P11.3 DISTRIBUTED COLLABORATIVE ADAPTIVE SENSING (DCAS) FOR IMPROVED DETECTION, UNDERSTANDING, AND PREDICTING OF ATMOSPHERIC HAZARDS

David J. McLaughlin[1*], V. Chandrasekar[2], Kelvin Droegemeier[3], Stephen Frasier[1], Jim Kurose[4], Francesc Junyent[1], Brenda Philips[1], Sandra Cruz-Pol[5], and Jose Colom[5]

[1]Dept. of Electrical and Computer Engineering, University of Massachusetts
[2]Dept. of Electrical and Computer Engineering, Colorado State University
[3]School of Meteorology, University of Oklahoma
[4]Dept. of Computer Science, University of Massachusetts
[5]Dept. of Electrical and Computer Engineering, University of Puerto Rico, Mayaguez

1. INTRODUCTION

Today's weather observing radars are designed for long-range (up to hundreds of km) coverage with single-beam antennas designed to comprehensively map winds, precipitation, and other phenomena over large volumes of the mid- to upper-troposphere. Data collected by these sensors serve as critical inputs to weather-related decision making in many public and private sector functions (such as hazardous weather warning, transportation, agriculture, energy, among others) and new uses continue to develop as data dissemination [1] and computational capabilities improve. Although the coverage of these radars is adequate for many situations, coverage at low altitudes far away from the radars is insufficient for many applications due to Earth's curvature and terrain-induced blockage [2]. For example, the WSR-88D (NEXRAD) system is unable to view ~ 80% of the troposphere's volume below 3 km altitude. This prevents the system from detecting the full vertical rotation of most tornadoes and can limit the accuracy of precipitation estimates near the surface. Long-range radars operate at wavelengths in the 5-10 cm range in order to minimize attenuation due to precipitation, and this necessitates the use of physically large antennas to achieve high spatial resolution. Despite the use of large antennas, spatial broadening of the radar beam with increasing range prevents these systems from resolving structures on the sub-km scale over most of the coverage volume.

Distributed Collaborative Adaptive Sensing (DCAS) is a new approach to radar sensing of the atmosphere being investigated to overcome the coverage limitations inherent in long-range radar networks. *Distributed* refers to the use of large numbers of small solid-state radars, spaced appropriately to overcome blockage due to the Earth's curvature and improve resolution degradation caused by beam spreading. In addition to providing the potential for high-resolution sampling throughout the entire troposphere, this distributed concept lends itself to the efficient utilization of low-power solid-state radars. These radars (once they are developed) are highly reliable, inexpensive, adaptive, and can operate *collaboratively*, via rapid coordinated targeting of multiple radar beams, based on atmospheric and hydrologic analysis tools (detection, tracking, and predicting algorithms) that diagnose weather conditions in real-time and re-steer radar beams onto atmospheric regions where threats exist. *Collaborative* operation is envisioned as a means to achieve greater sensitivity, precision, and resolution than is possible with a single beam by coordinating the beam-positions of multiple radars and by processing echoes from multiple beams viewing the same scattering region. *Adaptive* refers to the ability of these radars and their associated computing and communications infrastructure to rapidly reconfigure in response to changing conditions in a manner that optimizes the systems' ability to respond to competing end-user demands. For example, a DCAS radar network might pinpoint tornado locations with extremely high spatial resolution for public warning while simultaneously mapping the horizontal wind field associated with the parent thunderstorm and providing quantitative precipitation estimates for input to distributed hydrological models. The system accomplishes this by continually adjusting both radar parameters (such as pulse-repetition frequency, scan rate/dwell time) and computational functions (such as calculating spectral moments versus calculating full Doppler spectra) during the volume scans of multiple coordinated radars, all in response to changing weather.

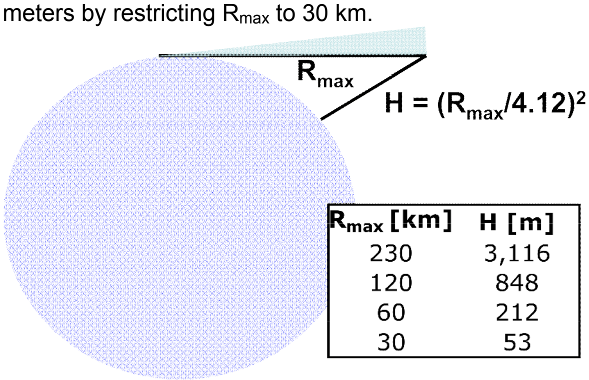
The U.S. National Science Foundation recently established an Engineering Research Center titled the Center for Collaborative Adaptive Sensing of the Atmosphere (CASA), formed by a consortium of four universities, namely (listed alphabetically), Colorado State University, University of Massachusetts (lead University), University of Oklahoma, and University of Puerto Rico at Mayaquez, and a partnership with industry and government labs to create the underlying knowledge, technology, and systems-engineering trade-off space for realizing future DCAS systems and to conduct

Corresponding author address: David J. McLaughlin, Director, Center for Collaborative Adaptive Sensing of the Atmosphere (CASA), College of Engineering, University of Massachusetts, Amherst, MA 01003, mclaughlin@ecs.umass.edu

proof-of-concept experiments that demonstrate how these systems can improve our ability to detect, track, and predict localized hazardous weather. This paper describes the geometric and physical principles governing key design trade-offs for DCAS radar networks and summarizes CASA's strategy for realizing test-bed demonstrations of this concept.

2. NETWORK GEOMETRY

The blockage of a radar beam by the curvature of the Earth is illustrated in Figure 1. (Note that this is a smooth-Earth calculation, and the effects of mountains and other topographical features, which will be important in radar siting and network design, are neglected in this simplified analysis.) The radar beam is tilted such that its lower beam-edge is at 0^o elevation angle, and the "coverage floor", H, is defined as the height of the lower edge of the radar beam above the earth at the maximum operating range of a radar, R_{max}. At the 230 km maximum Doppler operating range of a NEXRAD radar, the coverage floor is approximately 3 km [3]. The coverage floor is reduced for shorter-range radars. For example, the coverage floor is reduced to ~ 50 meters by restricting R_{max} to 30 km.



R_{max} [km]	H [m]
230	3,116
120	848
60	212
30	53

Figure 1. Coverage floor versus radar maximum range.

Future deployments of DCAS sensing networks may be located in: heavy population areas; geographic regions particularly prone to wind hazards or flash floods; valleys within mountainous regions; specific regions where it is particularly important to improve observation of low-level meteorological phenomena [4]; or deployment across the entire contiguous United States (or other nations and groups of nations). Figure 2 shows the total number of radars that would be needed for deployment over the contiguous United States as a function of R_{max}. The NEXRAD network, with 158 radars spaced approximately 230 km apart, appears on this plot in the lower right and is representative of a "sparse" radar network

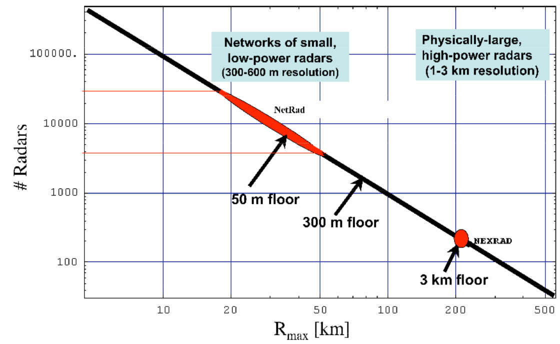


Figure 2. Number of radars needed for nation-wide deployment versus radar spacing.

A "dense" nation-wide network-of-radars (which we hereafter refer to as NetRad) containing 4000 – 15,000 small low-power DCAS radar nodes, spaced 10's of km apart, would have a coverage floor < 100 m and would potentially achieve spatial resolution ~ 300-600 m throughout the entire troposphere. Cost, maintenance and reliability issues, and aesthetics motivate consideration of small (~ 1 meter diameter) electronically-scanned antennas that could be installed on either low-cost towers or existing infrastructure elements (such as roof-tops or cellular communication towers). The cost to deploy and operate a DCAS network will include both the up-front cost of the radars and their associated communication and computation infrastructure and the recurring costs to maintain the systems, buy or rent land and space on towers/rooftops, and provide for data communication between the radars, operations and control centers, and users. These costs, in addition to numerous technological and system-level tradeoffs, need to balanced to ultimately develop an effective system design. CASA's strategy for creating the design basis for DCAS is described in Section 5 of this paper.

3. NETWORK TOPOLOGY

Dual-Doppler estimation of horizontal wind vectors, triangulation-based "pinpoint" tracking of storm features, bistatic scattering measurements, and other functions that require multiple-looks from different directions can be achieved by overlapping the coverage regions of adjacent radars. Brewster et al., [5] describes an analysis carried out to determine the optimal arrangement of a small network of radars to maximize dual-Doppler overlap. An extension of this work, shown Figure 3, shows the topology for a large network that maximizes dual-Doppler coverage.

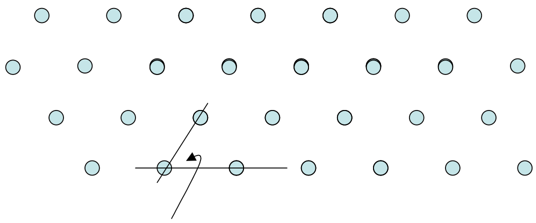


Figure 3. Hexagonal network topology that maximizes dual-Doppler coverage.

Maximum dual-Doppler overlap is achieved by arranging radars in hexagonal cells, such that the vertex formed by lines joining three neighboring radars forms a 60 degree angle. White [6] presents results of numerical studies designed to determine optimal configurations of networks of radar sites for various numbers of radars as well as adaptive scanning strategies optimized for retrieving wind fields with conservation-of-mass side constraints.

4. KEY RADAR PARAMETERS

4.1 Antenna beamwidth and size. The constraint of using small antennas in DCAS designs motivates consideration of short wavelengths (higher microwave frequencies than are used in long-range radar networks) to achieve high spatial resolution. Figure 4 shows the median azimuth and elevation (cross-range) spatial resolution achieved with a 1.2 meter antenna as a function of frequency for the case where R_{max} = 30 km. (Median resolution in this instance is defined as the resolution level achieved at 21 km range, since 50% of the volume observed in the lowest angle elevation tilt would have spatial resolution above, and below, this level.) A median spatial resolution of 500 m is achieved at X-band (10 GHz). Operating at frequencies higher than X-band potentially achieves higher spatial resolution but suffers substantially greater attenuation due to precipitation, as discussed in the next section.

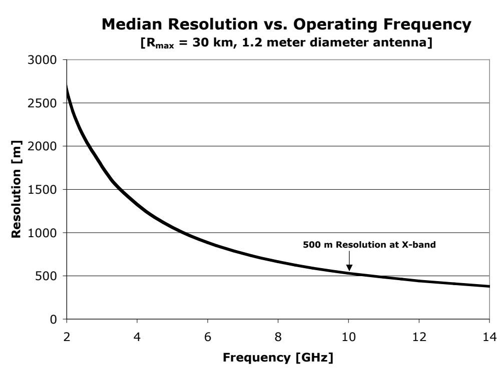


Figure 4. Cross-range (azimuth and elevation) resolution versus frequency for a 1.2 meter antenna. Values shown represent median resolution achieved for radars having R_{max}=30 km. Worse-case resolution is 41% larger than the values shown.

4.2 Attenuation. Table 1 compares the two-way attenuation of a radar beam passing through a hypothetical 10 km rain-cell having rainfall intensities ranging from 4 to 40 mm/hr. Whereas S- and C-band attenuation levels are small, attenuation at the shorter X-band wavelength is 20 dB/10 km. This level of attenuation precludes using X-band for today's long-range radars but represents a tolerable loss in signal power for a dense network of short-range radars.

Two- way attenuation through 10 km rain

Rain rate	S-Band	C-Band	X-Band
4 mm/hr	.04 dB	.2 dB	2 dB
20 mm/hr	.2 dB	1 dB	10 dB
40 mm/hr	.3 dB	2 dB	20 dB

Table 1. Rainfall attenuation for three different frequency bands.

Management of attenuation involves building an attenuation margin into the power-sensitivity budget of the radar design [7], compensation for the effects of attenuation on reflectivity estimation [8], and coordinated (or "collaborative") beam-scanning strategies that view storms simultaneously along multiple directions views of the storm along differently-attenuating paths [9,13].

4.3 Transmitter Power and Scan Strategy. Signal-to-noise analyses conducted to estimate the measurement sensitivity of a DCAS system are shown below for the purpose of comparing different volume scanning strategies. R_{max} is assumed to be 30 km and other key system parameters are listed in Table 2. Comparison of different scanning strategies is based on evaluating Z_{min} for different scan update-times, with Z_{min} defined here as the minimum reflectivity observable by the system which results in an RMS reflectivity-estimate error of 1 dB. The radar transmitter is assumed to have 12.5 kW of effective peak power and 25 W of average power. This is achieved by using either a small magnetron transmitter having 12.5 kW peak power or a chirped signal from a 75 Watt peak—power solid state amplifier having a pulse-compression gain of 22 dB. Received pulses are incoherently integrated and it is assumed for these calculations that volumetric echoes are uncorrelated from pulse-to-pulse. (The assumption of pulse-to-pulse decorrelation may not be satisfied for all meteorological targets at the 3 KHz PRF used here for a fixed radar carrier frequency. However decorrelation can be forced by "dithering" the transmitted frequency from pulse to pulse [10]. We believe this can be accomplished at a manageable cost of increased transmitter and receiver complexity using low-power solid state radar designs.)

Key System Parameters	
Operating Frequency [GHz]	9.3
Wavelength [m]	0.03
Antenna Diameter [m]	1.50
Antenna Beamwidth [deg]	1.5
Maximum Range [R_{max}, km]	30
Effective Transmitter Power [kw]	12.5
Average Transmitter Power [W]	25.0
Pulse Repetition Frequency [Hz]	3000.0
Noise Figure Fn [dB]	5.5
System Losses [dB] (inc. rainfall)	-20
Range Resolution [m]	100

Table 2. System parameters for sensitivity calculations in section 4. A 20 dB margin for system losses (including 15 dB for precipitation attenuation and 5 dB for microwave component losses) is included in the sensitivity studies to follow.

4.3.1. Full volume surveillance mode. We first consider the case where radars having R_{max}=30 km are spaced 25 km apart and configured for sampling the lower troposphere with emphasis on the region below 3 km using the volumetric scanning pattern shown in Fig 5. A sequence of seven azimuth scans is conducted with the antenna beam incrementing in two degree steps from one scan to the next, with the “cones of silence” above each radar being surveyed by neighboring radars.

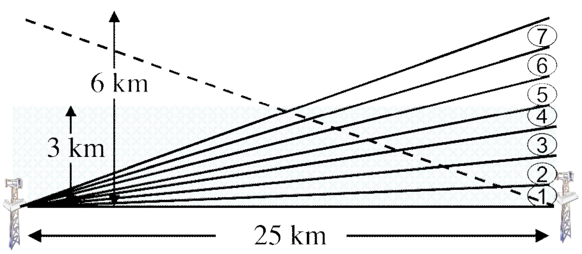


Figure 5. Volume coverage pattern comprised of 7 elevation beam positions spanning 0-12^{o} in 1.7^{o} steps for observing the lower-troposphere below 3 km altitude. The “cone of silence” above each radar is observed by adjacent radars in the network.

The measurement sensitivity of this system as a function of volume-scan-time is shown in Fig. 6. Volume scan times significantly exceeding ~ 5 minutes are undesirable since such a low update time precludes observing and tracking rapidly evolving events, and the minimum sensitivity of a DCAS system in this mode is thus Z_{min}=20 dB.

It is often tempting to compare Z_{min} values among different observing systems, and care must be taken when doing so, since Z_{min} is specified and used in different ways to characterize different observing systems and different sensing and detection functions. Interpretation of this sensitivity calculation means that the DCAS system considered here would have sufficient sensitivity to estimate reflectivity, to within 1 dB RMS error, during rainfall rates as low as 1 mm/hr throughout the entire coverage volume. This sensitivity would be inadequate for measuring the reflectivity of snowfall, convergence lines[1], and boundary layer winds[1] with this same degree of measurement precision.

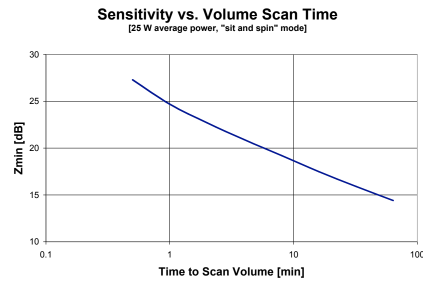


Figure 6. Radar sensitivity (minimum reflectivity causing 1 dB RMS reflectivity error at R_{max}) versus volume-scanning update time for the geometry shown in Fig. 5.

4.3.2 Selective sampling and limited-sector scans. Measurement sensitivity can be increased without increasing the update time by limiting the scan volume to those specific regions of the atmosphere where threats are exist and by taking advantage of integration-gain. Figure 7 considers the increased sensitivity associated with two limited-sector modes and contrasts these with the full-volume VCP previously discussed. Sensitivity is increased by 5 dB by restricting the azimuth scan sector to 45^{o} while still stepping through seven elevation beams (middle curve). The increase relative to the full-volume case is 12 dB when the system is configured to conduct the more limited 30^{o} azimuth sector scan with a single elevation beam (bottom curve). These curves illustrate how judicious scanning of particular regions of the atmosphere can be used to “concentrate” antenna beam resources to those regions of the atmosphere where (and when) the observing need is deemed greatest. A candidate architecture for a closed-loop system that diagnoses the atmosphere in real-time and continually re-steers beams in a DCAS network is described in [11,12].

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[1] The source of radar-scatter for clear-air convergence lines (including sea breezes, gust fronts, dry lines, and other frontal-induced features) and boundary-layer winds is primarily insect echo during the warm season, and the median reflectivity for these events is 10 dBZ [3]

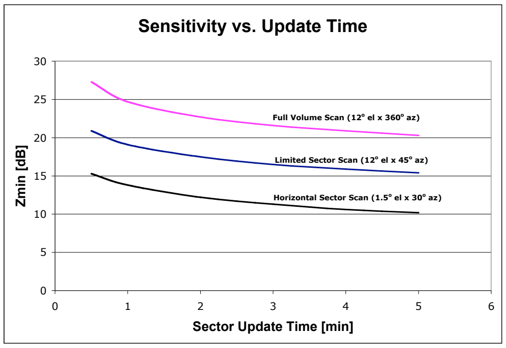

Figure 7. Comparison of three volume coverage patterns revealing the integration-gain benefits accrued by limiting the sectors covered.

5. RESEARCH STRATEGY

CASA commenced operations as a funded NSF Engineering Research Center in September 2003 and is organized around a strategic planning concept shown in Figure 8. The center's research goals are 1) to develop the underlying knowledge basis to support rational design tradeoffs for future DCAS systems; 2) to develop the key technologies needed to implement DCAS systems; and 3) to design, implement, and field test experimental systems to both demonstrate proof-of-concept and support further inquiry into the design of these systems. The center's research projects fall into the three different planes of fundamental inquiry; enabling technology development; and systems architecture/technology integration and are conducted to break down the 12 barriers listed in Figure 8.

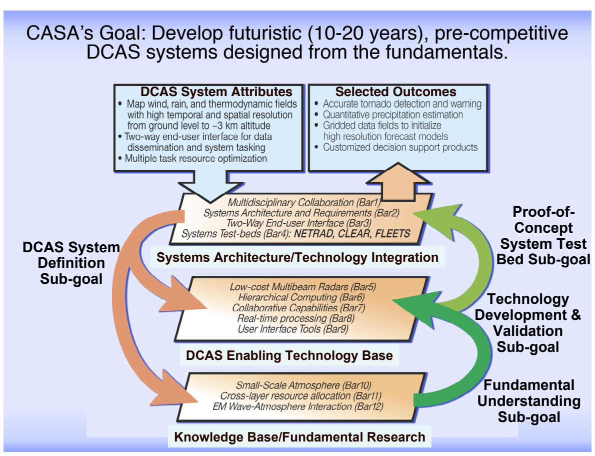

Figure 8. CASA's Strategic Planning Concept

"Integrative Projects" serve as a the main organizing construct of the center to focus research projects toward systems-level goals. Each such project is defined in terms of an end-to-end DCAS demonstration system that connects specific end users to field-deployed hardware and software. The first such project will demonstrate DCAS concepts for high temporal and spatial resolution mapping of winds in the lower troposphere for detecting, tracking, and predicting severe storms, with an emphasis on tornadoes [13], in western Oklahoma. This system will be deployed beginning September 2005, initially as a four-node (four magnetron radars) adaptive network [5] and later expanding to a larger number of nodes. Research and development projects are currently being conducted to design the radars, networking protocols [15], and command/control software architecture for this project [12] and quantify the system's ability to detect tornadoes [13], retrieve 2D and 3D wind fields [6], and improve data assimilation through ensemble Kalman filtering for numerical weather prediction [14]. The second "Integrative Project" is to design and test a DCAS system in Houston, TX to measure precipitation and support urban flood prediction near the Texas Medical Center [16]. The radar spacing in the Oklahoma and Houston systems will be 20 – 30 km, and the hardware elements will be deployed atop telecommunication towers, rooftops, and other elements of the built infrastructure. CASA's third Integrative Project, which is entirely led by a team of students, will be an "off-the-grid" DCAS system comprised of smaller radar nodes spaced ~ 5 – 20 km apart that generate their own power and communications and thus operate independent of the built infrastructure. All three systems will be designed to detect hydrometeor (rain and hail) scattering from precipitating storms as well as debris from tornadoes, and these initial DCAS networks are this being designed to achieve Z_{min} levels of 10-20 dBZ.

The fourth test bed project will target the non-precipitating atmosphere, relying on insects as well Bragg-scale turbulence to generate radar echoes. Bragg-scale turbulence presents extremely small radar echoes at X-band, since the resonant wavelength is smaller than the energetic high-wavenumber end of the inertial subrange. Therefore, this system will operate in bistatic scattering geometries that are expected to result in detectable scatter from small-scale turbulence elements as described by Tulu and Frasier [17].

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forecast offices in Norman, OK and San Juan, PR and the Massachusetts Department of Education, and all are contributing valuable time, software and creativity to the DCAS effort.

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