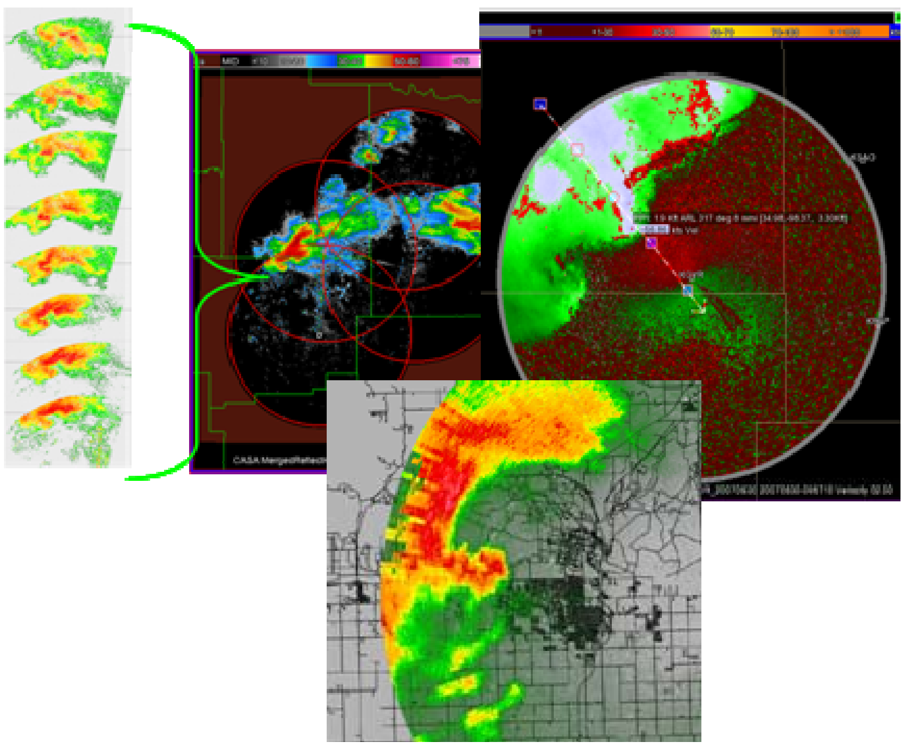
CASA Spring Experiment Operations Plan
Hazardous Weather Test Bed
Experimental Warning Project
2009



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I. Introduction

The Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) is a National Science Foundation Engineering Research Center that has operated since September 2003. This research center is a partnership among radar engineers, meteorologists, computer scientists, social scientists, human factors engineers, and decision scientists from the University of Massachusetts (lead), University of Oklahoma, Colorado State University and University of Puerto Rico Mayaguez, University of Virginia, University of Delaware as well as several government and industry partners such as NOAA, IBM, Raytheon, and WeatherNews International.

CASA seeks to create a new paradigm for weather sensing by developing and implementing systems of densely spaced, low power, X-band radar networks that can observe the lower troposphere at high spatial (100's of meters) and temporal (60 second) resolution for improved hazardous weather warning and response. We expect that CASA networks will lead to improved warnings , probabilistic warning products, more finely grained information about storm evolution, better use of wind information for warning decisions, and future advantages for warn-on-forecast.

Oklahoma Test Bed. CASA recently deployed a prototype test bed in southwest Oklahoma, the first demonstration of a CASA system. This end-to-end test bed includes a 4 node adaptive radar network that gathers and disseminates data in real-time to a pilot group of users including National Weather Service (NWS) forecasters, meteorological researchers and emergency managers for evaluation and feedback.

CASA radar networks have several advantages over the current radar technology:

- <u>Lower troposphere coverage</u>: CASA networks overcome the radar horizon problem through close spacing (30 km) of the radars. The radars can sense as low as ~200 meters AGL.

- <u>High temporal and spatial resolution volume scans</u>**.** CASA networks provide volume scans of important weather features at an average 500 meter resolution as fast as every 60 seconds.

- <u>Overlapping radar coverage areas</u>: Radars provide multiple views of the same feature and enable dual Doppler retrievals for 2-D and 3D wind products.

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- <u>Smart, network-based "VCP's</u>**"** - CASA's radar control software, called the Meteorological Command and Control (MC&C), analyzes incoming meteorological data in real-time and reconfigures the volume coverage pattern for the radar network every 1 minute in response to changing weather and diverse user needs. Each smart VCP may accommodate several scanning strategies at the same time, such as multi-Doppler retrievals, PPI scans (both 360 degree scans and multi-elevation sector scans) and RHI scans.

User Driven Design. CASA has embraced a user-centered approach to designing and operating its radar systems. NWS forecasters and emergency preferences for scanning (including which features are important, radar coverage and sampling rate) have been incorporated into the smart VCPs. In addition, we are interested in understanding how CASA systems will complement and improve existing and future operational warning environments. During 2007 and 2008, NWS forecasters and NOAA scientists in the Hazardous Weather Testbed/Experimental Warning Program identified potential advantages of CASA data and provided feedback on the technology. Modifications to the scanning strategy and improvements in data quality have been implemented based on the 2007 and 2008 feedback and are currently operating in the CASA's Spring 2009 experiment. We are pleased to be participating in the 2009 HWT/EWP for a third year and look forward to receiving user input on our system design.

II. CASA Experiment in the HWT/EWP

Goals. To evaluate the operational utility of Collaborative Adaptive Sensing of the Atmosphere (CASA) dense radar networks for severe weather decision-making.

1. What are the advantages of CASA moment data for severe weather warning decision making in light of existing sources of information?
    a. What new weather features are observed in CASA data?
    b. What additional information can CASA systems provide on known weather features?

2. What are the strengths and limitations of CASA's technical capabilities?
    a. High resolution data
    b. Lower troposphere coverage
    c. 1 minute refresh rate
    d. Adaptive scanning strategies based on user rules

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3. What are the potential advantages of CASA derived products?
    a. 2-D wind products (from 3D variational analysis)
    b. NWP forecasts that incorporate CASA data.

Experiment Protocol. Each week, a different group of visiting NWS forecasters or NOAA scientists participates in the Hazardous Weather Test bed/Experimental Warning Program. Forecasters are in the HWT/EWP from Monday – Thursday from 1 – 9 pm, with a debrief on Friday morning. Two CASA scientists will be assigned to the HWT each week to work with and observe forecasters. CASA scientists have a variety of backgrounds such as engineering, human factors, meteorology, computer science, and social sciences and are all working on the system design. The HWT/EWP Weekly Coordinator assigns forecasters to review CASA archived cases or real time data, depending on the location/timing of severe weather for the day/evening.

The CASA Experiment consists of evaluation of real-time data as storms pass through the network and archived cases when there is no weather in the test bed.

- <u>Radar Data Coding</u>**.** -In this mode, forecasters advance manually through a weather case, scan-by-scan, providing analysis of weather features, comparison of CASA to NEXRAD data and current conceptual models for severe weather. The goal of the case analysis is to uncover important weather features and capabilities observed in CASA that provide information for weather assessment, especially compared to NEXRAD. During case analysis, forecasters can stop and ask questions, and go backward and forward in time.

- <u>Actual and Simulated Real-Time evaluation of CASA data.</u> In addition, when events occur in the test bed, forecasters will review real time data and evaluate how it might add to the current warning process. In the real time cases, forecasters have to evaluate data with the rapid one minute update, navigate among the scan elevations, and consult other sources of data provided by AWIPs. When there is not weather in the test bed, forecaster should evaluate archived cases that are played back in simulated real time.

Logistics. On the first day of the experiment, forecasters should:

- Sign the IRB consent form (to allow CASA scientists to interview and tape conversations with the forecasters) created by CASA and return the form to Greg Stumpf, the project leader for the HWT or to the CASA researchers.
- Attend an overview presentation of the CASA program and related technology.
- Go though a training case, May 8, 2007, Super Cell case to familiarize forecasters with:
    - The resolution and update rate of CASA data
    - Navigating up and down the sector scans in WDSS II
    - WDSS-II software interface for interrogating weather data.
    - CASA single radar, merged composite, RHI and 2-D wind products
    - Completing the questionnaires

Real-Time Data Evaluation. The following provides details on evaluation of real-time data as storm pass through the test bed.

1. <u>Pre-Event Analysis</u> Experiment begins when storm cells are 20 kilometers away from the test bed and are expected to enter the test bed. Forecaster tasks:
    a. Review of current forecast data and products on AWIPS to prepare for case.
    b. Completion of pre-event questionnaire: Expectations for the event, what conceptual model is being used, important features to be monitored, areas of uncertainty, inclination to warn at that time, if appropriate.
    c. Configuration of CASA data on WDSS-II for use in the case study.

2. <u>Test Bed Analysis</u> When first echoes enter test bed until last echoes leave test bed. Forecaster Tasks:
    a. "Talk through" analysis of weather event using both AWIPs data and CASA data. What are the strengths and weaknesses of CASA data? What are the strengths and weaknesses of CASA's technology? What are the strengths and weaknesses of NEXRAD data?
    b. CASA data available:
        i. Merged Reflectivity Composite (updated every 1 min.)
        ii. Single Radar Velocity and Reflectivity (updated every 1 min.)
        iii. RHI reflectivity scans (updated every 3 min.)
        iv. 2-D wind analysis (updated every 5 min.)
        v. NWP forecast
    c. Draw a warning area using AWIPS if available, and complete the warning handout.

3. <u>Post Event Questionnaires</u>**.** Forecaster task:
    a. Notable weather features questionnaire

4. <u>Observer/Scientist Roles</u>
    a. Tape conversation, ask clarifying questions. Note times of interesting parts of the event.
    b. Try to understand from the forecaster which aspects of CASA high spatial/temporal resolution, lower troposphere scan, smart VCPs are an advantage or disadvantage.
    c. If time permits, take snap shots images of interesting weather features
    d. Compile any notes and snap shots and collect questionnaires.

Archived CASA Cases. When there is not weather in the test bed forecasters can review archived cases in displaced real time. In order to familiarize forecasters with CASA data, some manual archive cases should be reviewed before a real-time case occurs.

5. Review of current environmental data Forecasters should review current environmental data.for approximately 20 minutes.
    a. on AWIPS, if available, or
    b. Using printed materials to prepare for the case for 20 minutes**.**

6. **Completion of pre-event questionnaire -** Expectations for the event, what mental model is being used, important features to be monitored, areas of uncertainty, inclination to warn at that time.

7. **Test Bed Analysis -** When first echoes enter test bed until last echoes leave test bed. Forecaster Tasks:
    a. "Talk through" analysis of weather event using NEXRAD data and CASA data. What are the strengths and weaknesses of CASA data? What are the strengths and weaknesses of CASA's technology? What are the strengths and weaknesses of NEXRAD data? How does CASA data confirm or refute existing conceptual models?
    b. Using Feature Sheet, note weather features found in CASA data that provide incremental information.

8. **Post Event Questionnaires. Forecaster task:**
    a. Complete post-event questionnaire

9. Observer/Scientist Roles
    a. Tape conversation, ask clarifying questions. Note times of interesting parts of the event.
    b. Try to understand from the forecaster which aspects of CASA high spatial/temporal resolution, lower troposphere scan, smart VCPs are an advantage or disadvantage.
    c. **If time permits, take snap shots images of interesting weather features**
    d. Compile any notes and snap shots and collect questionnaires.

Appendix A. System Overview

The Oklahoma Test Bed, or Integrated Project 1 (IP1) is a four-node “end-to-end” system test bed aimed at precipitation and hazardous wind-sensing in “tornado alley” southwestern Oklahoma. This system is “end-to-end” in that end user populations are integrated into this test bed. The IP1 Test Bed covers a 7,000 square km region in southwestern Oklahoma that receives an average of four tornado warnings and 53 thunderstorm warnings per year. This four-node DCAS system is being operated in conjunction with an end user group comprised of the National Weather Service Forecast Office in Norman, OK, a group of emergency managers who have jurisdictional authority within and upstream of the test bed area, and CASA’s researchers themselves.

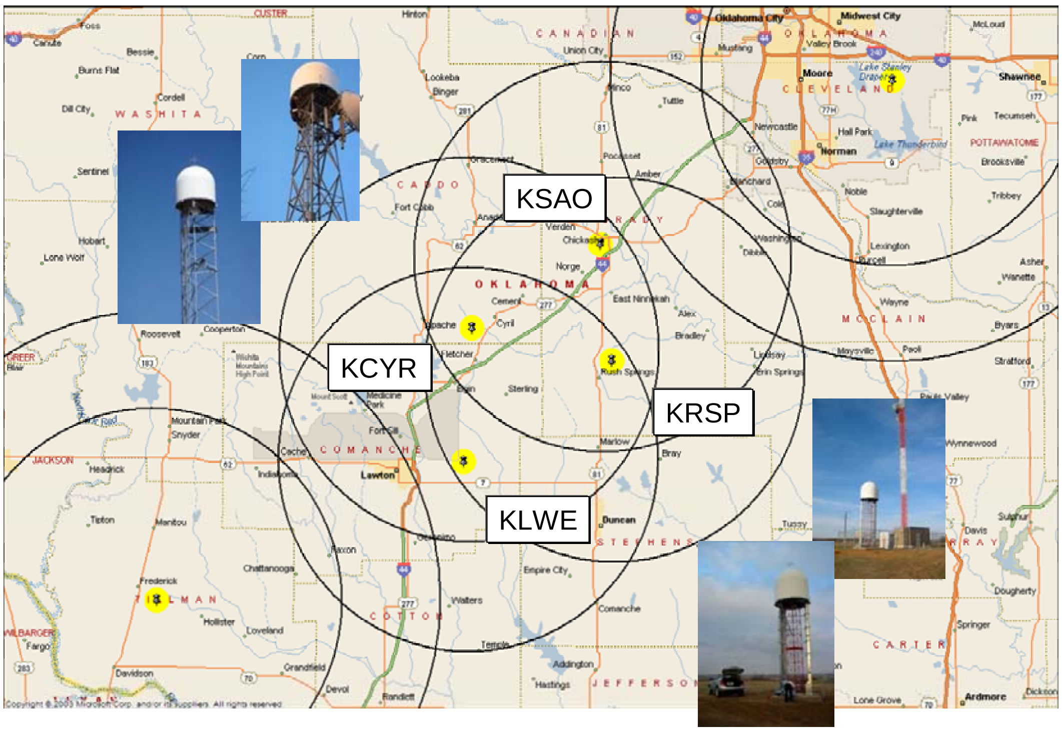

***Figure 1**. IP1 Test Bed. The radar nodes are installed along Interstate 44, Southwest of Oklahoma City, OK, and are under the coverage of the KFDR and KTLX NEXRAD radar units.* The four radar nodes are located in the towns of Chickasha, Rush Springs, Cyril and Lawton, OK, and each radar node is approximately 30 km away from the next unit. Redundant radio links provide Internet connectivity to the radar node sites with a maximum guaranteed bandwidth of 4 MBps

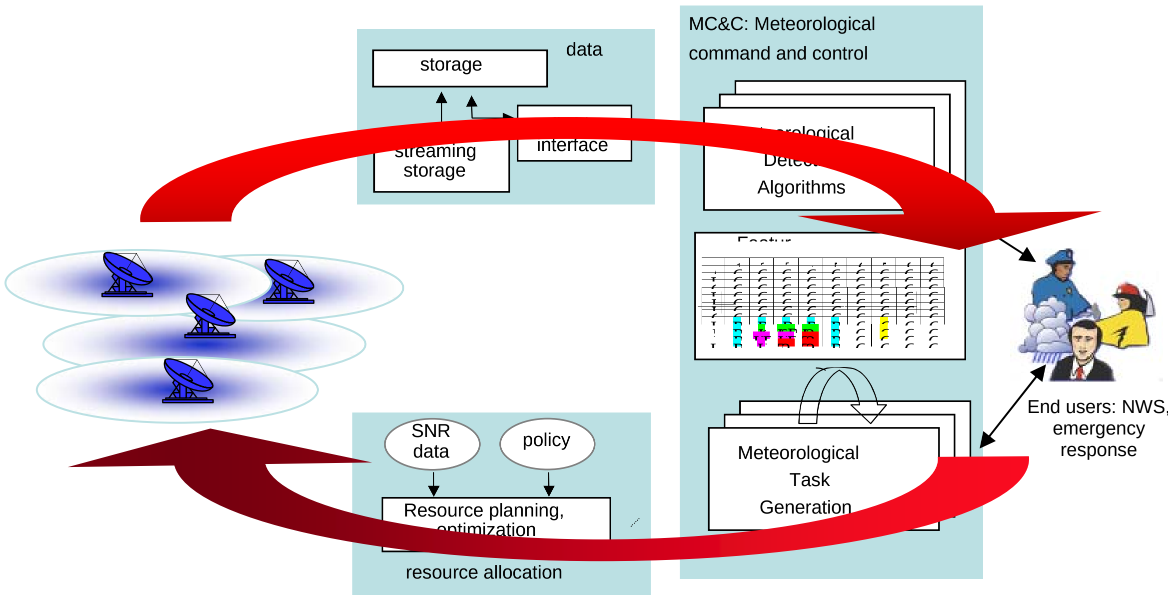

Figure 2. *IP1 system architecture. The radar nodes are connected to a central control site, which automatically generates radar control commands based on detected features in the incoming radar data stream and user needs for data*

The radar nodes are connected to a centralized control site known as SOCC, a cluster of computers and storage devices, which houses the Meteorological Command and Control (MC&C) algorithms responsible for the network automated operation. The MC&C continuously ingests and stores the weather moment data files received from each radar node, detects the relevant weather features in the individual and merged radar data, and creates a list of candidate scanning tasks associated to the detected features. The candidate scanning tasks are used to generate optimized scan strategies, based on the quality of the scan and its importance to users, that are then fed-back into the radar nodes with a 1 minute periodicity. This real-time, closed-loop, automated network operation system is illustrated in Figure 2.

The IP1 radar network is operated in "closed loop" mode, driven by MC&C installed in SOCC. The test bed has remained in near-continuous operation except for scheduled maintenances. The observations of several significant storms are regularly presented in storm debriefs with users and are analyzed in the DCAS paradigm. A number of CASA developed algorithms, from sensing node radar parameter computation to networked processing, from resource allocation to task optimization, from nowcasting to meteorological assimilation, from visualization algorithms to adaptive scan strategy, are being evaluated through these storm events. The system underwent practical functionality tests such as lightning strikes and weather-induced power outages. CASA conducts a Spring Experiment to systematically operate the end-to-end system and give a thorough validation of DCAS paradigm.

Radar Node

The general architecture of radar node is shown in Figure 3 and its specifications are listed in Table 1. The tower-top rotating assembly contains the radar antenna, transceiver, data acquisition system, and elevation actuator, all mounted on a frame on top of the azimuth positioner and housed inside an air-conditioned radome. On the radome floor, the non-rotating subsystems include a gigabit Ethernet switch, Ethernet controlled outlet strip, GPS amplifier, and position controller computer. At the tower base, there is a second gigabit Ethernet switch connected via optic fiber to the one on the tower top, a computer performing signal processing and communication tasks referred to as the Sensing Node Signal Processing Computer (SNSPC), and a RAID that stores the obtained radar data. A network router and Ethernet radio link provide Internet connectivity.

Table 1. IP1 radar node characteristics

Transmitter	
Type	Magnetron
Center frequency	9410 ± 30 MHz
Peak power output	8.0 kW
Average power output	12 W
Pulse width	660 ns
Polarization	Simultaneous H,V
Max. Duty Cycle	0.16%
Antenna and Pedestal	
Type (diameter)	Dual-polarized parabolic reflector (1.2 m)
3-dB Beamwidth	1.80 °
Gain	38.0 dB
Azimuth scan rate	up to 240 °/s
Elevation scan rate	up to 30 °/s
Acceleration	up to 120 $°/s^2$
Receiver	
Type	Parallel, dual channel, linear output I/Q
Dynamic range referenced at input (BW=1.5 MHz)	103 dB
Noise figure	5.5 dB
DAQ sampling rate	100 MSps
DAQ dynamic range (BW=500 KHz)	113 dB
DAQ data transfer rate	88.3 MBps
Video Bandwidth	Adjustable

The radar node can be completely controlled from any remote location with Internet connectivity.

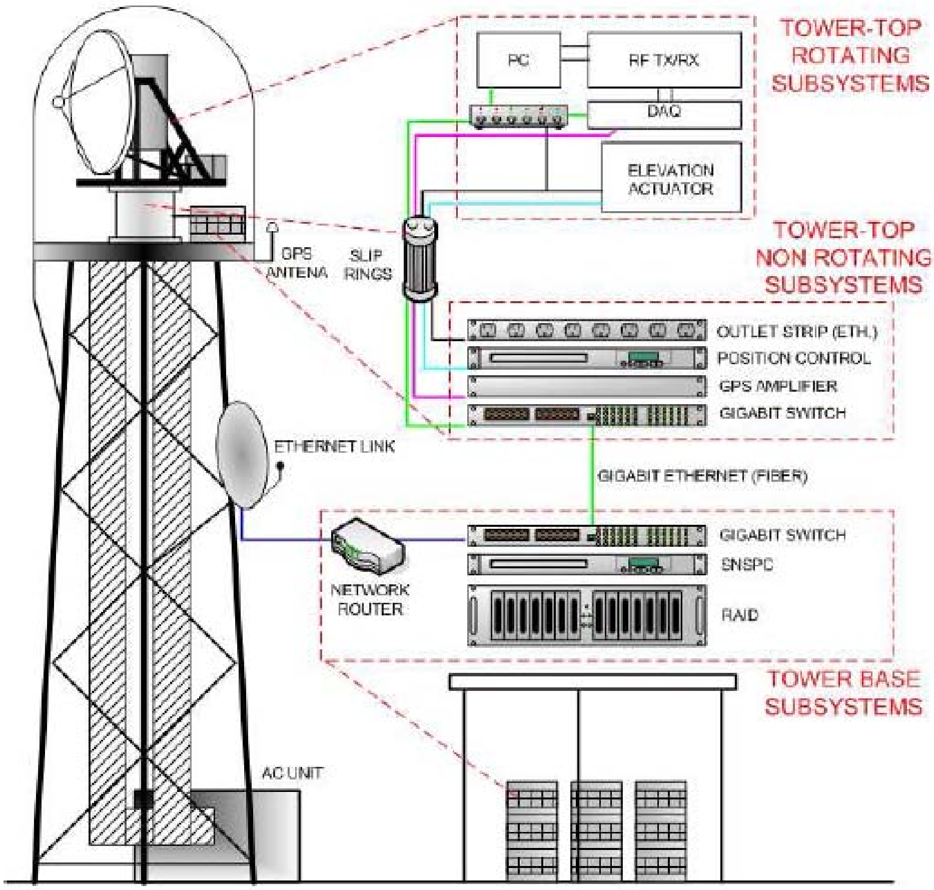

Figure 3. Radar node architecture.

Signal Processing

Key barriers to rapid sampling of the lower troposphere are attenuation, clutter and velocity folding. CASA researchers have created a suite of quality control algorithms, representing the state-of-the-art in X-band signal processing, which operate in real time and correct for attenuation, the removal of clutter and velocity unfolding. These real-time corrections enable more efficient downstream processing, including the use of data mining tools within the MC&C, the assimilation of data into forecast models and the dissemination of data of sufficient quality to end-users. These algorithms currently are based on single radar data; signal processing algorithms will operate in a networked environment during storm season 2008.

Attenuation Correction: Thanks to the polarimetric capability of these four radars, a dual-polarization attenuation correction algorithm has been developed and implemented in the IP1 test bed. The dual-polarization algorithm retrieves the specific attenuation and the specific differential attenuation from the attenuated reflectivity measurements with constraints imposed by the differential propagation phase. The attenuation correction algorithm has been designed specifically to improve the accuracy of the correction for heavy rain, to ensure robustness during light rain, and to meet the IP1 real-time operational requirements. The algorithm was installed into the real-time system in July 2006, and continues to be maintained and evaluated regularly. Since its installation, several corrections have been applied to the software to overcome problems with the challenging operational, real-time environment. Figure 3 illustrates the results of the attenuation correction algorithm on May 8 data.

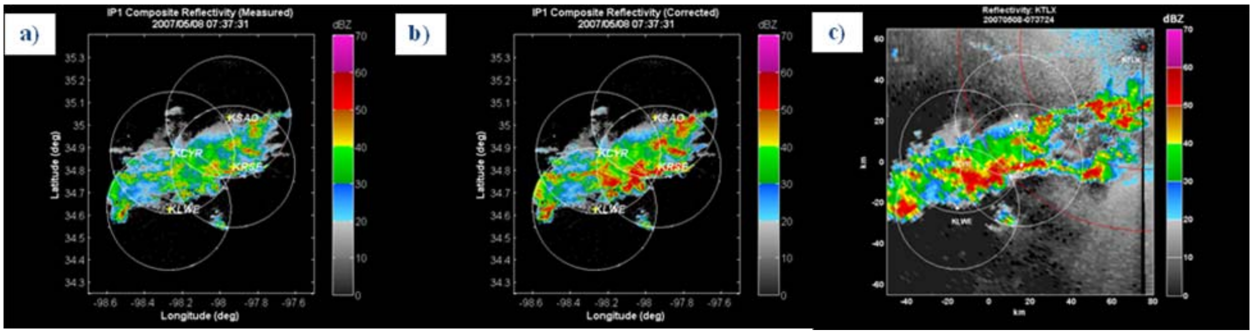

Figure 4: Data collected 8 May 2007. a) Merged reflectivity from IP1 without the attenuation correction. B) Merged reflectivity from IP1 with the attenuation correction applied. C) Reflectivity from the nearby WSR-88D radar at Twin Lakes (KTLX).

Ground Clutter Filtering: Ground clutter filtering is performed by applying a notch filter centered at zero Doppler velocity, though elliptic filters have been traditionally used. The advent of high speed digital processors enables clutter filtering in the spectral domain, thereby enabling a spectral approach to be employed in the IP1 test bed. In this spectral filtering methodology, clutter spectral coefficients are notched with a spectral clipper using a Gaussian model for the clutter spectral density. A Gaussian weather spectral density is recursively fit to the remaining points and the notched spectral coefficients are interpolated with the model. As a result of the recursive interpolation, the bias in reflectivity and velocity due to notch filtering is minimized. This algorithm has been integrated into the radar signal processing module (Figure 4).

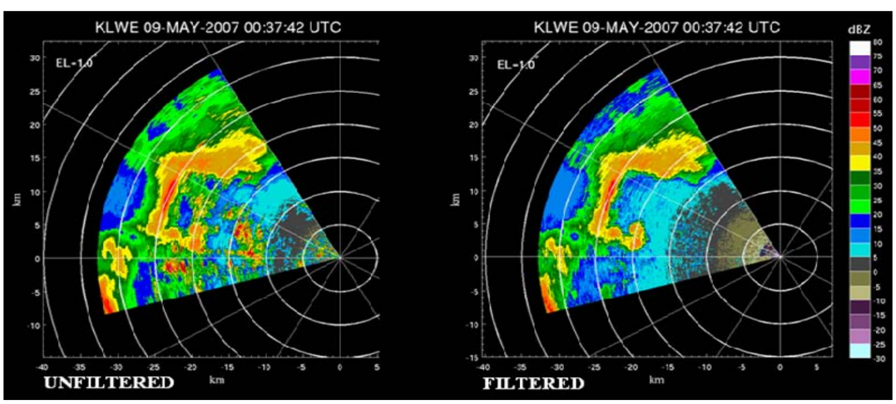

***Figure 5**: Data collected 8 May 2007 from the KLWE radar at the 1.0 degree elevation angle. Reflectivity is shown with and without the clutter filtering applied.*

Dual-PRF. The IP1 radars were designed with hardware support for dual-PRF processing to extend the unambiguous range. Dual-PRF processing has been implemented for real-time operation on each IP1 radar node. Dual-PRF velocity estimates have higher standard deviations and hence, it is only used to correct the original folded velocity. The unfolding is performed by comparing the difference in the two velocity estimates corresponding to the two distinct PRFs. However, unfolding errors still occur due to the inherent uncertainty in the folded velocity estimates. These unfolding errors are corrected during post-processing (Figure 5). A dual-PRF waveform with PRF_1=1.6 kHz and PRF_2=2.4 kHz is applied which yields a maximum unambiguous velocity of 38 m/s. Real time observation with dual PRFs in the IP1 systems have been used to demonstrate the retrieval of higher velocities.

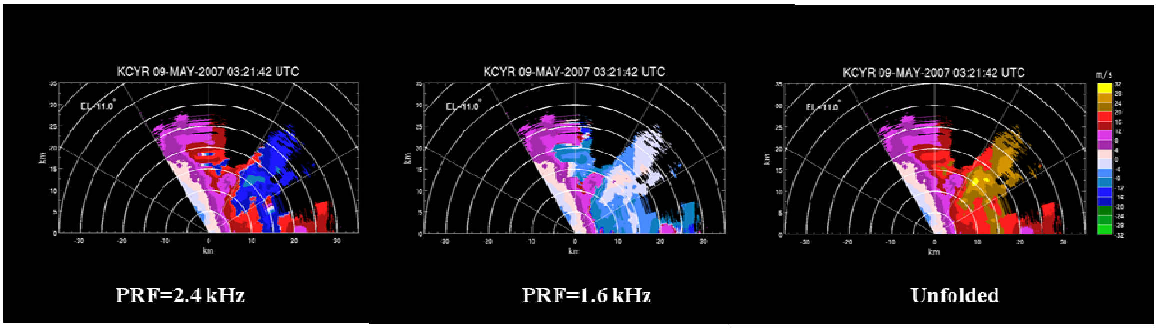

Figure 6*: An X-Y plot of data collected 8 May 2007 from the KCYR radar at the 11 degree elevation angle.*

MC&C

The Meteorological Command and Control (MC&C) software lies at the very heart (or perhaps more appropriately, the "brains") of the IP1 Test Bed, performing the system's main control loop – ingesting data from remote radars, identifying meteorological features in this data, making features available for presentation to end users, and optimizing the configuration of each radar's future scan strategy based on detected features and end user requirements (Figure 7).

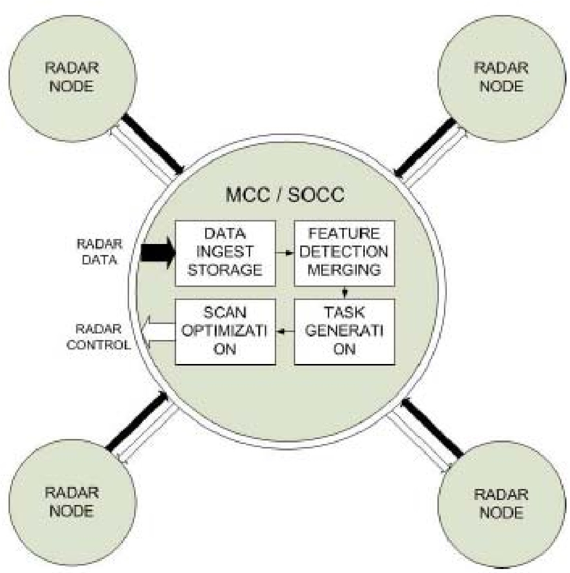

Figure 7. MC&C software drives the DCAS system.

The MC&C makes the IP1 system operate as a collaborative, adaptive user-responsive network. It takes reflectivity and wind velocity spectral moments as input from the set of four sensing nodes, applies quality control to the data, and invokes detection algorithms to generate high-level features. There currently are two types of algorithms implemented real time in the MC&C, namely the UMASS RT algorithm and the NSSL/ OU detection algorithms. During the experiment, the CSU DARTS algorithm will also be tested and evaluated using IP1 observations. The high-level features are used, in turn, to generate tasks that are passed to a Resource Allocation module, which combines the tasks and end user priorities to generate the radars' scan strategies for the next system heartbeat. All MC&C modules execute at the central node in the physical System Operations Control Center (SOCC), with the exception of the sensing module, which is distributed at the radar nodes

Scanning Strategy

The MC&C maximizes overall the utility of each heartbeat based on i) how important it is to scan a weather feature for different user groups (user utility) and *ii)* how well the radars are able to scan the feature (scan quality). User utility, in turn, is determined by user weights (the priority of each user in the system) and user rules, the stated preferences of different user groups for receiving data. For Spring 2009, Version 3 of the rules was developed based on user feedback from the Spring 2007. In addition two new users were added for Clear Air Research, one looking at moisture and another at boundaries. As shown in Table 2, The "Rule Trigger" determines whether a rule is activated based on a detected weather feature, such as an area of high reflectivity. The "Task Area", "Elevation" and "Radar Scanning" define how each radar should scan, "Sample Rate" designates the periodicity of the rule, and Contiguous Scans indicates whether data can be gathered over several heartbeats. The utility of a rule increases as the sample interval approaches.

Rule ID	Trigger	Task Area	Elevation	Radar Scanning	Sampling Rate	Contiguous Scans
			CLEAR AIR MOSITURE			
CM4	Absence of precipitation	360	1 degree	Clear	1min	NA
			CLEAR AIR BOUNDARIES			
CM5	Absence of precipitation	360	2 degree	Clear	1 min	NA
			MORPHOLOGY			
M!	**Storm Cell** > 40dBZ (SCIT)	**Sector** Meteorological Object using CDA *	As high as possible within heartbeat	Standard – PPI Multi Radar	2 minutes	Yes, within 2 min Stacked scans preferred?
M2	**Rotation** (LLSD)	**Sector** Meteorological Object using CDA *	As high as possible within heartbeat	Standard – PPI Multi Radar	1 min	No
M3	**Storm Cell** > 40dBZ (SCIT)	**RHI scan** in area of highest reflectivity to 28 deg.			3 min	no
			NWP			
NWP 1	**Storm Cell** > 40dBZ (SCIT)	**Sector** Meteorological Object using CDA *	To cover Azimuth	Standard – PPI Multi Radar	5 min	Yes, within 10 min
NWP 2	**Rotation** (LLSD)	**Sector** Meteorological Object using CDA *	To cover Azimuth	Standard – PPI M ulti Radar	5 min	Yes, within 10 min

Table 2. User Rules for Scanning

Data Dissemination and Visualization

Figure 8 summarizes the dissemination plan of the IP1 system.. IP1 data have been categorized into Tiers (I, II, III) that reflect the stage of processing prior to dissemination to users; time series (Tier 1) data are processed at the radar, and moment (Tier II) data are transmitted from individual radars to the SOCC, where they are quality controlled, merged, and ingested into WDSS-II.

Output from WDSS-II (Tier III) is used in the optimization of the scanning strategy. Tier II and Tier III data are disseminated to end users in real-time and are stored on tape in the CASA archive. A description of the availability of the data is as follows:

- Tier I data: This data collection process is enabled for special application and diagnostic purposes;
- Tier II data: Radar moment and dual-polarization data are archived as NetCDF files;
- Tier III data: These include mosaic radar images and the products generated by the WDSSII algorithms.

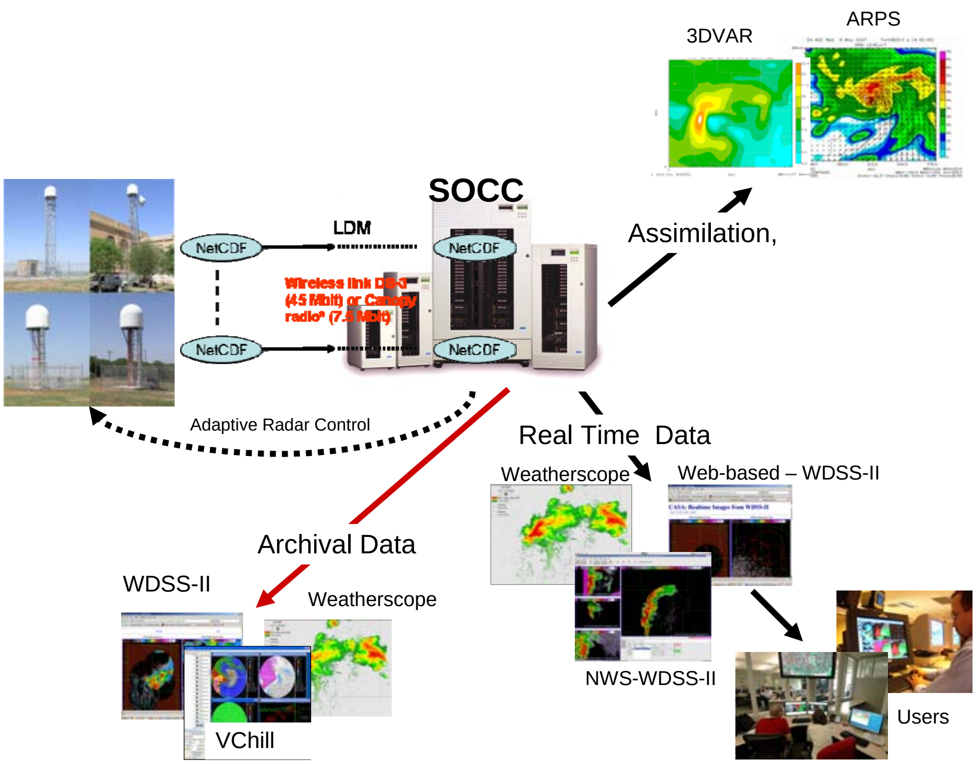

Figure 8. IP1 data dissemination

Four methods of visualization of IP1 data are available to end users: WDSS-II, Google Earth, Weatherscope, and V-CHILL.

- **WDSS-II** is an NSSL operating platform that allows for visualization of real-time and archived data. The Norman, OK Weather Forecast Office (WFO) of the National Weather Service and CASA researchers access data via WDSS-II. IP1 data are displayed in real-time via WDSS-II on CASA's public web pages.
- Real-time data from IP1 is also displayed using **Google Earth** tools. GIS allow IP1 data to be displayed in real-time overlaid with surface data and satellite imagery. This visualization is also accessible via the CASA public web pages.
- **Weatherscope** is a software application that allows interactive access to weather and hydrological information over the Internet. Emergency managers primarily view IP1 data with Weatherscope. Use of Weatherscope is open to all CASA participants, but is password protected.

- **VCHILL** visualization product also works for CASA data and is available for researches for detailed analysis.

Products for CSET 2009 include merged composite reflectivity, single radar reflectivity and velocity, 2d wind products (every 5 minutes), refractivity products, and forecast products (not produced in real-time.)

End User Integration

Users are an integral part of the IP1 test bed and evaluate both real-time and archive case studies of CASA data in a quasi-operational environment. A multi-method approach is used to study users including focus groups, event debriefs, participant observation during real-time events and case studies, and surveys. Research on user needs and behavior provides input into two primary areas:

- Feedback on system design. - User observation provide feedback on system design issues such as visualization, data quality, adaptive scanning strategies, and user policy The user policy and end user rules that contribute the adaptive scanning strategy are reviewed and updated based on user evaluations. Version 3.0 of the user rules will operate in the system for CSET 2009.
- Hazards Response– Research to understand how DCAS data incrementally impacts user severe weather assessments and warning decisions is being conducted to create an end-to-end decision model of a DCAS system, called the Integrated Systems Model (ISM). The ISM will quantitatively link "upstream" technical capabilities, such as targeted radar observations, to their incremental impacts on later "downstream" responses such as warning decisions, risk communication, public response, and the resulting socio-economic impacts. This model will create a quantitative link between human warning behavior and response and engineered system operation. During CSET 2009 the following research will occur:
    - Development of formal multi-attributes defines how users trade-off different data attributes, and establishment of intra-user trade-off coefficients.
    - Descriptive decision making model of NWS decision making through review of best practices and observations of forecasters
    - Descriptive decision making model of Emergency managers through post-event web-based surveys and product usage analysis of 10 EMs with jurisdictional authority in the test bed,
    - Public response survey to create a quantitative model of public response to severe weather warnings based on social, demographic, meteorological, and warning issuance considerations.