The Bytheway Method for optimal radar beam scheduling in the CASA IP1a test bed

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Abstract

The radars being prototyped by the National Science Foundation's Engineering Research Center - Collaborative Adaptive Sensing of the Atmosphere (CASA-ERC), unlike the WSR-88D, will not complete a 360^{o} scan for each measurement taken, and will include a Distributive Collaborative Adaptive Sensing (DCAS) feature. DCAS will attempt to allow the critical users of the radar data to choose which regions to sense and allow each radar to focus on particular meteorological phenomena of interest. In order to ensure that each end user receives the critical data necessary to make decisions during weather events that pose threats to life and property, an end user policy must be developed. This policy should account for end-user interests, as well as population density and strategic assets, such as military bases and ground truth verification instrumentation. Several such policies are being developed and will be tested in simulations as the CASA radar design process continues. The following paper details one such policy, which was subjectively tested against WSR-88D (KFDR) data from a tornadic event that occurred within the CASA Oklahoma test bed on May 24, 2004.

1. Introduction

The CASA-ERC radars are being designed to observe low-level features of the atmosphere that are undetectable by the WSR-88D. Generally, the WSR-88D is unable to take observations of the lowest kilometer of the atmosphere, and when severe weather is imminent, forecasters are unable to focus the radar beam on a particular feature of interest. The CASA radars will be mounted atop cell phone towers and will be capable of measuring the lowest sections of the atmosphere while selectively sensing a specific volume for a specific meteorological threat. They will also be capable of taking more frequent observations than the WSR-88D, and therefore will have higher resolution both spatially and temporally. The goal of the CASA radars is not to replace the WSR-88D network, however to supplement and augment the observations they make. The first stage of the CASA project calls for four radars to be placed in Comanche, Caddo, Grady, and Stephens counties in southwest Oklahoma, with expansion of the system to nine radars over the next five years. The radars will be equipped with a DCAS capability that allows the users of the radar data to make requests for data and to prioritize this data. The principle users of the CASA-ERC radars are:

- The National Weather Service, Emergency Managers, and Oklahoma Climatological Survey (OCS):

  The NWS, Emergency management agencies, and OCS are government agencies. The NWS provides “weather, hydrologic, and climate forecasts and warnings for the US and its territories, adjacent waters, and ocean areas for the protection of life and property and the enhancement of the national economy” (NWS). The OCS provides “high-quality climate information tailored to meet the needs of individual citizens and decision makers in Oklahoma" (OCS). The OCS provides weather information and training for local-level emergency managers in Oklahoma.

- Baron Services

  Baron Services is a private company focused on providing weather information to small communities and neighborhoods. Baron Services provides graphics to broadcast stations across the country, as well as to emergency management agencies and other businesses (Baron Services).

- Vieux and Associates, Inc.

  Vieux and Associates is another private company that provides its clientele with rainfall rates and hydrologic modeling that can be used to design sewage infrastructure, forecast runoff, and plan for flooding (Vieux and Assoc.).

- CASA researchers

  CASA researchers are classified as a primary end user so that the "needs for data for scientific research and test bed validation are met" (CASA System Requirements Document, v. 2.6, 2004).

In order to determine what volumes to observe, multiple algorithms will be run within the CASA Meteorological Command and Control (MC&C) and Systems Operation Control Center (SOCC). The first algorithm is a meteorological one designed to detect various meteorological phenomena. Each of these algorithms will have an Algorithmic Utility Value (AUV) that assigns the importance of specific radar data to a specific algorithm, thus determining the primary meteorological feature of interest for a scanned volume (ongoing research by Zihui Ge, et al, 2004).

One of the largest challenges in beam scheduling results from it being a central part of CASA's most important barrier – Interdisciplinary Collaboration (Systems Requirements Document, v. 2.6, 2004). The second algorithm, and focus of this paper, is the end-user utility, which computes the value of each meteorological algorithm to each end user. The method of calculation of the end user utility will be selected by running simulations of several end-user policies that are being developed by various members of the CASA team. The author has proposed several such policies, and the policy that follows, heretofore referred to as the Bytheway Method, has shown the most desirable results.

2. Methodology

In order to establish the most efficient end user policy, several methods will be considered. Each method will be programmed into a simulation to attempt to determine its feasibility for real world use. One method suggests dividing the radar scan area into a grid (ongoing research by David Westbrook, 2004), and the author has tested five such methods that have divided the scan area into beam widths, pixels, and one that does not divide the area at all. The method showing the most favorable results divides the region into pixels. Because the CASA project is in its infancy, the simulators designed to run these tests with quantifiable output have yet to be developed, and it is important to mention that without access to this simulation software, each test of this method was performed subjectively, and illustrated by hand. For this reason, the number of pixels considered in testing the system was limited, however, with proper programming, each 2-D radar scan may be divided any number of times as the engineers see fit.

To test the Bytheway Method, each radar has been divided into twenty-four 15^{o} beam widths with six 5 km range rings, yielding 144 pixels per radar. Each radar scan surface was correlated with population density and strategic features, as well as regions of overlap from the other radars in the test bed (Figure 1).

Using data from the WSR-88D at Frederick, Oklahoma (KFDR), meteorological features were hand plotted on each radar in the pixel in which they were sensed. Multiple features could be plotted in one pixel if they were present; for example, hail and flooding rain (Figure 2).

Several schemes to score the meteorological features were created based on information gathered from the end-users themselves. For example, Vieux and Associates has a particular interest in accurate rainfall measurement, and little interest in tornadoes, while the NWS is particularly interested in tornadoes, but has indicated it can depend on the WSR-88D to estimate rainfall if necessary. Therefore, Vieux and Assoc. would have a higher score for rainfall and a low score for tornadoes, while the NWS would do the opposite. Due to the limited information available at this time, the scores tested were mostly arbitrary, however, these particular scores can be changed as interviews with end-users progress and more information is acquired. The scores tested varied from a 1-10 scale to a normalized scale in which each user was allotted five “points” to divide amongst all possible feature-sensing tasks (Table 1). Each feature was required to have a score greater than zero, to prevent any one end user from putting excessive priority on any one feature in order to sway the radars.

Each end-user was also assigned a weight, whereby the needs of one user could overtake those of another in certain situations. As suggested in the CASA System Requirements Document (v. 2.6, 2004), the NWS will have the highest weight, while Vieux and Baron have lower weights equal to each other. The CASA System Requirements Document fails to include a weight for research purposes, however in this policy a weight has been assigned to them, lower than that of Baron and Vieux (Table 2).

Each region of vulnerability has also been assigned a score. Population density has been divided into five categories on a logarithmic scale, and assigned a score from 1 to 5 accordingly (Table 3).). Strategically placed instrumentation that could be used to ground truth radar data, or locations that should be carefully monitored during severe weather, such as the ARS Micronet and military bases, have been grouped into the highest category with areas of a population density greater than 10,000 people per square mile. For purposes of comparison and uniformity, population data illustrated in the CASA Systems Requirements Document (v. 2.6, 2004) were used to determine the locations of high and low population density.

The number of radars able to monitor each region was also considered. Logically, if two severe weather features are present within a radar scan, one that can be observed exclusively by only one radar, and one that can be observed by multiple radars, the radar should focus on the feature that only it can observe, and leave the other feature to be observed by the other radars. The scoring for the visibility was originally based on the ratio of areas covered by one, two, three, and all four radars. This method tended to put too much emphasis on the visibility of a feature, and because of this sometimes focused the radars away from severe weather.

The scoring method that produced the best results was based on the number of pixels that could be covered by a certain number of radars. There are a total of 576 radar pixels considered in this method, 19 of which can be monitored by all four radars, 72 that can be monitored by three, 194 that can be monitored by two of the radars, and 291 that have exclusive radar coverage. Each of these values was divided by 19, and then again by 3 in order to avoid putting excessive emphasis on the visibility, and to place the visibility and vulnerability on scales of similar magnitude (Table 4).

These four sets of scores were then used to calculate a Sensing Utility Score (SUS) for each 15° beam width of the radar's scan area. Several methods were tested, however the majority of the methods were dependent on simple addition and multiplication to calculate the score.

3. Calculations

While several methods of score testing were used, the calculations producing the most favorable results included the following User Utility formula suggested in the CASA Systems Requirement Document (v. 2.6, 2004):

> User Utility = (User A weight x Feature Score A) + (User B weight x Feature score B) +…+ (User N weight x Feature Score N).

This formula is favorable because it allows room for the addition of more end users as the CASA project continues. The feature score in the formula represents that user's score of each meteorological feature sensed within a pixel. If multiple features are present in one pixel, the respective scores of each feature are added together to calculate the feature score. For example, the User Utility for a pixel in which hail and flooding rain was sensed would be calculated as follows, using the feature scores from Table 1 and the end user weights from Table 2:

User Utility = (2.0 x (1.0 +0.6)) + (1.2 x (0.5 + 1.5)) + (1.2 x (1.0 + 1.0)) +
(0.6 x (0.5 + 0.7))
= 3.2 + 2.4 + 2.4 + 0.72
= 8.72.

Because a limited number of features have been scored, it is possible to calculate the User Utility scores for every possible combination of features that can be detected in a pixel, and program these into the algorithm rather than performing this calculation each time the radar takes an observation.

Once the User Utility for a pixel is calculated, it is then multiplied by the vulnerability and visibility scores for that pixel to determine the Pixel Score. The SUS for a beam width is the sum of each Pixel Score within that beam width. Returning to the example above, if the pixel in question were in an area with 2-radar visibility (score = 3.4) and a population density of 500 people per square mile (score = 3) then:

Pixel Score = 8.72 x 3.4 x 3
= 88.94.

If this example pixel were located within a beam width in which each pixel were experiencing both hail and flooding rain:

Sensing Utility Score = 6 x 88.94
= 533.66.

Once each beam width has been scored, the scores are then ranked in order from highest to lowest. If multiple adjacent beam widths have equal scores, they are counted together as a single beam width. For example, if beam widths 14, 15, 16, and 17 all have a score of 533.66, when ranked they will be counted as beam width 14-17. The top five highest scoring beam widths or groups of beam widths will be sensed, including the area in between. In some instances, this may result in a large portion of the radar's sensing area being monitored, while in others the result may be 5 adjacent beam widths having the 5 highest scores.

4. Results

The Bytheway Method of calculating end-user utility was tested against WSR-88D data from KFDR (Frederick, Oklahoma) on May 24, 2004. On the evening of May 24, two supercell thunderstorms passed through the four counties that will comprise the Oklahoma test bed. For purposes of comparison, the same data and time intervals were used as those tested in Westbrook's (2004) grid method.

Of the five methods tested by the author, the final method was most successful in achieving the goals of the CASA radars. The radars generally focus on the most severe weather in the lowest levels of the atmosphere, while leaving much of the region to the surveillance of the WSR-88D.

The beam width that scores the highest tends to be the epicenter for a number of beam widths with relatively high scores. This grouping of high beam width scores surrounding a severe weather feature allows the region around the feature to be monitored for further development or intensification of that feature (Figure 3 a-e). For example, at 6:30 PM, the beam width of the Cyril radar with the highest score was beam width 14, where a mesocyclone had been detected. The next highest scores were from beam widths 12, 13, 16, and 15, respectively. At 6:30:30 PM, a tornado was detected in beam width 15, a beam that had been under surveillance due to the epicenter effect from the 6:30 scan.

This method also allows for dual-Doppler coverage of the most severe features occurring in regions where multiple radars have coverage. From 6:30:30 to 7:30 PM, the Cyril and Lawton radars would both be focused on the detected tornado and surrounding regions (Figure 3 c-e).

5. Discussion and Conclusion

While this method of calculating a SUS achieves the goals of the CASA project, it is not without fault. When there is little going on within a radar's scan area, or only scattered activity is present, high scores become scattered, and a large area is then scanned. This more general realm of surveillance often results in the radar monitoring regions were nothing is occurring.

For example, at 7:00 PM, hail and flooding rain were observed in a region that can be sensed only by the Chickasha radar, but in a low population density. The low visibility creates a relatively high score for this beam width. More than 90^o away from this feature, rain is occurring in an area that can be sensed by both the Chickasha and Cyril radars, but is over the ARS Micronet, an important strategic location for verification of Quantitative Precipitation Estimation (QPE) done by the radars. When these two isolated high scores rank within the top five scores, the large area between them, in which very little or nothing is occurring, becomes a sensing priority, and the radar is sensing a large unnecessary area (figure 3 d).

At 7:00 PM, the Cyril radar is focused mainly on the tornado detected near the city of Lawton and the surrounding area, some of which includes rain falling on the ARS Micronet, but not the entire region it shares with the Chickasha radar. The Rush Springs radar is also sensing another part of the ARS Micronet that it shares with the Chickasha radar. It must be decided if this partial coverage of the Micronet is sufficient, or if it is necessary to have as much of the Micronet covered as possible.

This issue suggests that it would be very worthwhile to have an algorithm in which the radars can "communicate" with each other what areas they are assigned to sense. In some instances, this would prevent the problem mentioned above, as well as prevent too many radars focusing on a certain feature. If it were determined that only partial coverage of the Micronet were sufficient, this communication between radars would tell the Chickasha radar to focus on only the hail and flooding rain that only it can monitor.

Despite these faults, the Bytheway Method, by design, leaves room for changes to be made within the policy. As previously mentioned, the number and size of the pixels, the feature scores for each user, number of users, and number of radars can easily be changed as the CASA project progresses, while maintaining the formula used to calculate the SUS for each beam width.

While this method is still subject to more testing using simulations and more precise information as the interview process with end-users continues, its preliminary results and adaptability to ongoing changes makes it a viable method for scheduling the CASA radar beams to fulfill end user needs and provide data to protect life and property in the area.

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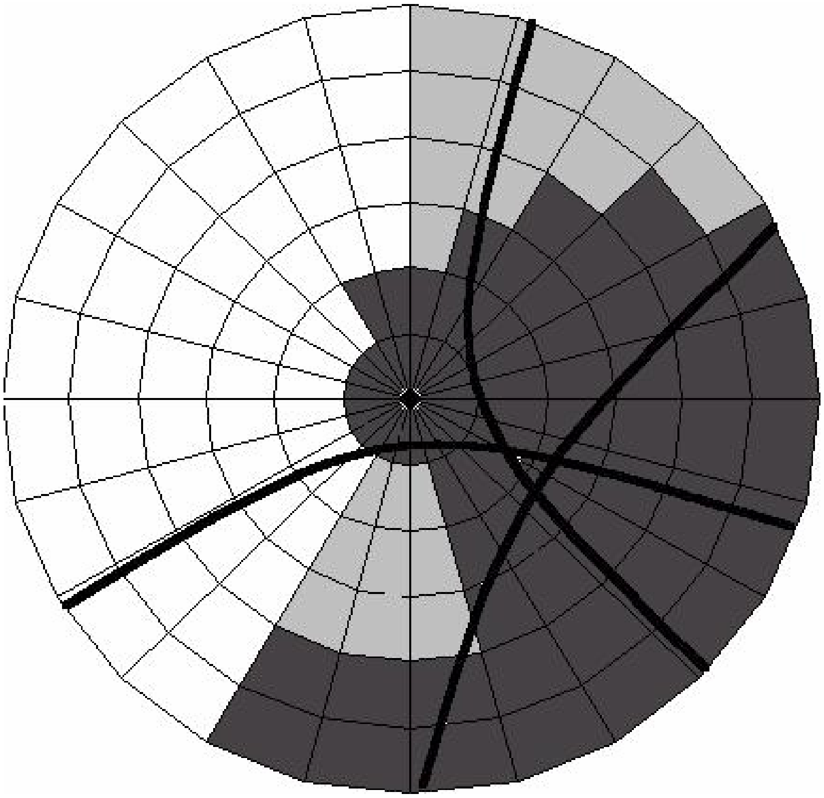


Figure 1. Example of division of a radar scan area into pixels, including the illustration of multiple radar overlap and shading of varying population densities.

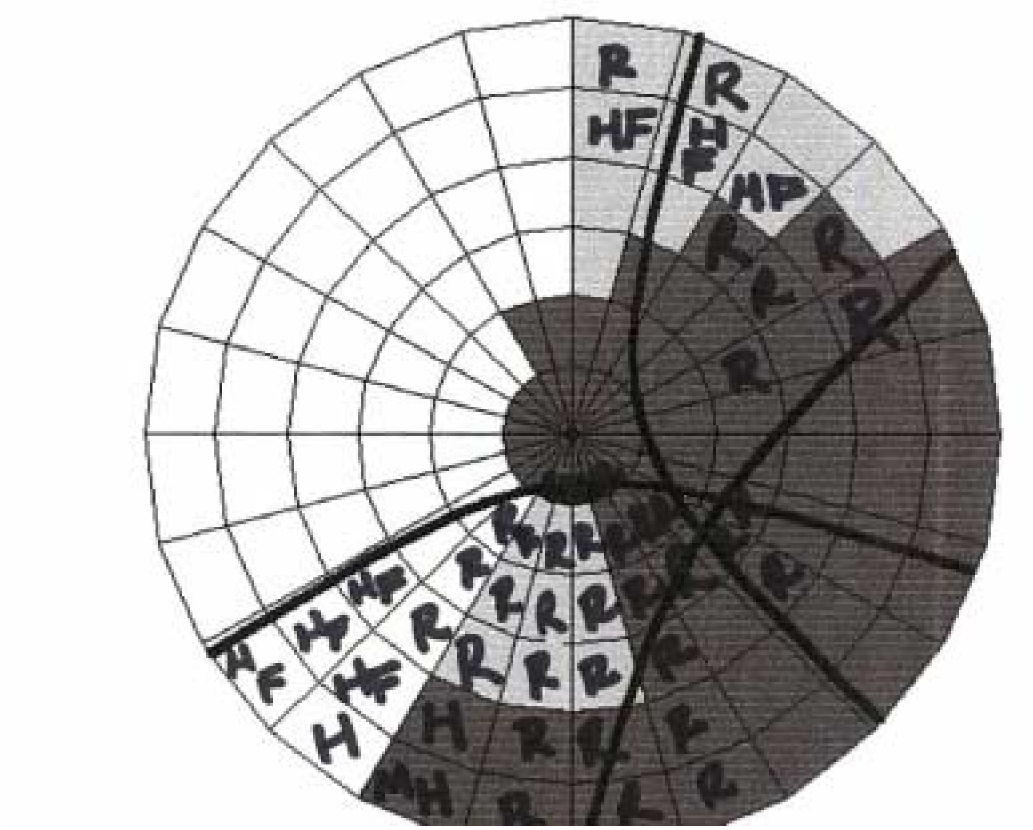


Figure 2. Example of labeling of features on each radar. The features labeled here are those within the sensing range of the Cyril radar at 6:30 PM on May 24, 2004.

Table 1. End user feature scores for each meteorological feature detected by the CASA radars.

Feature	NWS	Vieux	Baron	Research
T- Tornado	1.5	0.2	1.0	1.1
M – Mesocyclone	1.0	0.2	1.0	0.9
H – Hail	1.0	0.5	1.0	0.5
F – Flooding Rain	0.6	1.5	1.0	0.7
R – Rain	0.3	1.2	0.4	0.4
S – Storm Cells	0.2	1.0	0.3	0.7
C – Convergence	0.3	0.3	0.2	0.6
G – General Surveillance	0.1	0.1	0.1	0.1

Table 2. Various end-user weights tested throughout the process of designing an end user policy for the CASA radars.

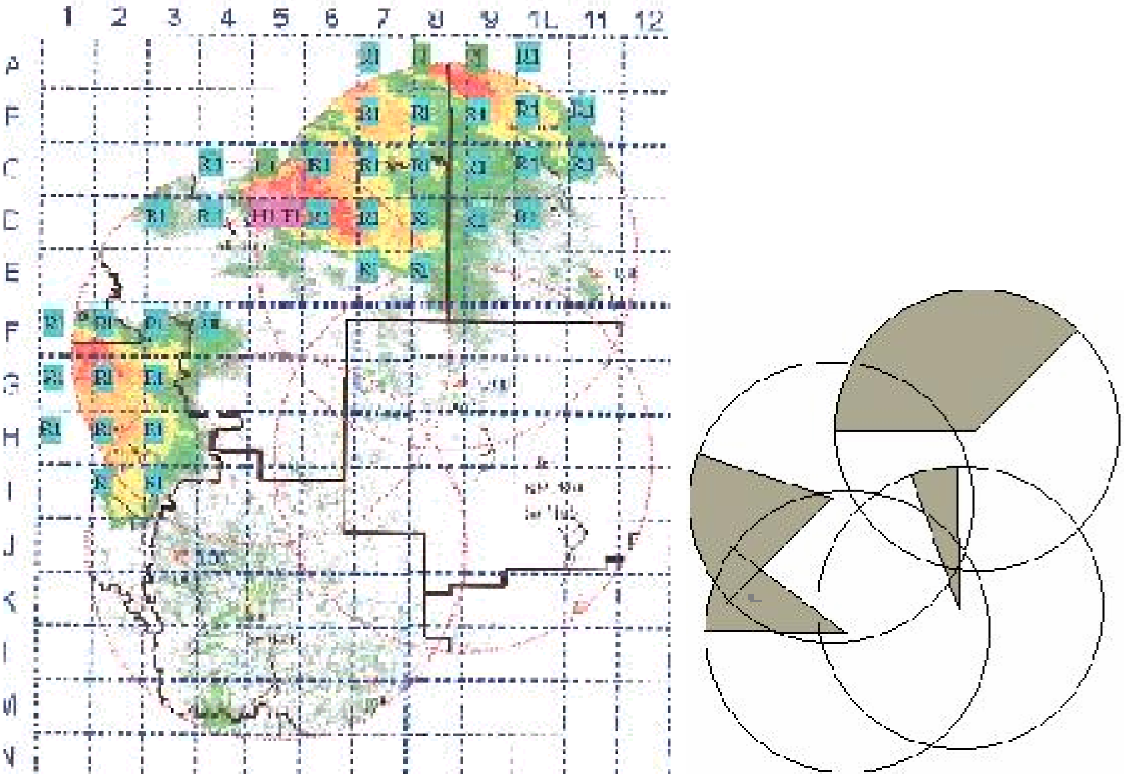
User	**CASA Suggested Weight**	**Tested Weight**	**Tested Weight**	**Tested Weight**	**Final Weight**
NWS	0.4	5	4	2	2.0
Baron	0.2	2	2	1	1.2
Vieux	0.2	2	2	1	1.2
Research	N/A	1	2	1	0.6

Table 3: Vulnerability scores for a logarithmic scale of population density.

Vulnerability (per square mile)	**Score**
0 - 10	1
10 – 100	2
100 – 1000	3
1000 – 10000	4
10000 + or Strategic	5

Table 4. Visibility scoring scheme, by number of pixels, and normalized to prevent skewing of Pixel Scores.

Visibility	**Number of Pixels (Total 576)**	**#/19**	**#/3**
Exclusive	291	15.3	5.1
Half	194	10.2	3.4
Three	72	3.8	1.3
All	19	1.0	0.3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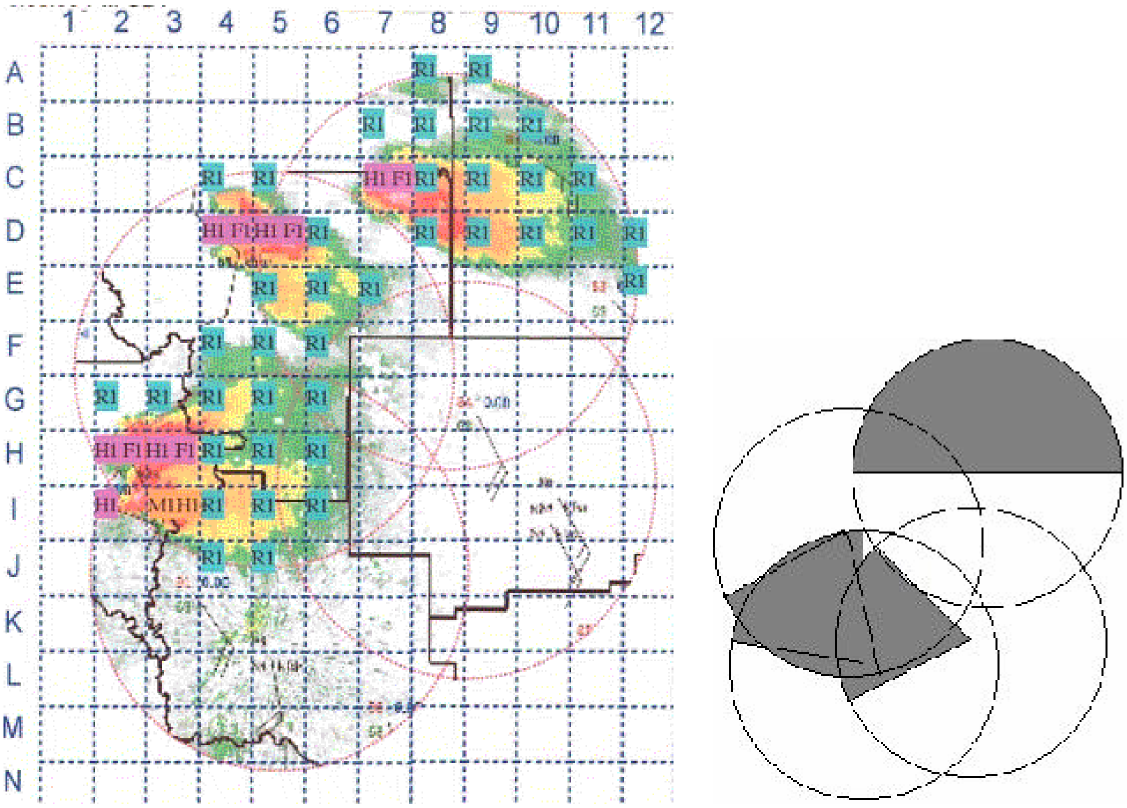
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M1 H1

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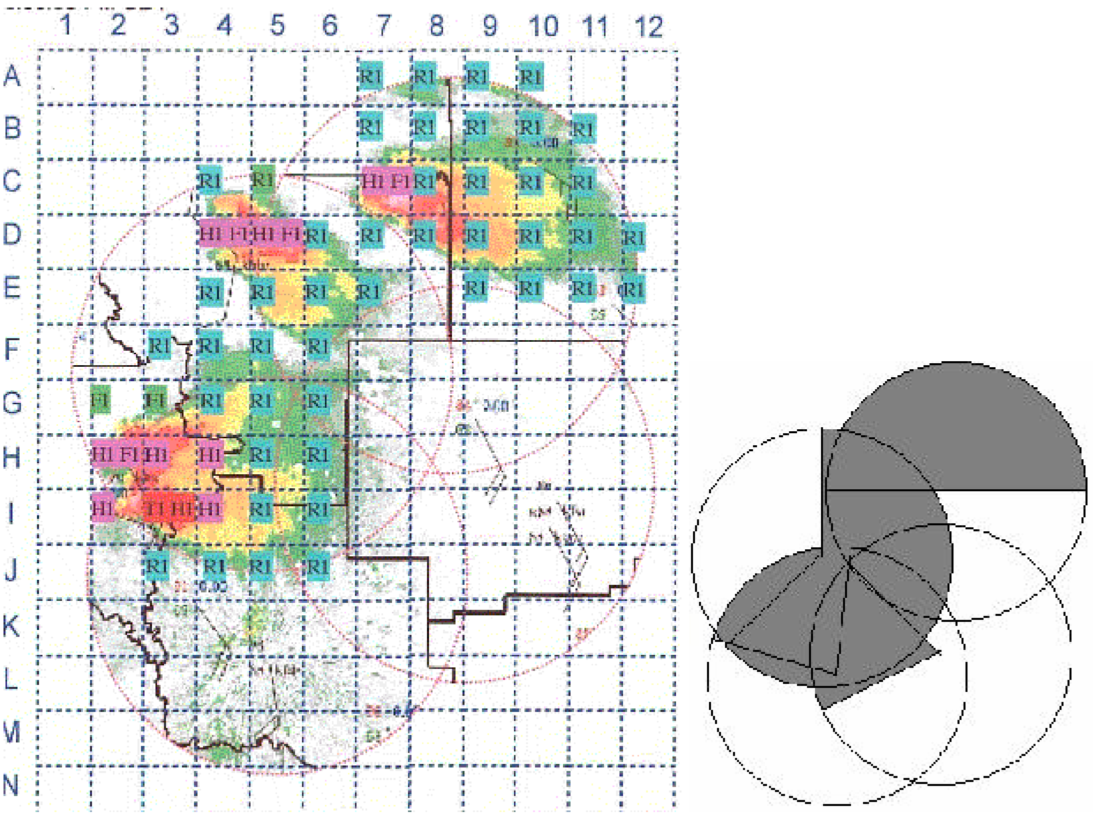
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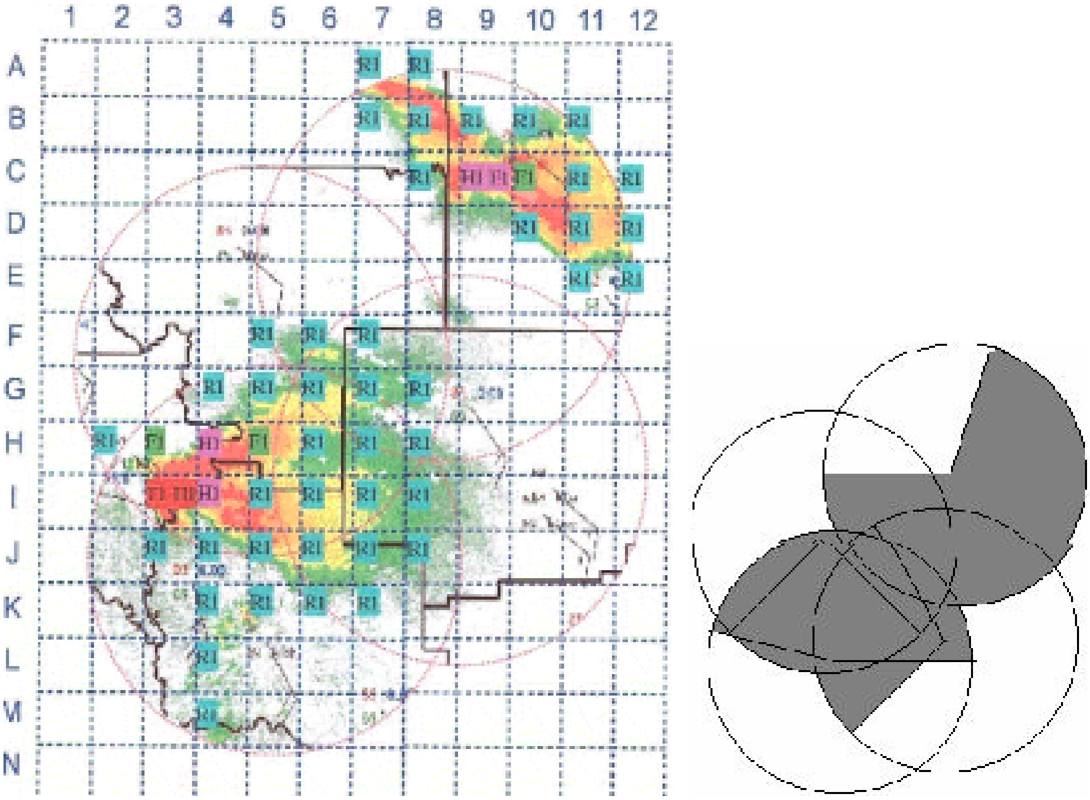
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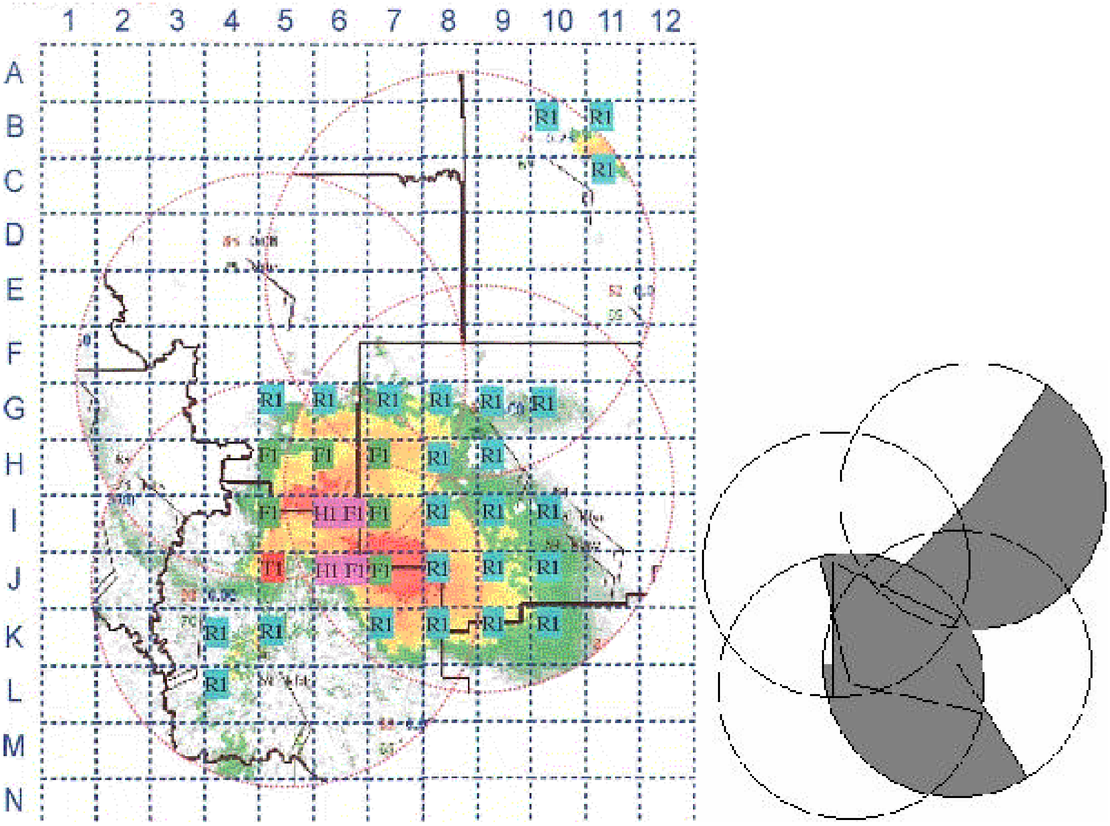

e

Figure 3. Comparison of radar data with meteorological features overlaid from KFDR on May 24, 2004 to areas of beam focus of the CASA radars based on the Bytheway Method of beam scheduling. Times for each radar scan are 3a) 6:00 PM CDT; 3b) 6:30 PM CDT; 3c) 6:30:30 PM CDT; 3d) 7:00 PM CDT; and 3e) 7:30 PM CDT (Labeled radar data from ongoing research by David Westbrook, 2004).