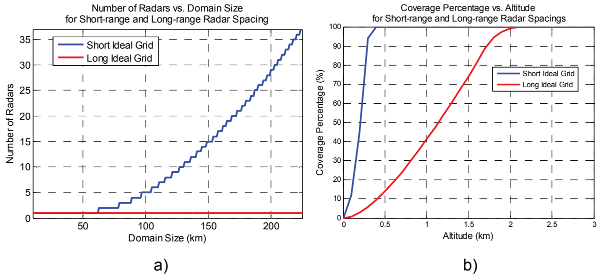

Figure 3: a) Number of radars needed to populate a given domain size for short-range (35 km) and long-range (225 km) radar spacing. The domain considered is square with the side of the square defined by the "domain size" in kilometers. b) Percent coverage evaluated at a given altitude for short-range (35 km) and long-range (225 km) radar spacing. Percent coverage is evaluated at the center of the radar beam, 0.9 deg and 0.5 deg for the short-range and long-range radars, respectively, and takes into consideration the curvature of the earth.

3.2. Coverage for example radar networks

The above calculations place no geographic restrictions on the radar locations within the domain of interest. To investigate the role of radar placement to overall radar coverage and separate the effects of irregular radar placement from those of terrain blockage, the calculations done in this section are carried out for an example radar network. The short-range radars presented (crosses) are sited to be accessible by road and not to be obscured by local topography. The layout is nominally a triangular grid with roughly 35 km spacing. Long-range radar placements are shown as circles placed in nominally ideal locations that coincided with roughly the centers of the domains. Both short-range and long-range radars were sited with the goal of covering the domains of interest. Coastal settings where the domains of interest extend substantially over the ocean prohibit complete coverage by short-range radars. Radar coverage for the additional radar(s) as a function of altitude (AGL). For the Wyoming domains (Figure 4a and b), coverage is complete at about 1.8 km for long-range radars. For short-range radars there is 100% coverage down to ~0.7 km for domain A and 98% coverage at ~0.7km in domain B. Generally, in domains A and B the short-range radars have superior coverage from the surface to about 1.5 km. Figure 4c shows the coverage for the coastal domain of western Washington. Similar to the figures for Wyoming, short-range radars give superior coverage at low levels over land. The coverage for the short-range radars plateaus with ~70% coverage, which results from the inability of the small radars to make observations over the ocean at ranges greater than 40 km.

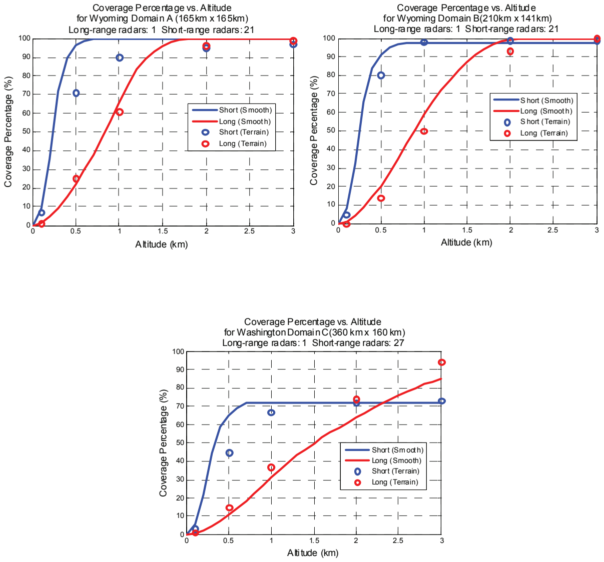

Figure 4: a) Percentage coverage of long-range (red) and short-range (blue) radar systems at given altitudes for a) northeastern Wyoming (Domain A), b) southwestern WY (Domain B), and c) western Washington (Domain C). The solid lines represent the calculations with the example network described in section 3.2 without terrain and circles represent the coverage simulated with terrain, as explained in Section 3.2

3.3. Radar coverage simulations.

To determine radar coverage of short-range vs. long-range radars in terrain, simulations of radar occultation are calculated for the given radar locations using software that uses high resolution digital elevation maps to calculate beam blockage. The radar beam is considered blocked when the path integrated occultation is greater than 50%. The blockage calculations were performed using the University of Oklahoma's Advance Regional prediction System (ARPS). Geospatial analysis and visualization was performed using Geographic Resources Analysis Support System (GRASS) and Geographic Information System (GIS).

3.3.1. Wyoming

In northeast Wyoming, the radar coverage possible using one long-range radar and a network of twenty-one short-range radars are shown in Figure 5a and 5b, respectively. As expected, both radar systems dramatically increase the coverage. The long-range radar covers progressively higher altitudes with range, whereas, the short-range radars have virtually complete coverage at these altitudes out to their maximum range. This difference in coverage at low-levels results from the high density of short-range radars.

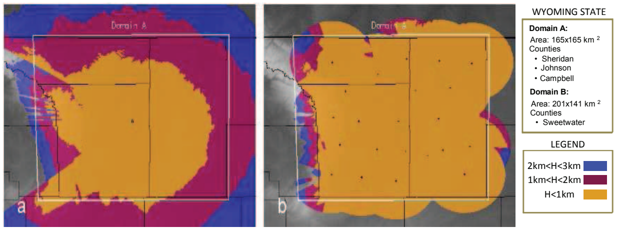

Figure 5: Radar coverage maps of Domain A in northeast Wyoming at 1, 2, and 3 km AGL for a) one long-range radar and b) twenty one short-range radars.

Table 2 shows the percentage coverage of Domain A by the additional radars at 100, 500, 1000, 2000, and 3000 m AGL for both radar systems. To show consistency with the idealized calculations, these values are also shown in Figure 4a.

Table 2: Coverage in northeast Wyoming (Domain A).

Altitude (m)	Coverage (%) Long (1 radar)	Coverage (%) Short (21 radars)
100	1%	7%
500	25%	71%
1000	61%	90%
2000	96%	95%
3000	99%	97%

Figure 6a and 6b show similar coverage results for southwest Wyoming with the coverage of the domain almost complete between 2-3 km altitudes. Table 3 shows the coverage statistics which are also consistent with the smooth-earth calculations.

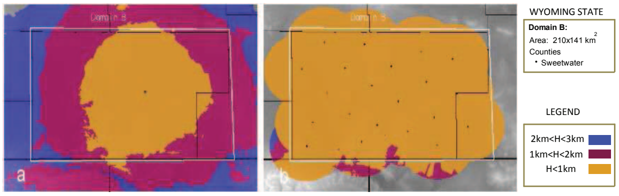

Figure 6: Radar coverage maps of Domain B in southwest Wyoming at 1, 2, and 3 km AGL for a) one long-range radar and b) twenty-one short-range radars.

Table 3 Coverage in southwest Wyoming (Domaing B)

Altitude (m)	Coverage (%) Long (1 radar)	Coverage (%) Short (21 radars)
100	0%	5%
500	14%	80%
1000	49%	98%
2000	93%	99%
3000	100%	99%

3.3.2. Western Washington

The mountainous coastal regions of western Washington State exemplify the strengths and weaknesses of both radar systems. Figure 7a is the simulated coverage of one long-range radar placed in Westport, WA, and Figure 7b is the coverage of twenty-seven short-range radars placed throughout Domain C. As shown in Figure 7a and statistics in Table 4, long-range radar placed on the coast gives substantial long range coverage over the ocean, while the network short-range radars (Figure 7b) are more effective at observing low-levels over the rugged terrain of the Cascades. What is not shown is the additional radar coverage over the ocean above 3 km, as provided by the long-range radar.

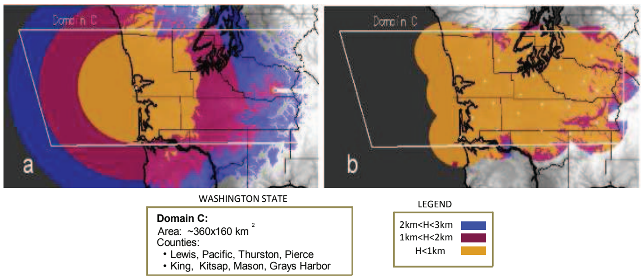

Figure 7: Radar coverage maps of Domain C in western Washington State at 1, 2, and 3 km AGL for a) one long-range radar and b) twenty seven short-range radars.

Table 4: Coverage in western Washington (Domain C).

Altitude (m)	Coverage (%) Long (1 radar)	Coverage (%) Short (27 radars)
100	1%	3%
500	15%	45%
1000	37%	67%
2000	74%	72%
3000	94%	73%

4. COST CONSIDERATIONS

4.1. Long-range radar

The general criteria used to establish the original installation sites for the NEXRAD radar network are described by Leone et al. 1989 [8]. The placement of weather radar includes site selection, evaluation of infrastructure, safety, and environmental assessment. In addition, an environmental assessment and frequency allocation analysis are required, and local zoning laws and building permits must be followed. In the case of NEXRAD, site selection required from one to three years to complete, per site. Further, identifying a site with adequate roads, utilities, and communications was necessary, and in urban areas there was the potential for sitting to become a political issue. An estimate for the up-front cost for long-range S-band radar (including the costs to buy and install the radar as well as the land and supporting infrastructure) is $10M. This figure was cited in 2008 in a National Research Council report (NRC 2008) based on a Lincoln Laboratories estimate. This estimate is derived based on the fact that the 156 radar NEXRAD radar network cost $1.56 billion to deploy between 1990 and 1997, or ~ $10M per radar. The yearly operation and maintenance costs of the WSR-88D network are currently approximately $78 million (OFCM 2006). Dividing this cost by 156 radars results in an estimate of a recurring cost of ~$500k per radar.

4.2. Short-range radar

The concept being pursued by the CASA project is to place short-range radars close together (e.g., 10‘s of km apart) to accomplish two things: (1) defeat the earth curvature and terrain blockage problem that limits the low-level coverage of large radars and (2) enable the use of small, lightweight, low-cost radars that can be installed on simple dedicated towers or on buildings and existing infrastructure. The CASA project has set an aim-point of $200k as the up-front cost for each radar in a dense radar network and a per-site recurring cost of $20k per radar per year.

CASA‘s costs to build, install, and operate the radars of its Oklahoma test bed is described in [2]. Four prototype radars were designed and fabricated by CASA participants during 2004-2005. The total parts-cost of the transceiver, antenna, computers, and data acquisition system is $78k. The total parts cost for each of the radars, including all needed towers and other infrastructure, was $229,500 Assuming that the cost to purchase one of these radars is twice the cost of the parts, the price tag for one of these radars would be $459,000. CASA‘s recurring costs for each radar is $29k. Two caveats are noted: 1) the CASA radars were developed by an academic team for use as an experimental research facility, and cost-containment was not a strong design driver in realizing this system; 2) these represent low volume costs, given that the CASA project produced only four radars for this test bed.

The CASA project has set a “cost bogie” of $200k as the price tag for these radars when they are manufactured in larger quantities than the CASA Oklahoma deployment. When compared to the performance of CASA is fielded research radars and the $200k cost bogie, lower cost & performance and higher cost & performance radars do exist in the market for various applications; this provides a bracketing context for envisioning the low-cost weather radars envisioned here. As is the case with other electronic components, cost is driven by both required performance and sales volume. Current market offerings for X-band radars include $200 solid-state radars manufactured in high volumes for automobile collision avoidance, marine radars with rotating antennas in the $2k-$20k range, mechanically-scanned weather radars in the sub-$1M to $10M range, up to very high-performance multi-function phased array radar systems developed for defense applications costing hundreds of millions to billions of dollars.

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