3.14 INTEGRATING END USER NEEDS INTO SYSTEM DESIGN AND OPERATION: THE CENTER FOR COLLABORATIVE ADAPTIVE SENSING OF THE ATMOSPHERE (CASA)

Brenda Philips[1], David Pepyne[1], David Westbrook[1], Ellen Bass[2], Jerry Brotzge[3],
Walter Diaz[4], Kevin Kloesel[3], Jim Kurose[1], David McLaughlin[1], Havidan Rodriguez[5], Michael Zink[1]

University of Massachusetts[1], University of Virginia[2], University of Oklahoma[3]
University of Puerto Rico[4], University of Delaware[5]

1. INTRODUCTION

The Center for Collaborative Adaptive Sensing of the Atmosphere (CASA), a National Science Foundation Engineering Research Center, is creating a new type of weather observation system featuring networks of low-power, low-cost radars that adaptively and collaboratively collect high resolution data in the lowest 3 km of the atmosphere, a region which is under sampled by current technology. These radar networks have the potential to improve our ability to observe, understand, forecast, and respond to weather hazards. Called Distributed Collaborative Adaptive Sensing (DCAS) networks, these systems will map wind, rain, and thermodynamic variables in the lower troposphere, supplying real-time, dynamic data to decision makers, such as National Weather Service (NWS) forecasters and emergency managers, based on their information needs. Unlike current radar systems that “push” the same data out to all users, DCAS systems feature a data “pull” where user needs drive the operation of the radar network. (McLaughlin et al. 2005).

This paper describes how CASA is embedding end user needs for data into the design and operation of DCAS systems through resource allocation and optimization algorithms that determine where and how the radars scan. It will describe how preferences for data were elicited from different user groups and then translated into quantitative input for system operation. This approach creates the technological link between user preferences for information and radar observations. Such an effort requires multi-disciplinary collaboration among engineers, computer scientists, meteorologists, social scientists, decision scientists, and the user community. CASA, as part of the Engineering Research Centers program, provides the research infrastructure, such as test beds, and the organizational culture to achieve this goal.

2. OKLAHOMA TEST BED

Now in its third year of a ten year grant, CASA is deploying proof-of-concept test beds in Oklahoma, Texas and Puerto Rico with radars, IT infrastructure, and users of weather data. The Oklahoma test bed is a four node network of agile, adaptive X-band radars designed for researching and demonstrating DCAS concepts

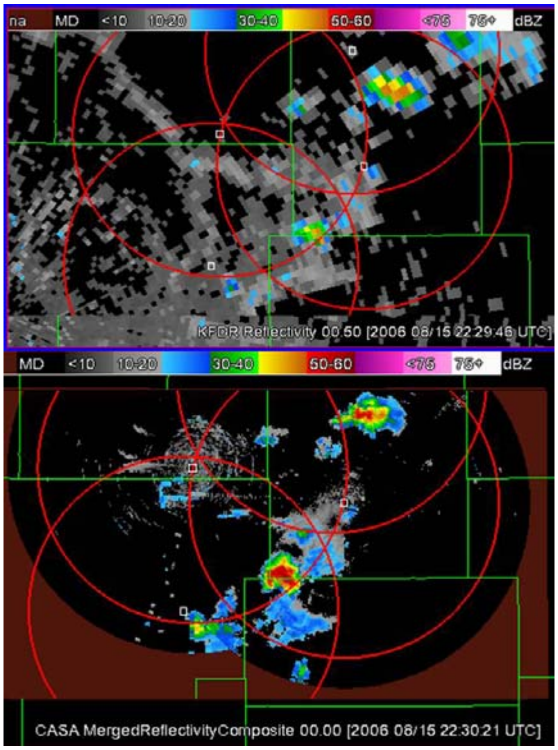
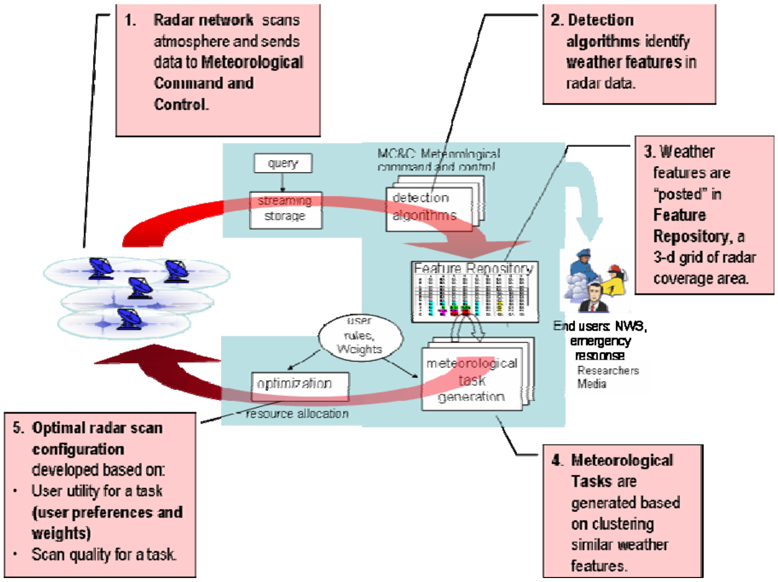


Figure 1. *Early data from the Oklahoma test bed (lower image) demonstrates the improved resolution of DCAS data vs. NEXRAD (top image).*

Corresponding Author: Brenda Philips, Center for Collaborative Adaptive Sensing of the Atmosphere, University of Massachusetts, 209 Knowles Engineering Building, Amherst, MA 01003, email: bphilips@ecs.umass.edu for severe storms, with an emphasis on tornados. DCAS capabilities include the ability to map winds in the lowest 3 km of the atmosphere at a spatial resolution of 25 – 100 m and the ability to triangulate and pinpoint the location of localized shear-regions within storms. Key to these capabilities is a scheduling and radar beam steering technology for performing sector scans between 60 and 270 degrees. Sector scanning permits more focused data collection, enabling multiple elevation scans to be made in the same amount of time as a single 360 degree scan.


1. **Radar network** scans atmosphere and sends data to **Meteorological Command and Control.**

2. **Detection algorithms** identify **weather features** in radar data.

3. **Weather** features are "posted" in **Feature Repository,** a 3-d grid of radar coverage area.

4. **Meteorological Tasks** are generated based on clustering similar weather features.

5. **Optimal radar scan configuration** developed based on:
- User utility for a task **(user preferences and weights)**
- Scan quality for a task.

Figure 2. *DCAS System Architecture*

The test bed covers a 7,000 square km region in southwestern Oklahoma that receives an average of four tornado warnings, 53 thunderstorm warnings, 15 strong to severe wind events and 19 severe hail events per year. Users of weather data -- the National Weather Service Forecast Office in Norman, Oklahoma, a group of emergency managers who have jurisdictional authority within and downstream of the test bed area, several private sector entities, and CASA's science researchers -- are an integral part of the test bed. The test bed became operational during summer 2006 and as of fall 2006 was undergoing functional validation. Early data has shown promising results as illustrated in Figure 1. For more details and results, see Brotzge et al. 2007.

.

3. EMBEDDING END USER NEEDS INTO SYSTEM OPERATION

In the current design, the DCAS system dynamically adapts radar scans at 30 second intervals to sense the evolving weather, feeds data to customized weather detection algorithms and disseminates information to users based on their changing preferences for data. See Figure 2 for an overview of the system architecture.

To illustrate the value of the DCAS concept, consider how different user groups may have distinct preferences for DCAS data: an NWS forecaster may analyze the vertical structure of a storm to determine whether to issue a warning by viewing a sector scan at multiple elevations, while an emergency manager may require two radars to collaborate in order to pinpoint the location of the most intense part of a storm for spotter deployment, and a CASA researcher may require 360 degree scans at all elevations to initialize a numerical weather prediction model. These diverse information preferences require different radar scanning strategies that, in some cases, could exceed the resources (sensing, computation, and bandwidth) available in the system. Which user information preferences should the system serve first?

In order to manage diverse user preferences and address these potential resource conflicts, CASA has created an *end user policy* that maintains *i) user rules,* specifying in what manner and how often different kinds of weather phenomena should be scanned by radars (user preferences) and *ii) user weights* to establish the relative priority of different user groups in case of resource conflict. The end user policy interacts with the optimization and resource allocation algorithms that determine where the radars scan next.

Figure 3 shows the optimization equation that is evaluated during step 5 in Figure 2. The goal is to deliver the best quality data that is most important to users. This equation maximizes overall utility of a scan, J, based on *i)* U(t,k), how important a candidate meteorological task t is to the user community at time k, and *ii)* Q(t,C), how well the radars are able to scan the task where C is the set of beam steering commands sent to the radar. U(t,k) is called end user policy which, in turn, is a function of the

$$J = \max_{configurations,C} \sum_{tasks,t} U(t,k)Q(t,C)$$

End User Policy – How important is task *t* to the users?

$$U(t,k) = \sum_{groups,g} w_g U_g(t,k)$$

User Weights

User Rules

Figure 3. *Optimization Equation*

utility of a user rule Ug(t,k) for user group g weighted by wg, group g's priority in the system. The value of Ug(t,k) depends on the time since the task was last successfully scanned, to enforce a periodic sampling strategy. In the current system design, user preferences are encoded in the user policy as rules; however, future designs of the system will include the ability for users to dynamically change their preferences through real-time interaction with the system. For a detailed technical overview of the optimization function, see Kurose et al. 2006, Pepyne et al. 2006.

4. TRANSLATING USER PREFERENCES INTO RULES

Several challenges had to be overcome in developing the initial End User Policy (Version 1) for the Oklahoma test bed. The first challenge involved obtaining user preferences for data for a system that did not exist as yet, and that would most likely result in new ways of analyzing radar data. Because of the newness of the system, our strategy focused initially on obtaining qualitative information from a limited number of Subject Matter Experts (SME's). SME's provided input based on their use of current radar data for decision making and their best determination of how DCAS data would provide additional benefits. The second challenge involved translating these preferences into rules and utility functions that could be used by the optimization and resource allocation equations. This translation required ensuring that the computer scientists and engineers designing and coding the system had an understanding of

Rules	Rule trigger	Sector Selection	Elevations	# Radars	Contiguous	Sampling interval
			NWS			
N1	time	360	Lowest two	1	Yes	1 / min
N2	storm	task size	full volume	1	Yes	1 / 2.5 min
			Researcher			
R1	rotation	task size	full volume	2+	Yes	1 / 30 sec
R2	reflectivity	task size	Full volume	2	Yes	1 / min
R2	velocity	task size	lowest two	2+	Yes	1/ min
R3	time	360	Full volume	1	No	1/ 5 min
			EMs			
E1	time	360	lowest	1	Yes	1 / min
E2	reflectivity over AOI	task size	lowest	1	Yes	1 / min
E3	velocity over AOI	task size	lowest	2	Yes	1/ 2.5 min
			OS			
O1	time	360	lowest two	1	No	1 / 5 min

Table 1. *User Rules, End User Policy, Version 1*

the decision process of the users. Our methods included review of best practices for current decision making, in-depth interviews, development of user requirements, and table-top experiments using simulated DCAS data with users. Many of these efforts included the multidisciplinary group of CASA researchers.

Table 1 contains the current version of rules devised from user preferences, for the three different user groups. The "Rule Trigger" determines whether a rule is activated based on a detected weather feature, such as an area of high reflectivity, or an interval of time. The "Sector Selection", "Elevations" and "Number of Radars" define how each radar should scan, and "Sample Interval" designates the periodicity of the rule. As discussed earlier, the utility of a rule (*Ug*) increases as the Sample Interval approaches. For example, the NWS rule, N2 specifies that based on the time since last scanned, each radar should scan a 360 degree sector at the lowest two elevations every minute.

The following sections discuss how decision making processes for different user groups were translated into rules.

4 .1 *National Weather Service Forecasters*

The National Weather Service (including the Weather Forecast Office (WFO) in Norman, Oklahoma and the Warning Decision Training Branch) will participate as pilot users in the test bed. The overarching goal of the WFO is to save lives and property by issuing severe weather warnings, and communicating expertise to emergency mangers, the media and the public.

The warning process involves 6 iterative stages: anticipation/ expectation (developing a conceptual model of the evolving event, determining staffing needs); data selection; feature recognition; ground truth (media, spotters, mesonet data); warning generation and dissemination; and non-meteorological factors (location and impact of weather, staffing, and equipment availability). Forecasters analyze radar data by creating a "mental movie" using the closest radar to the phenomena of interest. By recognizing specific features and signatures in base velocity and reflectivity data and linking these back to conceptual models, forecasters use radar data to increase or reduce their confidence in an existing or potential warning decision. (Quoetone, 2005, Hahn 2003).

CASA's first strategy for translating the severe weather warning decision process into rules involved assigning utilities (through user rankings) to specific weather features, such as a tornado or a mesocyclone, that correlate to the features forecasters seek to identify in the data. The radar network would execute sector scans of these features giving higher priority to the strongest features. This early version of rules was demonstrated to NWS forecasters in a table top experiment using simulated CASA data. Through this experiment, the system designers came to understand that the NWS warning decision process focused more on visually analyzing data at regular intervals to look for patterns, than on evaluating specific weather features based on strength. We also learned that the "jumpiness" of the sector scans executed by alternating radars interfered with the continuity of the "mental movie" that forecasters use to analyze data. These findings resulted in the following changes to the rules and system design:

- **Incorporation of interval-based scanning.** In the current version, user rules are triggered by time (e.g., every 2.5 minutes scan a severe storm at all elevations) as well as by the detection of weather features. Utility is based on the time since last scanned.
- **Expansion of the definition of a storm cell.** We modified the sector size of the storm-cell rule, so that it includes areas of lower reflectivity. NWS forecasters are interested in looking at lower reflectivity boundaries for cues on how a storm may evolve or where new storms may develop.
- **Introduction of contiguous scans**. While keeping the advantages of sector scanning which allows for rapid vertical analysis of storm structure, system designers addressed the "jumpiness" of the radar scans by creating methods to force the system to favor scans the promote continuity in the data. This issue will also be addressed in the visualization of the data.
- **Dynamic Data Requests.** In the future, the ability for forecasters to dynamically change or add preferences for data will be incorporated into the system. Forecasters frequently use radar data to evaluate areas of uncertainty. However, the location of an area of uncertainty is often determined by information sources beyond the radar data (for example spotter reports). Such preferences would be difficult to codify in the user rules.

A second table-top experiment was conducted using a numerical storm simulation to obtain feedback on Version 1 of the policy. This version was acceptable to the expert group of NWS forecasters.

4.2 *Emergency Managers*

A pilot group of 11 emergency managers with jurisdictional authority within and surrounding the test bed will participate in the project. Emergency manager practices vary from sophisticated users to those with limited or no access to the internet or training on interpreting radar data. The emergency managers selected for this stage of system development are a technologically sophisticated group that receives periodic training on interpreting weather information from a state-run organization called the Oklahoma Climatological Survey (OCS) that distributes decision support products via a customized web site for emergency mangers (Morris et al 2001). By understanding how sophisticated users utilize DCAS data, we can create the appropriate rules and then work to create the appropriate decision support tools that will assist emergency managers with less training and access to the technology.

While NWS forecasters have a well-documented decision making process, similar documentation does not exist for emergency managers, primarily because emergency managers in Oklahoma work for local jurisdictions, rather than a central organization. OCS trains emergency managers to analyze weather data, but does not prescribe how this information should be used for local decision making. Therefore, we are creating a descriptive decision model of emergency managers in Oklahoma through in-depth interviews, questionnaires and weather case simulations. In-depth interviews with emergency managers (N=47) provided information for system design on topics such as attitudes toward tornado tracking and detection, risk and frequency of weather-related threats, and emergency manager priorities for end user policy. (Donner, forthcoming 2007; Rodriguez et al. 2006). In addition, a questionnaire was administered to 11 emergency managers from the test bed area to understand how their information gathering, weather assessments, and decisions changed from the pre-storm environment through the occurrence of an actual event. (Baumgart et al. 2006).

These OCS-trained emergency managers make decisions about the notification and deployment of spotters and first responders, and notification of the public through tornado sirens, cable television overrides and/or cooperation with the local media. Their decisions are focused on the local level, encompassing several towns or a county. They interact with WFOs, and analyze weather information and local ground truth reports from spotters and local media to understand how an evolving weather event will impact their jurisdiction.

Given the focus on specific counties and towns, emergency manager rules allow for local pinpointing of areas of wind shear and high reflectivity (E2, E3). A surveillance scan each minute at the lowest elevation helps to maintain situational awareness (E1). The data output based on these rules were demonstrated in a high resolution simulation of the data.

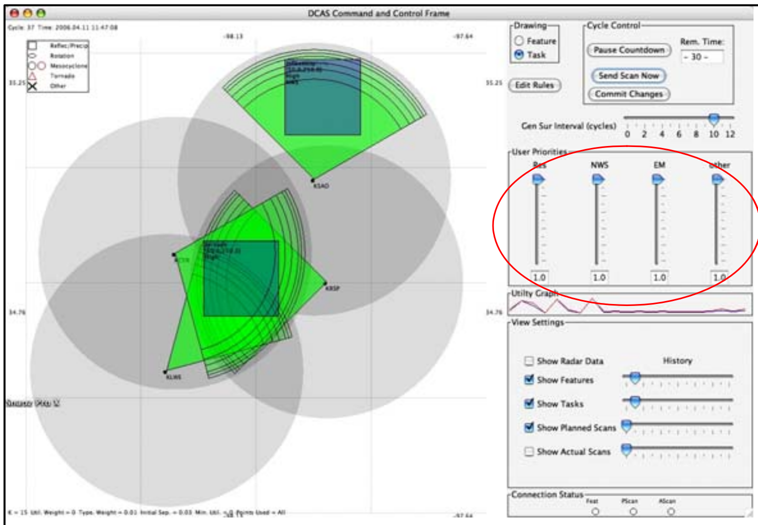
4.3 *CASA Researchers*

CASA researchers are also treated as a user group. The researchers developed a user requirements document to enable research on a variety of topics including storm morphology, dual-Doppler analysis, and data assimilation. For storm morphology, researcher rules focus on obtaining detailed information from as many radars as possible, for example when strong shear or tornado signatures are detected. (The radars have overlapping coverage areas). These are covered by R1, R2 and R3. The Numerical prediction rule, R4, specifies gathering data at all elevation angles with 360 degree scans every 5 minutes. However, these multi-elevation scans do not have to occur sequentially. They can be interleaved with other scanning tasks. In the future, we will also accommodate rules for vertical scanning of the atmosphere.

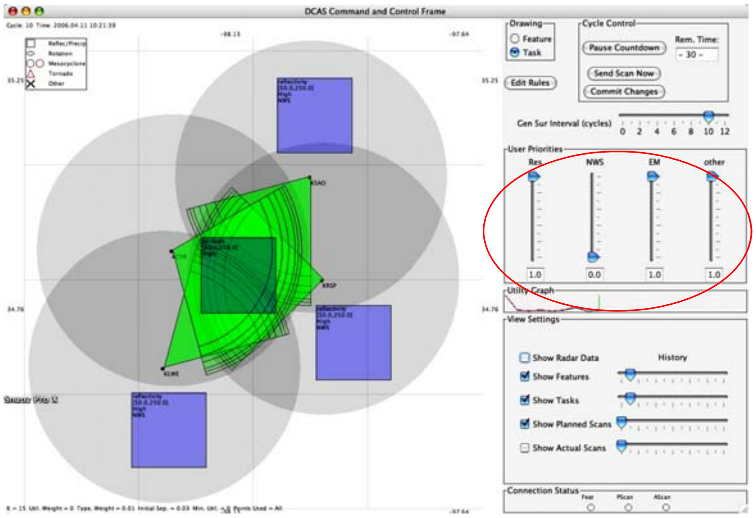
5. USER WEIGHTS

Section 4 discussed the development of user utilities Ug(t,k) through the creation of user rules. This section will discuss wg, the user weights that determine which users (NWS, emergency managers, and researchers) have priority. In the Oklahoma test bed, the system currently has the *capability* for weighting different user groups. However, we do not yet have an overall *Policy* for assigning and adjusting weights, recognizing the potentially contentious nature of gaining consensus among the different users as to how these weights should be set. As a first step toward creating this *Policy*, we are conducting system sensitivity experiments to understand the level of resource contention in the system per user given the current set of rules. In addition, future research is planned to incorporate socioeconomic impacts of the system into the weighting function. (See Section 7, next steps.)

Figure 4 below shows a prototype interface that controls and displays results of the resource allocation and optimization algorithm. It demonstrates how adjustments to user weights can change the scanning strategy selected by the system. User weights or priorities (wg in Figure 3) are controlled by the sliders circled in red. Grey circles show the location and coverage area of the four radars in the Oklahoma test bed. Blue squares represent candidate scanning tasks (t in Figure 3) based on meteorological detections; green sectors represent the actual radar scans selected by the optimization and resource allocation algorithm based on the user rules and weights.



- Weights/Priorities: All Users = 1, highest priority
- Tornado scanning task in quad doppler area
- Storm scanning task in single radar area
- Scanning strategy: 3 radars on tornado; 1 radar on storm
- Rationale: NWS rules state that storms should be scanned with one radar at multiple elevations (N2); EM and Researcher rules specify scanning tornados with multiple radars. (R1, E3)



- Weights/Priorities: NWS=0; Other Users =1
- Tornado scanning task in quad doppler area.
- Storm scanning task in single radar areas
- Scanning strategy: 4 radars on tornado; none on storm
- Rationale: NWS rules have no priority; therefore EM and Researcher rules for scanning tornados with multiple radars cause all radars to focus on the tornado task.

Figure 4. *Prototype Interface*

6. OKLAHOMA TEST BED: EARLY RESULTS OF END USER DRIVEN DCAS

A storm that occurred in the middle of the test bed on August 15, 2006 demonstrates how end user policy functions in actual severe weather. Figure 5 shows merged reflectivity data. The light grey areas show the regions scanned by each radar. Since these data were collected as the test bed was becoming functional all system capabilities were not operational. In particular, three of the four radars were functioning and only the following reflectivity rules were included in the optimization:

- N1 – 360 scans, lowest two elevations, every 1 minute.
- N2 – Sector scans of storms, with multiple elevations every 2.5 minutes.
- R2 – Sector scans of storms, with 2 or more radars every 1 minute.
- R4 – 360 degree full volume scans every 5 minutes.
- E1 – 360 scans, lowest two elevations, every 1 minute.
- E2 - Sector scans of storms, with multiple elevations every 2.5 minutes.

In addition, all the user weights were equal (wg = 1). Although it is not shown in merged data below, the 360 degree scans are at the two lowest elevations and the sector scans have up to 6 elevations of radar data.

The sequence demonstrates how the system is able to interleave 360 scans with multi-elevation sector scans to satisfy the sample periods required by both types of rules. In the third image, two radars are collaborating to obtain a multi-Doppler sector scan of the storm cell to satisfy researcher rule R2. For additional analysis of the system's response during this storm see J. Brotzge et al. 2007.

7. NEXT STEPS

7.1 Observing Users in the Test Bed.

Eliciting and understanding user preferences for DCAS data and then defining user policy will continue to be an iterative process. Now that End User Policy Version 1 has been established, research will shift to focus on studying user behavior with actual data in the Oklahoma test bed. The results of this research will be used to make on going modifications of end user policy for future versions.

As an example, emergency managers within the four county test bed area will receive DCAS data in their operational environment. After any weather event for which the NWS issues a severe weather watch or warning for the test bed area, participating emergency managers will complete a web based post event debriefing survey to determine what weather information and resources they used; the usefulness of this information for decision making; and their opinions as to strengths and limitations of DCAS in relation to their work as emergency managers. A control group of managers in the upstream counties will answer the survey with analogous questions focusing on current WSR-88D radar technology. This data will be collected for this small group of users and then our findings will be validated and generalized by creating case studies for experimentation with larger groups of emergency managers. A similar approach is planned for NWS forecasters.

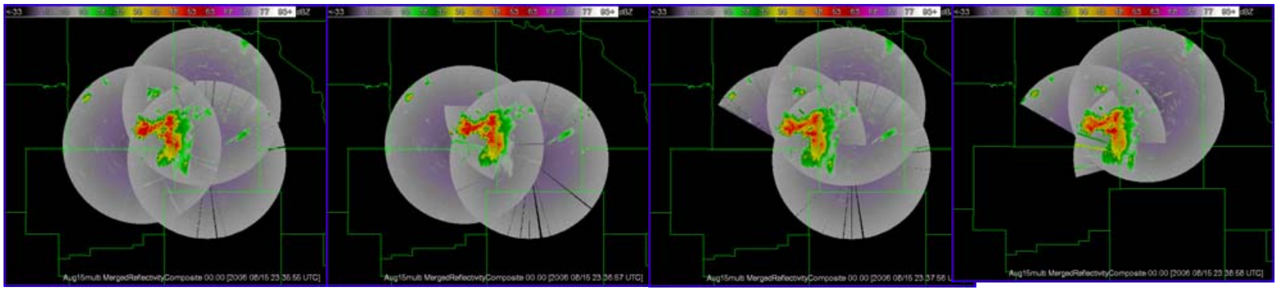


Figure 5. *Merged Reflectivity Data from the Oklahoma Test bed showing adaptive scanning*

7.2 *Incorporating Public Response to Warnings*

CASA also includes the public as users of DCAS information. This research is grounded in sociological theories of public warning response. Using qualitative techniques, researchers have been building on current models of how social and cultural factors influence public response to tornado and wind events. A next step is to create a quantitative model of how the public takes protective measures given variations in i) receiver characteristics, such as age, income, gender or education level; ii) the content, frequency, and sources of warning information; and iii) message accuracy.

7.3 Formulation of the resource allocation and optimization in socioeconomic terms

CASA will conduct research to formulate the resource allocation and optimization algorithms in socioeconomic terms going beyond the current focus on user preferences. CASA plans to develop a decision science framework that would quantitatively link socioeconomic impacts to the engineered system through the end user policy. This would be achieved by creating an integrated decision model of its end-to-end system that quantitatively links “upstream” technical capabilities, such as the targeted radar observations, to their incremental impacts on later “downstream” human response such as warning decisions, risk communication, public response, and the resulting socioeconomic impacts. The end-to-end decision model will enable valuation of DCAS capabilities, such as the improved information or a specific targeted radar observation, in terms of their socioeconomic value.

8. AKNOWLEDGEMENTS

This work is supported primarily by the Engineering Research Centers Program of the National Science Foundation under NSF award number 0313747. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation.

9. REFERENCES

Baumgart, L. A., Bass, E. J., Philips, B. & Kloesel, K., 2006: Emergency management decision-making during severe weather. The 50th Annual Meeting of the Human Factors and Ergonomics Society. San Francisco, CA, October 16-20, 2006, 381-385

Brotzge, J., Brewster, K., Chandrasekar, V., Philips, B., Hill, S., Hondl, K, Johnson, B., Lyons, E., McLaughlin, D. and Westbrook, D., forthcoming 2007: CASA IP1: Network Operations and Initial Data. Preprint, *23rd Conference on IIPS*. San Antonio, TX.

Hahn, B.B, Rall, E., & Klinger, D.W., 2003: Cognitive task analysis of the warning forecaster task. Prepared for the National Weather Service Office of Climate, Water and Weather Services in Norman, OK. *Final Report Order No. RA1330-02-SE-0280*. Fairborn, OH.

Donner, W., Forthcoming 2007: Decision Making as Community Adaptation: A Case Study of Emergency Managers in Oklahoma. *Disasters*.

Kurose, J., Lyons, E., McLaughlin, D., Pepyne, D., Philips, B., Westbrook, D. Zink, M., forthcoming 2006: An End-User-Responsive Sensor Network Architecture for Hazardous Weather Detection, Prediction and Response, AINTEC Asian Internet Engineering Conference, November 2006.

McLaughlin, D. et al., 2006: Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere. Annual Report Year 3, Volume I and II, March 20, 2006 under NSF cooperative agreement no.EEC-0313747. Amherst, MA: University of Massachusetts.

McLaughlin, D.J., V. Chandrasekar, K. Droegemeier, S. Frasier, J. Kurose, F. Junyent, B. Philips, S. Cruz-Pol, and J. Colom, 2005: Distributed Collaborative Adaptive Sensing (DCAS) for Improved Detection, Understanding, and Prediction of Atmospheric Hazards. Preprints, *9th Symp. Integrated Obs. Assim. Systems - Atmos. Oceans, Land Surface (IOAS-AOLS),* Amer. Meteor. Soc., San Diego, CA.

Morris, D. A., K.C. Crawford, K. A. Kloesel, and J.M. Wolfinbarger, 2001: OK-FIRST: A Meteorological Information System for Public Safety. *Bul. of the American Meteorological Society*, 82, 1911-192.

National Research Council, 2002: Weather Radar Technology: Beyond NEXRAD, *National Academy Press.*

National Research Council, 2006: Completing the Forecast: Characterizing Uncertainty for Better Decisions Using Weather and Climate Forecasts*, National Academy Press*,.

Oklahoma Climatological Survey, 2004: OK-FIRST. <http://okfirst.ocs.ou.edu>.

Pepyne, D., et al., 2006: CASA technical report: end-user-MC&C-integration. April, 2006.

Quoetone, L., 2005: NWS Warning Process, seminar for CASA, February 17, 2005.

Rodriguez, H., Diaz, W., Donner, W., Santos, J. and D. Marks, 2005: Allocation of Radar Resources and Policy Implications: The End-User Community in Oklahoma. University of Delaware, Disaster Research Center, Preliminary Paper No. 345. http://dspace.udel.edu:8080/dspace/handle/19716/1297.

Zink, M., D. Westbrook, S. Abdallah, B. Horling, V. Lakamraju, E. Lyons, V. Manfredi, J. Kurose, and K. Hondl, 2005: Meteorological Command and Control: An end-to-end architecture for a hazardous weather detection sensor network, *Workshop on End-to-End, Sense-and-Respond Systems, Applications, and Services*, Seattle, WA, USA, June 5, 2005, 37-42.