2008 American Control Conference
Westin Seattle Hotel, Seattle, Washington, USA
June 11-13, 2008

Distributed Collaborative Adaptive Sensor Networks for Remote Sensing Applications

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Abstract—**Enabled by a dense network of Doppler weather radars with overlapping coverage, Distributed Collaborative Adaptive Sensing (DCAS) represents a new paradigm in remote sensing. Rather than each radar periodically sampling its surroundings with sit-and-spin volume coverage patterns as with today's NEXRAD weather radars, DCAS is an end-user driven approach that targets sensitivity when and where the needs of its end-users are greatest. The advantage is that by adaptively allocating sensitivity, higher quality measurements are possible due to the ability to dwell longer in volumes where echoes are weak, sample faster in volumes with rapidly evolving dynamics, and obtain multi-Doppler looks for high accuracy wind field retrieval. This paper describes the multi-user, multi-attribute utilities-based approach being used to coordinate the scanning activities of the weather radars in the first prototype DCAS system being fielded by the National Science Foundation sponsored Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA-ERC).**

I. Introduction

LONG-RANGE ground-based radars form a core component of today's infrastructure for short-term forecasting and hazardous weather warning. In the U.S. this forecasting and warning role is performed by the system of WSR-88D (NEXRAD) Doppler weather radars operated by the National Weather Service (NWS). To achieve a 230 km range, these radars are very large size (28 foot diameter antenna) and very high power (half megawatt). At approximately \$10 million per site, they are very expensive, and as a consequence sparsely deployed; just over 150 are used to cover the entire lower 48 U.S. states. As the NEXRAD radars approach the end of their expected operational lifetime, concepts for their replacement are being proposed. These include MPAR, a large-size, long-range concept based on phased array radar technology [19]. While such an evolutionary approach can be expected to provide improvement over the NEXRAD system it would replace, the performance of any long-range radar system is fundamentally limited. Over a large fraction of its volume a long-range radar is completely blind to the lowest regions of the troposphere due to earth curvature and terrain blockage; it is resolution limited at long range due to beam spreading; and its volume update times often lag behind the weather dynamics due to its pencil beam and the long dwell times required to achieve the wide range of sensitivities inherent in weather phenomena. These coverage gaps at low altitude and in rough terrain are considered a serious deficiency of the current NEXRAD system [16].

The Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA-ERC) is disrupting this tradition of small-numbers of high-power, high-cost, long-range radars with a paradigm based on Distributed Collaborative Adaptive Sensing (DCAS). DCAS involves a dense network of thousands to tens of thousands of small-size, low-power, low-cost, short-range, Doppler weather radars whose short-range allows them to see down low and into rough terrain and whose massive overlapping coverage allows them to collaborate to amplify their individual capabilities by dynamically changing their sensing strategies to adapt to the needs of the system's end users and to the context of the environment being sensed [14, 15]. The promise of DCAS is that it can lead to higher temporal and spatial resolution, better wind field retrieval, and the ability to accommodate the competing sensing needs of multiple end-users [8, 17].

The CASA-ERC is demonstrating the DCAS concept with the deployment of the first of several planned research test beds. This first test bed, referred to as Integrative Project 1 (IP1), is a four-node network of mechanically steered, 1.2 meter diameter parabolic dish, X-band polarimetric Doppler radars located in the heart of Oklahoma's "tornado alley" in the towns of Chickasha, Rush Springs, Lawton, and Cyril. With each radar separated by about 30 km and having a range of about 40 km, these locations were chosen to maximize the amount of overlap in the radars' coverage patterns [3]. With this overlapping coverage and high-performance antenna positioning hardware that can emulate the beam agility of a phased array panel, one of the main goals of the IP1 test bed is to demonstrate the DCAS concept for the anticipation, detection, and tracking of tornadoes. This paper describes the multi-user, multi-attribute utilities based approach used to implement DCAS in the IP1 Oklahoma test bed and gives a brief summary of its performance during a severe storm event that occurred in the test bed in the summer of 2006.

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.

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II. PROBLEM FORMULATION

Unlike the NEXRAD radars, which must sit-and-spin in order to keep track of their entire surrounding volume, the radars in a DCAS system, because they have overlapping coverage, can collaborate to match their sensing to the weather being sensed and to the specific needs of its users. In IP1 this involves varying the temporal resolution (update rate) to match the fast dynamics of tornadoes, and synchronizing scans of regions where multiple radar beams overlap to obtain the high accuracies needed for the retrieval of fine-scale wind wind features. By matching sensing to the dynamics of the weather – taking faster updates where dynamics or end-user interest is high and slower updates where dynamics or end-user interest is low – complete situational awareness can be maintained, while at the same time achieving temporal and spatial resolutions beyond the current state of the art NEXRAD system [5].

The chief control challenge of DCAS scanning is that it takes a finite time for a radar to scan a given volume. In IP1, the network of radars is synchronized so that a new set of radar beam steering commands is sent to each radar once with every 1-minute system "heartbeat." For the first 20 seconds of each heartbeat, each radar does a single 360 degree surveillance sweep at a 2 degree elevation angle. This provides a general view of the weather at an intermediate altitude and allows the generation of smooth visual displays of the weather as it moves through the network. The remaining 40 seconds of each heartbeat is used for DCAS scanning. In IP1 this involves commanding each radar to scan a sector, defined as a wedge in azimuth of a given angular width between 120 and 360 degrees and compass orientation between 0 and 359.9 degrees, 0 being due north, 90 being east and so on. The radar sweeps back and forth over the wedge, stepping up through a predefined list of 7 tilt angles at the completion of each sweep for as many sweeps as possible in the 40 seconds allotted.[1] When sweeping back and forth, the radar rotates at 21 degrees/second [2]. [2] Hence, for a sector size of S degrees, a radar can cover (40x21)/S = 840/S elevations, i.e., a radar can only cover the full 7 elevations if the sector size is no more than 120 degrees in size. In an end-user responsive system, this limitation on how long it takes to scan a given volume introduces both intra-user and inter-user conflicts as, for example, when a user wants complete 7 tilt coverage of a large convective feature, or when one user wants to scan a volume at the edge of the network while another wants to focus multiple radars on a wind event passing through the middle of the network, where all four radars have overlapping coverage.

[1] In IP1 these 7 elevation tilts range from 1 degree to 14 degrees in order to cover the low altitude region from 50 m above ground level (AGL) to 3 km AGL; an altitude band not covered by the NEXRAD radars (KFDR and KTLX) that serve the test bed area.

[2] When setting up for a scan the IP1 pedestal is capable of rotation rates of up to 240 deg/sec.

III. REPRESENTING END-USER NEEDS

Unlike most sensor networks that "push" the same data to all end-users, a key defining characteristic of a DCAS network is data "pull" where end-user information needs drive the allocation of the sensing resources. In IP1 these end-users include the National Weather Service (NWS) forecast office in Norman Oklahoma whose role is to issue severe weather watches and warnings; a group of regional Emergency Managers (EMs) in and downstream of the test bed whose role is to alert the public about weather hazards and to coordinate first responders; and CASA's researchers working on a variety of projects ranging from improved forecast models, to storm morphology, to weather radar technologies, to decision making and public response, to sensor allocation algorithm. With some of these users interpreting the radar data through visual displays and others running it through signal processing algorithms and models, their data collection preferences and needs vary widely.

In the IP1 DCAS architecture, end-user needs are represented internally by a set of rules. These rules, given below in Table I, obtained through a review of best practices, in-depth interviews with subject matter experts, and hands-on demonstrations with both simulated and live IP1 data, tell the system what to scan and how to scan it [12, 17]. Even more than an internal representation, we found the rules in Table I to be the most natural way for our users to both convey their needs and to understand the operation of the system.

TABLE I
END-USER RULES FOR IP1.

Rule	Trigger	Coverage in Azimuth	Coverage in elevation	#Radars	Revisit
NWS – issue watches and warnings					
N1	Reflectivity	Task size	All 7	1	1 / 180 sec
Researchers – tornado understanding					
T1	Reflectivity	Task size	All 7	1	1/120 sec
T2	Storm cell	Task size	All 7	2	1/180 sec
T3	Rotation	Task size	All 7	2+	1/60 sec
Researchers – numerical weather prediction					
P1	Reflectivity	Task size	All 7	1	1/600 sec
Researchers – storm understanding					
R1	Reflectivity	Task size	All 7	1	1/120 sec
R2	Storm cell	Task size	All 7	2	1/180 sec
Emergency Managers – public notification, spotter/first responder deployment.					
E1	Reflectivity	Task size	Lowest 2	1	1/120 sec
E2	Rotation	Task size	Lowest 2	2	1/120 sec

The rules above describe the sense-and-respond nature of the IP1 DCAS design. The "trigger" column gives the list of detections the users are interested in collecting data on. The remaining columns "coverage in azimuth", "coverage in elevations", "radars", and "revisit" give the end-user preferences for how the system should respond to a given trigger. The table lists three types of triggers – areas of elevated reflectivity (reflectivity), areas with storm cells (storm cell), and areas with elevated gate-to-gate shear (rotations). Feature detection algorithms for each of these three triggers generate so-called scanning tasks. Associated with a task is an area, which is the projection onto the earth's surface of a convex contour placed around the weather object associated with the trigger. Regarding the other columns, the "coverage in azimuth" column indicates that the sector should be wide enough to cover the entire area of the detection; the "coverage in elevations" column indicates the number of elevations that should be scanned so that the user can study vertical structures such as the helical rotations associated with tornadoes; the "#radars" (number of radars) column indicates how many radars to use, multiple views from multiple radars being necessary for improved resolution and velocity field retrieval; and the "revisit" column tells the sample rate and is related to the expected dynamics of the weather phenomena such as its horizontal movement over the ground, its growth rate in size, and the evolution of its internal structure.

IV. DCAS Criterion Function

The control problem is to select at each system heartbeat the set of sector scans that will maximize user satisfaction over time. From a sector selection point of view, the rules give two things. The first thing they give is the set of attributes to use to assess the utility of a proposed scan. The second thing they give is the most preferred outcome for each attribute. NWS Rule N1, for example, identifies area of task covered in azimuth, number of elevations covered, number of radars covering the task, and time since the task was last scanned as key attributes in assessing the utility of a scan. The rule then gives the most preferred outcome for each attribute as complete coverage of task area in sector width (azimuth), sector sweeps at all 7 elevations, and revisit rate that does not exceed more than 3 minutes between samples.

What the rules don't tell what to do when it is not possible to get the most preferred outcome for each attribute. For example, the rules don't tell what to do when the sector size needed to obtain complete task coverage in azimuth doesn't allow the radar to sweep the complete set of elevations. Is coverage in azimuth more important than coverage in elevation? The rules don't say. In addition to these inter-attribute conflicts, there can be inter-user conflicts. For example, emergency managers are only interested in scans at the lowest two tilts, whist researchers want coverage at the the full list of 7 tilts. Coverage to all 7 tilts limits the sector width, which limits the number of tasks that can be scanned. Are researchers willing to defer their needs to the needs of emergency managers? Again, the rules don't say. To resolve conflicts such as these, the IP1 MC&C uses a multi-user, multi-attribute utilities based approach. As a systematic method for decision problems involving multiple users with multiple competing preferences and objectives, multi-attribute utility theory (MAUT) [10] is becoming increasingly popular for allocating resources in sensor networks [1, 7].

The MC&C assigns two utilities to each task – a task utility $U(t)$ telling how important the task t is to the collective population of end-users, and a scan utility function $Q(t,C)$ that relates how well a particular proposed set of scan commands C would meet the scanning requirements of the rule(s) from Table I that are associated with the task. These two utilities of how important and how well are combined in a criterion function, which we maximize to obtain the optimal set of scan commands to use during the next system heartbeat as described next.

A. Task Utility U(t)

The task utility $U(t)$ reflects the collective end-user preference for scanning task t at the next system heartbeat. It is calculated in two steps. First each of the different user groups g (NWS, EMs, Researchers) assign a utility value to the task according to,

$$U_g\left(t,k-k_s\right)=\begin{cases}0.0 & \text{if this user is not interested in this task}\\ 0.3 & \text{if } \left(k-k_s\right)<r_t\text{, this task is not due for scanning}\\ 0.8 & \text{if } \left(k-k_s\right)=r_t\text{, this task is due for scanning}\\ 1.0 & \text{if } \left(k-k_s\right)>r_t\text{, this task is overdue for scanning}\end{cases} \quad (1)$$

Here k is the index of the current heartbeat, k_s is the index of the heartbeat when the task was last scanned, and r_t is the interscan period as defined in the "revisit" column in the rule table in Table I. To get k_s we have a simple tracker that associates tasks detected on different heartbeats and tracks their movement through the radar network. Recall from the rules in Table I that only tornados, which have very fast dynamics, need to be scanned at the once per minute system heartbeat. Thus, by raising and lowering the utility of a task, the system will interleave conflicting tasks to alternate heartbeats allowing it to maintain the desired sample update rates even with very large numbers of tasks in the network. This is a simple idea that allows us to skirt what is otherwise a very hard multi-stage optimization problem (see [13] for a stochastic dynamic programming approach to the CASA DCAS problem).

Given U_g for each user group g, the collective utility for scanning the task during the next heartbeat is obtained from (1) according to,

$$U(t)=w_g U_g\left(t,k-k_s\right) \quad (2)$$

where w_g is the "priority" of user group g. Taking values between 0 and 1, w_g determines the relative effort the system will make to satisfy user g's scanning needs. While priority weights are a common way to combine user needs in multi-users systems, getting users to agree on what their priority value should be can be very difficult. We view w_g as a *mechanism* for setting user priorities. An on-going research project to relate the value of each user group to the socioeconomic impact of the role that they play will ultimately develop a *procedure* for assigning the w_g values [23]. Also note that in our small four-node system, U_g depends only on time since last scanned. In a large network it could also depend on other attributes such as location since, for example, an emergency manager is generally only concerned with their local area of responsibility and would not want to be overwhelmed by the weather far outside this area.

B. *Scan Quality Q(t,C)*

The scan quality function $Q(t,C)$ estimates the degree to which a proposed set of scan commands C will satisfy the scan requirements spelled out in columns 3-5 of the user rules in Table I. The value of Q is calculated in two steps. First each radar determines its individual scan quality q. Then the individual scan qualities are combined to get the network scan quality Q.

Individual scan quality – The individual scan quality $q(t,r,s_r)$ gives the degree to which the sector s_r scanned by radar r satisfies azimuthal and elevation coverage requirements of task t's rule. Specifically, let us define: $w(s_r)$ = the azimuthal width (in degrees) of radar r's sector; $a(r,t)$ = the minimal azimuthal angle that would allow radar r to just cover task t's area; $h(r,t)$ = the distance from the radar to the geometric center of the task; and $h_{\max}(r)$ = the range of radar r. Then the individual scan quality is given by,

$$q(t,r,s_r) = F_c(c(t,r,s_r))[\alpha F_e(e(w(s_r))/e_r(t) + (1-\alpha)F_d(d(r,t))] \quad (3)$$

where, in terms of the above definitions, $c(t,r,s_r) = w(s_r) / a(r,t)$ is the coverage of task t by radar r with sector s_r; $e(w(s_r)) = 840 / w(s_r)$ is the number of elevations a radar scanning a sector $w(s_r)$ degrees in azimuth at an angular rotation rate of 21 degrees per second can do in the 40 second DCAS time period; $e_r(t)$ = the number of elevations required by task t's rule; $d(r,t) = h(r,t) / h_{\max}(r)$ is the normalized distance from radar r to the geometric center of task t; $\alpha \in [0,1]$ is a tunable parameter (set to 0.9 in the current implementation); and F_c, F_e, and F_d are the step functions defined in Fig. 1a-c respectively.

The rationale for Equation (3) is as follows. The first term $F_c(c(t,r,s_r))$ accounts for how well the task is covered in azimuth. Noting that this term multiplies the other terms in the equation we see that if the task is not entirely covered in azimuth the scan quality is zero. The second term $F_w(w(s_r))$ penalizes scans that don't get all of the elevations requested by the task's rule. The third term $F_d(d(r,t))$ is included to decide which radar(s) to use when the task is in the coverage area of more than one radar. According to $F_d(d(r,t))$, radars closer to a task tend to result in better scan quality due to considerations such as intervening attenuation and resolution degradation caused by increased angular beam spreading with distance.

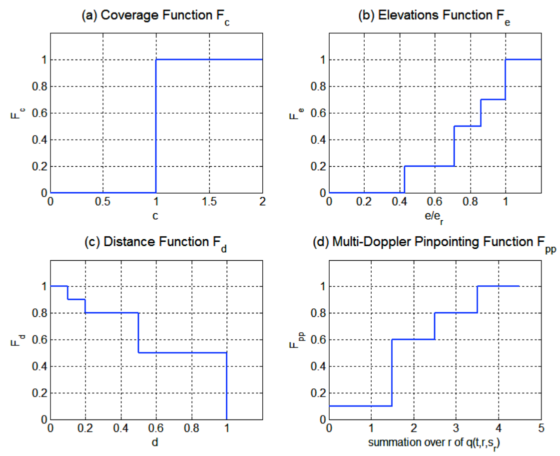

Fig. 1. Definitions of the step functions used in equations (3) and (5).

Combined Scan Quality – Given the q values obtainable by each radar individually, the combined scan quality Q gives the degree to which the radars acting together in a coordinated fashion satisfy the scanning requirements of the task. Looking back at the "#radars" column in Table I we see that there are tasks that only require one radar (generally any task just looking for areas of reflectivity) and tasks that require views from multiple radars (generally tasks requiring velocity field retrieval). For tasks requiring a single radar, we simply take the maximum of the individual scan qualities,

$$Q(t,C \mid \#radars = 1) = \max_{r=1,2,3,4} \left[q(t,r,s_r) \right] \quad (4)$$

where as before r is the index of the radar and s_r is the sector scanned by radar r under scan configuration C.

For tasks that require multiple radars we combine the individual scan qualities according to,

$$Q(t,C \mid \#radars = 2+) = F_{pp}\left(\sum_{r=1,2,3,4} q(t,r,s_r) \right) \quad (5)$$

where the function $F_{pp}(\,)$ is as defined in Fig. 1d. Noting that $q(t,r,s_r) \in [0, 1]$ for each radar r, the interpretation of equation (5) is to give increasing utility for each additional radar that scans the task – the more radars scanning the task, the better the ability to resolve velocity vectors.

C. *Overall Scan Utility U(C)*

Given task utilities $U(t)$ and scan qualities $Q(t,C)$, the overall utility for a proposed set of scan commands C is given by,

$$J(C) = \sum_t U(t) I\left(Q(t,C) \geq 0.8 Q_{\max}(t)\right) \quad (6)$$

Here $Q_{\max}(t)$ is the maximum scan quality the network could achieve if task t were the only task in the network, and $I(\,)$ is the indicator function (= 1 if its argument is true; 0 otherwise). The second term in the sum says that a task t is satisfied iff the scan quality exceeds 0.8 times the maximum achievable by the network. Optimizing (6) can thus be interpreted as the preferential allocation of the sensor resources to satisfy those tasks that the end-users have collectively agreed are the most important to satisfy.

V. IMPLEMENTATION

The CASA-ERC is building a number of test beds within which to develop and test the DCAS concept. The four node IP1 test bed, located in Oklahoma in the heart of tornado alley, is the first of these. Figure 2 below shows the basic flow of data and control within the IP1 network [6, 20, 21].

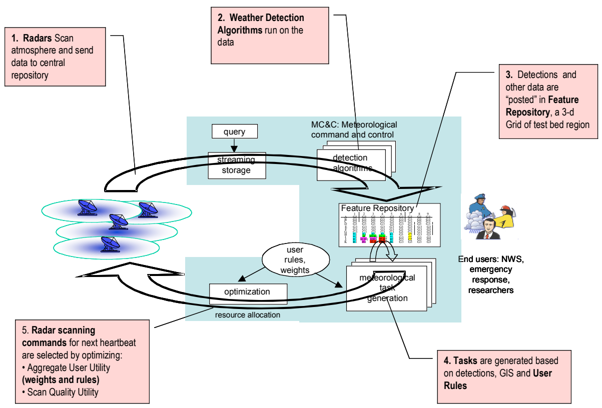

Fig. 2. Schematic showing the flow of data and control within IP1.

Starting at the radars let us go clockwise around the loop. At each radar, radar echoes are received, sampled into digital form, and processed by signal processing algorithms to extract the meteorological moments and polarimetric variables. For Doppler weather radar, the 0^{th} moment, the reflectivity, is probably familiar to most readers as it's the radar image most commonly shown by television weather people. Reflectivity is a measure of the density of the water droplets, so that in general the brighter the color the greater the precipitation. The 1^{st} moment, the Doppler velocity, measures the component of the wind moving toward or away from the radar. The 3^{rd} moment gives the wind shear. Polarimetric variables can tell the shape of the water droplets and can thus be used to estimate rainfall amounts. See [4, 9] for additional details about polarimetric weather radar. The moment and polarimetric data goes to a feature repository from where it is distributed over the Internet to end-users, e.g., for visualization. The feature repository contents are also sent to the detection algorithms that trigger the end-user rules. The outputs of these detection algorithms are clustered based on type and location. Each cluster triggers one or more of the rules from Table I. An optimization algorithm then searches the space of scan commands for the one that maximizes the overall utility criterion in (6). This process from feature detection, clustering and task generation, to optimial scan generation repeats with every 1-minute system heartbeat.

VI. PERFORMANCE EVALUATION

Experiments were conducted to assess how well the IP1 DCAS design is able to satisfy end-user needs by evaluating how well the system is able to satisfy the rules that define those needs. For the purposes of the evaluation, a task is considered satisfied if its scan quality $Q(t,C) \geq 0.8Q_{max}(t)$, i.e., if the scan quality obtained is equal to or greater than the maximum achievable. Data for the experiments was obtained from actual scans of a severe storm that passed through the IP1 testbed between 2:30AM and 5:00AM on 16 August 2006. See [5] for a system level discussion of network operations during this August storm event. This storm was of sufficient severity for the NWS to issue one thunderstorm warning and several severe wind reports.

A. DCAS Sector Scanning Algorithm Performance

Over the 2.5 hours of the experiment there were a total of 2943 tasks submitted to the optimization for scanning, for an average of 10.3 tasks per heartbeat. Of these a total of 1221 tasks, or an average of 4.3 per heartbeat, could not be satisfied during a heartbeat due to resource conflicts. As expected, the tasks that the system had difficulty satisfying were those requiring full coverage in elevation with multiple radars. Specifically, of the average 8.9 such tasks generated per heartbeat, an average of 4.3 (48%) were not satisfied by the scan selected for the heartbeat.

On the other hand, recall that if a task due to be scanned at a particular heartbeat is not satisfied we increase its utility and continue to resubmit it for satisfaction until such time as it is either satisfied or moves out of the network. A consequence of this strategy, however, is that unsatisfied tasks from previous heartbeats could accumulate to eventually overwhelm the system. Analysis of the number of tasks in the system shows that this is not happening, meaning that although the system is not able to satisfy every task submitted at every heartbeat, the system does eventually satisfy all tasks and they do not accumulate. In fact, because we record the total delay between the time a task is submitted and the time it is satisfied we can estimate the sample rate performance of the system. For tasks associated the with full elevation scans, the average sample rate was 55.26 seconds between scans, thus more than satisfying the once per 120 second required sample rate.

B. Sit-and-Spin Algorithm Performance

To show the advantages of the DCAS approach of targeted sector scanning we compared its performance to the so-called sit-and-spin scanning algorithm. Sit-and-spin scanning can be viewed as the no control case – the sit-and-spin strategy simply repeating 360° sweeps of the lowest 2 elevations with every heartbeat. The results were obtained by replaying the tasks generated during the 16 August 2006 storm event through the MC&C while we operated it in sit-and-spin mode. Except for the fact that we did not use the output of the optimization to generate the beam steering commands, sit-and-spin went through all the same steps of task generation, task utility assignment, and resubmission of unsatisfied tasks as used by our sector scanning algorithm.

Over the 2.5 hours of the storm, 8287 tasks – or an average of 28.1 tasks per heartbeat – were submitted to the sit-and-spin algorithm for satisfaction. Of these, only 7% were satisfied at any given heartbeat. As expected, because sit-and-spin can only get 2 elevations in 40 seconds very low value was obtained for any task requiring full elevation scans. The resubmission of these unsatisfied tasks from one heartbeat to the next explains why sit-and-spin had so many more tasks than the sector scanning algorithm.

VII. CONCLUSIONS

This paper described a multi-attribute utility-based approach for resource allocation in a distributed collaborative adaptive sensing (DCAS) network of weather radars. This approach, which is being tested by the CASA-ERC is showing good closed-loop performance in severe weather situations.

The implementation described in this paper deals primarily with the problem of deciding where to point the radars in a DCAS network. Exciting ongoing work within CASA includes a distributed implementation of the data and control loop in Fig. 2 with a multi-agent negotiation protocol for fusing detections and performing scan optimization [11]. Also being addressed are techniques for optimizing other scan attributes such as the radar waveform (pulse repetition frequency, pulse length), scan strategy (dwell time, beam trajectory), and signal processing (adaptive clutter filtering, automated calibration). DCAS designs are also being developed for future CASA IPs, which will use advanced phased array radars with multiple "zero intertia" beams.

This paper did only a very limited analysis of the IP1 DCAS design. Other research projects within the CASA-ERC [18] are working with our end-users to evaluate the data quality being obtained under the end-user scanning rules. As the end-users become familiar with the new paradigm of targeted sector scanning this will surely suggest new scanning strategies and new rules to execute them. Under a supplement to the CASA grant, we are also doing research to incorporate the socioeconomic value of CASA data into our end user policy and resource allocation algorithms. This is involving the development of an integrated systems model (ISM) of the end-to-end IP1 system to quantitatively link "upstream" technical capabilities, such as targeted sector scans of the bottom 1km of the troposphere, to their impacts on "downstream" responses such as NWS warning decisions, EM risk communication, public response, and the resulting incremental socioeconomic impacts. This end-to-end model will allow us to identify and optimize on those DCAS capabilities that provide greatest socioeconomic value.

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