Collaborative Adaptive Sensing of the Atmosphere

New Radar System for Improving Analysis and Forecasting of Surface Weather Conditions

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An Engineering Research Center for the Collaborative Adaptive Sensing of the Atmosphere (CASA) was formed in the fall of 2003 by the National Science Foundation to develop a dense network of small, low-cost, low-power radars that could collaboratively and adaptively sense the lower atmosphere (0 to 3 km above ground level). Such a network is expected to improve sensing near the ground dramatically through a process called distributive collaborative adaptive sensing. The CASA network is a dynamic, data-driven application system, whereby strategy for scanning is an optimized network solution among competing end-user needs and weather constraints. Decision making is made in real time, with end users providing automated or manual input, or both, to the system. Furthermore, each radar will have dual-polarization capability and signal processing designed to minimize ground clutter contamination. Data collected from the CASA network will be assimilated in real time for use in detection algorithms, numerical weather prediction and transportation models, and output disseminated to a wide array of end users. Because of distinct advantages of such a radar network, significant improvements are expected from the system, in analysis and prediction of surface weather conditions.

Weather plays a disruptive role in normal operation of the nation's transportation systems. A single low-pressure system in the Midwest can create impassable blizzard conditions in the Rocky Mountains, flooding rains and winds across the Great Plains, and severe weather across the South, causing traffic congestion in many cities and disrupting airport and train schedules across the country. Nationally, weather is responsible for nearly 1.5 million vehicular accidents per year, causing 7,000 fatalities and $42 billion in damages. Snow, ice, and fog cause drivers an additional 500,000 h of delays annually (*1*).

Accurate analysis and forecasting of surface weather conditions enable preventive measures to be implemented, which can reduce the numbers of traffic accidents, deaths, and delays due to weather-related problems. One way to improve weather analysis and prediction is by increasing the number of surface (in situ) measurement systems, including automated surface observing systems (ASOS), environmental sensor stations, and surface mesonets. Remotely sensed observations from the middle and upper atmospheric levels, from such tools as the National Weather Service (NWS) and FHWA radar networks and from National Oceanic and Atmospheric Administration and National Aeronautics and Space Administration satellites, could also be used more effectively. Projects such as the Clarus Initiative (*2*) are beginning to collect and assimilate these large data sets into transportation models. Nevertheless, the 0.01- to 3-km above ground level (AGL) atmosphere remains a largely unsampled yet critical region for analysis and prediction of surface weather conditions. Observation of that layer is crucial for detection of tornadoes, downbursts, and surface boundaries; for identification of flooding rains in urban and mountainous regions; and for prediction of thunderstorm initiation, fog, and freezing rain and snow events.

The current NWS Weather Surveillance Radar (WSR-88D) network [(also known as Next Generation Radar (NEXRAD)] provides much of the nation with moment (reflectivity, velocity, and spectrum width) data in near real time (with updates every 5 to 6 min). NEXRAD consists of 158 radars spaced an average 230 km apart, collecting data with an azimuthal resolution of 1.0° and a range resolution of 100 m. However, several limitations with NEXRAD prevent data from being routinely collected near the surface between 0 and 3 km. First, the curvature of the earth inhibits low-level NEXRAD observations from being collected. As the beam range (R) increases from the radar, the beam height above ground level, measured at the bottom edge of the beam, increases at the rate of $(R/4.12)^2$ (*3*). At the maximum NEXRAD range of 230 km and assuming a 0° elevation angle, the beam is at a height of approximately 3 km AGL. Current regulations further limit the lowest elevation angle used by NEXRAD to 0.5°. In total, 72% of the atmosphere below 1 km is not observed with the current WSR-88D network. In addition, many NEXRAD sites in the western United States have limited coverage due to terrain blockage and limited coverage due to site placement along the coasts (*4–6*). Such problems significantly limit the utility that existing radar networks provide for analysis and prediction of near-surface conditions.

DESCRIPTION OF COLLABORATIVE ADAPTIVE SENSING OF THE ATMOSPHERE

In September 2003, the National Science Foundation established the Engineering Research Center (ERC) for Collaborative Adaptive Sensing of the Atmosphere (CASA) (*3*). Each ERC is established as a 10-year center, with emphasis on bringing together academic and industrial partners to solve complex engineering problems.

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The University of Massachusetts (lead institution), University of Oklahoma, Colorado State University, and University of Puerto Rico at Mayaguez combined efforts with organizations such as Raytheon, Vaisala, and NWS to develop an innovative radar system that can overcome the deficiencies of existing radar networks. The 10-year vision is to create a distributed network of low-cost, low-power solid-state radars that have Doppler, dual-polarization capability and that can be installed easily on cell phone towers and rooftops. Such a system has the potential to revolutionize sampling of the near-surface atmosphere.

Distributed Collaborative Adaptive Sensing

To enable collection of radar data below 3 km, CASA has adopted a new approach to scanning called distributed collaborative adaptive sensing (DCAS). Instead of a single long-range, large antenna radar, a dense, distributed network of small antennas is used to focus resources exclusively on scanning near the surface. Each small antenna radar will have a range of 30 km and be spaced an average 25 km apart. Much of the domain will have overlapping beam coverage.

Because of the small antenna size, DCAS radars will be limited to using a 3-cm wavelength (X-band) and will thus incur greater attenuation. A networked approach will minimize this problem, however, for each storm will be viewed from different angles by multiple radars. Adjacent radars will collaborate on their scanning strategies to best resolve small-scale temporal and spatial structure, as demonstrated by Maddox et al. (7).

CASA radars will also have the unique ability to rapidly adapt to changing conditions and needs. Unlike traditional radars, CASA radars will automatically adapt their scanning strategy, radar parameters (e.g., pulse repetition frequency, scanning rates), and networking flow rates to changing weather, environmental, and computing needs. In addition, the CASA system is designed as a multiple end-user system. Thus, scanning strategy will also be formulated in a manner that optimizes user preferences and needs, in conjunction with technical limitations such as attenuation and computing limitations.

CASA System Architecture

The architectural design of the CASA radar network allows for dynamic, end-user feedback as input to system operation (Figure 1). Data flow within the CASA system begins at the radar nodes, where data are collected in real time in 30-s increments, or heartbeats. Spectra level radar data (Tier I) are quality controlled and processed into moment-level data (Tier II). NetCDF files of Tier II data are generated and transmitted via wireless DS-3 microwave link to a central location known as the System Operations Control Center (SOCC). At the SOCC, all NetCDF files from all radar nodes are collected and archived. Additional quality control is applied to the real-time data stream, and detection algorithms "mine" the real-time data stream searching for hazardous weather and other features of interest. All CASA radar data are then integrated with additional meteorological observations, including NEXRAD, satellite, and surface measurement systems and assimilated to produce a single three-dimensional (3-D) gridded volume of weather output (Tier III level data). The objective of this 3-D grid is to produce the most accurate representation of the atmosphere as possible using all available resources. Areas of greatest measurement uncertainty within the grid can be ascertained from a numerical scheme such as ensemble Kalman filtering, and it is these areas of greatest uncertainty where additional observations can be targeted for the next assimilation cycle (e.g., during the next 30-s heartbeat).

The next step in the CASA system data flow is interaction of the end user with the data stream. The CASA network is an example

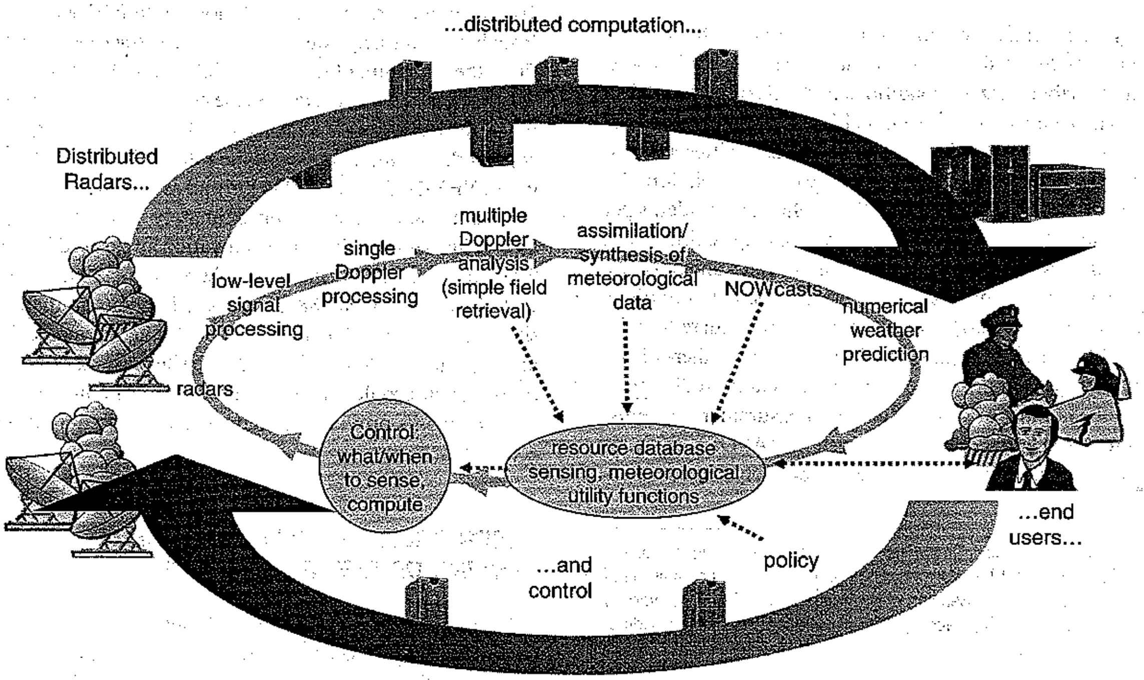

FIGURE 1 Schematic demonstrating architectural design and data flow of network. (Figure courtesy of Jim Kurose)

of a dynamic, data-driven application system (*8*), in which system end users contribute, directly and indirectly, to operation of the system. End users may include local emergency managers and law enforcement, state and federal agencies (e.g., NWS), private industry (e.g., trucking, shipping or energy companies), air traffic control, and local broadcast media, among others. End users will be able to interact with the system in real time either through automated, a priori tables, computer programs, and numerical models, or manually, through a graphical user interface.

Tier III level (gridded) radar data are then combined with end-user input, attenuation information, detection algorithm output, and computing requirements within an optimization process. This optimization program integrates a variety of data; then it uses a blackboard system architecture to determine the best use of radar resources for the next heartbeat. The optimization code calculates the scanning parameters for each radar for the next cycle. Scanning parameters are then transmitted via DS-3 wireless microwave link back to each radar node. The complete CASA radar cycle begins again for the next heartbeat of the system.

Specifications of the radars, signal processing, and feature detection and optimization software, and how they relate to improving analysis and prediction of surface transportation weather, are described next.

Radar Specifications

Table 1 lists the specific radar parameters for the first test bed of CASA to be deployed (*3*). Each radar will be magnetron, mechanically scanning in both elevation and azimuth, and it will have dual-polarization capability. As the system matures, the mechanically scanning radars will be replaced with solid-state, phased array systems.

Signal Processing and Quality Control

A modified dual-pulse repetition frequency scheme using random phase coding is being implemented to mitigate the range-velocity ambiguity problem (CASA System Requirements; CASA ERC, IP1–Phase A, Version 2.8. Feb. 23, 2005). For more information on radar waveform design and signal processing, see Bharadwaj and Chandrasekar (*9*, *10*) and Cho et al. (*11*). Such signal processing is critical for minimizing the effects of ground clutter when sampling the lower atmosphere.

TABLE 1 Radar Specifications for Integrative Project One

System Parameter	Value
Operating frequency	9.3 GHz
Wavelength	3 cm
Antenna diameter	1.2 m
Antenna bandwidth	1.8 deg
Maximum range	30 km
Effective transmitter power	12.5 kW
Average transmitter power	25 W
Pulse repetition frequency	3000 Hz
Range resolution	100 m

Feature Detection

A suite of detection algorithms is being developed for real-time, automated identification of hazardous weather features from CASA data (*12*, *13*). Four algorithms will be developed that operate on single-radar data only, including the Storm Cell Identification and Tracking, Linear Least Square Derivative, Mesocyclone Detection Algorithm, and Tornado Detection Algorithm. Additional algorithms are being developed that operate on multiple-radar, multiple-sensor, and gridded four-dimension volume data. Furthermore, anticipation algorithms are being tested that project the probabilities and expected paths of detected and forecast features. Output from such algorithms can be easily integrated into surface weather transportation models, for public warning and dissemination.

IMPROVEMENT IN SURFACE ANALYSIS AND PREDICTION

The primary impetus for focusing radar beams on the lower atmosphere is to improve real-time analysis and short-term prediction (0 to 6 h). As part of a 10-year effort to improve analysis and prediction of short-term, mesoscale phenomena, the Center for the Analysis and Prediction of Storms, an integral partner of CASA, developed the Advanced Regional Prediction System (ARPS) (*14–16*) and the ARPS Data Analysis System (ADAS) (*17*). ARPS is a compressible, nonhydrostatic mesoscale weather prediction model. ADAS assimilates NEXRAD, Aircraft Communication Addressing and Reporting System, surface ASOS, and mesonet data to best initialize the mesoscale atmospheric structure. A number of case studies with ADAS and ARPS have demonstrated the value of radar input to improving initialization and prediction (*18–20*). Leyton and Fritsch (*21*) and Grover-Kopec and Fritsch (*22*) have shown that inclusion of radar data also improves less sophisticated, short-term probabilistic forecasts of surface variables such as surface temperature and dew point depression. These forecasts are already being used by the private sector. But how much improvement in model accuracy should one expect from an additional radar data source?

While the first CASA radars have yet to be fully deployed, some observing system simulation experiments have been conducted to quantify the impact that even just a few additional CASA radars would have on a forecast. Xue et al. (*23*) assimilated simulated Doppler radar data into the ARPS using an ensemble square root Kalman filter. Xue et al. compared two experiments: a null case assimilating data from a single NEXRAD radar and a second experiment assimilating simulated data from both a CASA radar and a NEXRAD radar. A comparison of differences between experiments showed that root-mean-square error (RMSE) decreased significantly with the additional CASA radar, with the greatest improvements found at the lowest vertical levels. RMSEs for wind (u, v, w) decreased by almost 0.5 ms^{-1}; in fact, RMSEs decreased for all model state variables including temperature, pressure, and moisture. Furthermore, RMSEs remained lower for the second experiment for a longer period of time as the additional CASA radar captured a low-level cold pool not seen by the NEXRAD radar. Forecasts were improved for more than 40 min after initialization simply with the addition of a single CASA radar.

The CASA network will also provide data for development and testing of several new assimilation techniques that are expected to improve analysis and forecasting even further. An associated project, Linked Environments for Atmospheric Discovery (*24*), is developing a numerical modeling system that dynamically adjusts numerical model runs based on targeted observations. Similarly, the observing systems (in this case, CASA radars), will dynamically respond in part to the numerical model output. A new approach for data assimilation of radar data is ensemble Kalman filtering, and several studies are under way to use this technique for assimilating CASA data (*23*). Finally, the use of ensemble forecasts at the mesoscale will be explored by using CASA data. Initial tests from the Storm and Mesoscale Ensemble Experiment showed that an ensemble from multiple models outperforms any single individual model result (*25*). It is hoped eventually that output from mesoscale model ensembles will be used by the radar optimization and targeting process.

TIME LINE AND CASA TEST BEDS

The strategic vision for CASA is to revolutionize the ability to observe the lower troposphere through DCAS. To realize vision, a series of integrative projects (IPs) will be developed during the 10-year span of the ERC to both demonstrate and spur scientific development of DCAS. Each IP will be created as an end-to-end system, linking research tools in the field to operational end users.

Each of these test beds will focus on a different aspect of low-level sensing. The first test bed, known as IP1, to be located in southwestern Oklahoma, will focus on the high spatial and temporal mapping of winds in the lower troposphere. The second test bed, IP2, to be located in Houston, Texas, will focus on improving quantitative precipitation estimation (QPE) and urban flooding prediction. The third test bed, IP3, to be located in Puerto Rico, will be used to study QPE and terrain-induced flooding prediction. A fourth test bed, known as CLEAR, will be used to study measurement of the nonprecipitating atmosphere. Bragg-scale turbulence will be sensed possibly by using bistatic scattering measurement technologies.

Each IP focuses on a key problem in transportation services: severe and hazardous wind events and urban and terrain-induced flooding. Research from CLEAR is expected to improve analysis and prediction of more subtle near-surface conditions, including detection and prediction of low-level boundaries and inversions, key to improving forecasts of low-level fog, icing events, and atmospheric pollution.

IP1 AS FIRST TEST BED

The first IP will focus on detection and prediction of severe and hazardous weather (*26*). IP1 will consist of four mechanically scanning magnetron radars, and it will be located near the towns of Chickasha, Cyril, Lawton, and Rush Springs in southwestern Oklahoma (Figure 2). Each CASA radar has a range of 30 km, and the average spacing between sites is 25 km. The first radar was installed in early March 2006, and all four radars are expected to be operating by midspring of 2006. IP1 is the first test bed to demonstrate DCAS and the value of low-level sensing, and a number of

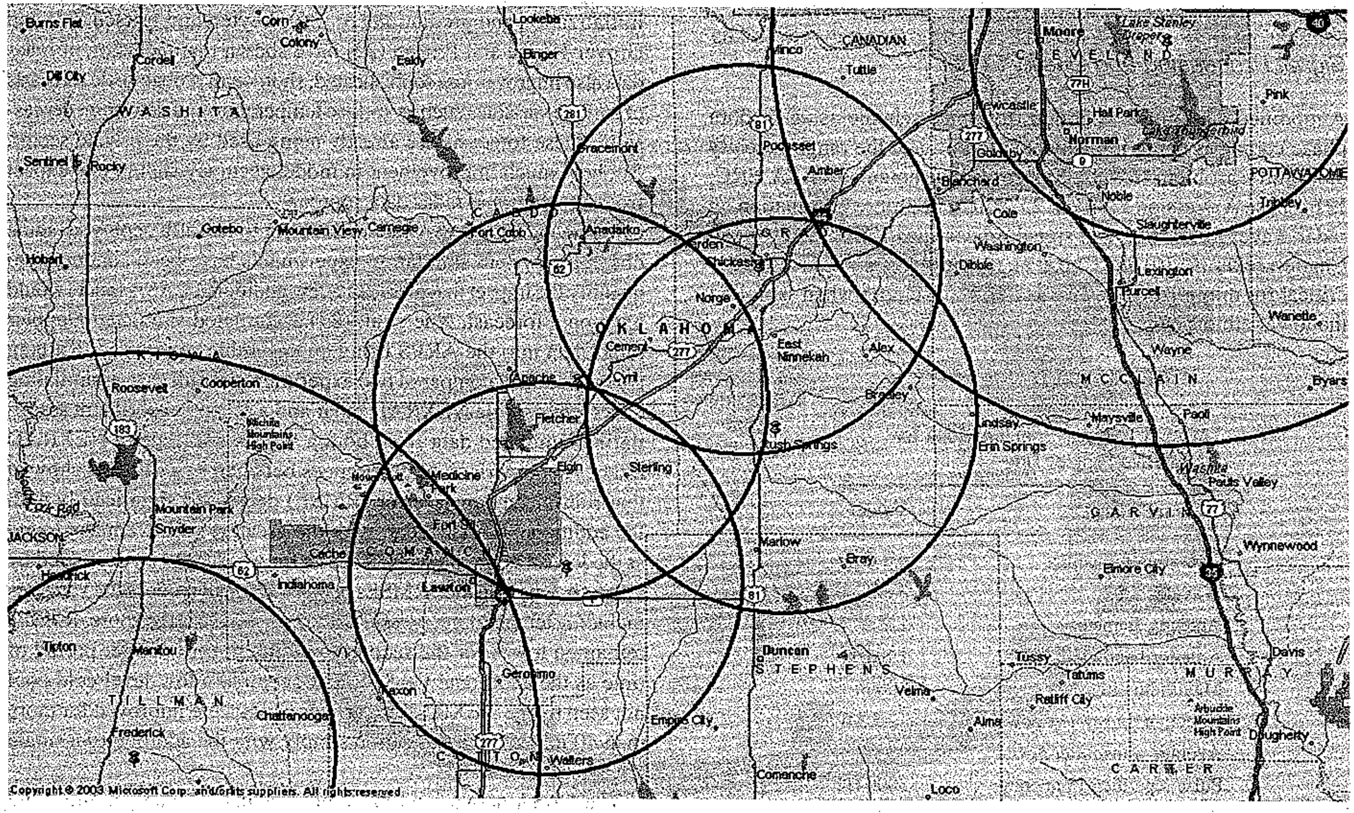

FIGURE 2 Schematic showing four radar locations that constitute IP1 and two nearest WSR-88D radars located near Twin Lakes and Frederick.

research opportunities will be made available by the system. The IP1 network will be expanded from four nodes to as many as nine nodes within the next 5 years.

The IP1 test bed will be well situated for testing the impact of CASA on improving surface transportation weather analysis and prediction. Federal Interstate I-44 and U.S. Routes 81, 277, and 62 traverse the four-node IP1 coverage domain, and a portion of I-40 will be included in the expanded test bed area. Geographic information system (GIS) information on all transportation throughways in the test bed will be included into a single database, along with information from other infrastructure such as airports and high-population density areas, to be used by the optimization program in selecting scanning strategies. The value assigned to each target will be determined by end-user needs.

All data collected during IP1 will be archived and made available for model development and verification. While specific transportation research experiments are beyond the immediate scope of IP1, the CASA network is specifically designed to accommodate road weather research, and such cross-disciplinary collaborations are encouraged.

DEMONSTRATION SCENARIOS

Although the CASA system is in many respects still being developed, a final operational and commercially deployable system is expected within the decade. Such networks of low-cost, low-power radars are expected to be integrated into a wide array of cross-disciplinary technologies. Following are several scenarios of how such systems could one day be employed operationally.

Analysis and Numerical Model Integration

In response to daytime surface heating and land-surface inhomogeneities, wind convergence zones within the atmospheric boundary layer begin to form. Data collected by a nearby network of radars scanning in general surveillance mode are fed, in real time, to hazardous weather pattern detection algorithms that identify and classify the specific features being sensed, and that generate a wide variety of metadata. The feature ID information is fed into an optimization system that, in combination with other data (e.g., user priorities for the radars at that particular moment, geometry of the radar network, local terrain, geometry of the features being detected), yields an optimal remote sensing configuration to which the radars automatically configure, that is, scanning strategies, frequencies, and polarization diversity. The metadata travel into a data repository, where they are combined with GIS databases for semantic-rich data mining.

Simultaneously, the radar observations are fed into an end-to-end atmospheric-transportation data assimilation system where, coupled with land-surface, vehicle infrastructure integration (VII) data and other information, unobserved fields are retrieved and a fine-scale 3-D state analysis is produced. This analysis serves as initial conditions for a high-resolution numerical prediction model, run in a 100-member ensemble mode, and along with the raw observations themselves, it serves as input to data mining engines. These data mining engines use decision trees, neural networks, pattern recognition algorithms, and knowledge discovery tools to identify atmospheric hazards in great detail, as all atmospheric fields (observed and retrieved) are available. When the 100-member ensemble model runs conclude, output is processed to generate probabilistic forecasts that, combined with observations and analyses, yield statistically reliable conditional probabilities in 1,000 categories (e.g., probability of precipitation greater than 0.5 in. in 1 h). This information is fed into off-site, proprietary risk assessment models, say, of a local law enforcement agency, where if the probability of the forecast exceeds a predetermined risk-assessment threshold, a decision automatically is made to begin evacuation of certain neighborhoods. The raw ensembles are transferred to a data repository where they can be mined in real time, by other scientists, in combination with other information.

Winter Weather

In central Iowa, mixed precipitation of rain, sleet, and snow begins to develop. The CASA radars, scanning below 3 km, detect the first regions of developing snowfall from the low-topped storms, areas of precipitation below that seen by the nearest WSR-88D. Furthermore, the dual-polarization CASA radars discern those areas of frozen precipitation, and optimal retrieval algorithms extract the vertical thermodynamic and wind profile. This information is combined with VII data for detailed surface and atmospheric analysis and prediction. Then data are relayed in real time to transportation, media, and emergency services.

Urban and Terrain-Induced Flooding

Near downtown Houston, rainfall begins to develop along a surface convergence zone, and a network of CASA radars adjusts their mode of operation, automatically via the optimization system, to provide extremely fine-scale, calibrated precipitation rate estimates to local hydrologic models and stream flow decision-support systems (*27*). High-resolution mesoscale models predict the rapid development of heavy rainfall over the downtown area, prompting local emergency managers to begin flood mitigation procedures (*28*). Meanwhile, digitized model output is ingested into road hazard communication databases and then disseminated via wireless communication links to onboard vehicle integration software (*2*). Millions of dollars are saved as floodgates and street closings minimize damage to life and property, and drivers are automatically rerouted around affected areas.

Severe Weather

Meanwhile in Oklahoma, detection by a real-time data mining engine of a small circulation within a storm cell triggers the two radars nearest the circulation into a tornado-tracking mode, where they hand off tracking responsibility to neighboring radars as the tornado progresses eastward. The location, intensity, movement, and projected path of the tornado automatically are reported via wireless links to NWS, local media outlets, and emergency managers (*29*). Affected highways are closed in anticipation of the coming tornado, and several mobile home communities are evacuated in advance. When the tornado destroys two Doppler radars within the network and also disrupts local communication links, other nearby radars assume responsibility, via automated fault-tolerant software both at the data transport and application levels; then the network reroutes local communications to ensure quality of service.

Clear Air Environment

In California, a network of bistatic radars installed along I-280 senses rising levels of moisture being advected into the area. Neural networks, using digitized terrain and radar data, recognize the high probability for fog development (*30*), and warning information is disseminated to highway administration officials. Automated road signage alerts drivers to the hazard.

Elsewhere in California on I-5, a chemical spill occurs. A nearby network of bistatic radars collects clear atmospheric wind and moisture field data. These data are assimilated into a 1-km grid resolution version of the Weather Research and Forecasting model, and output from the model is used by emergency personnel to evacuate nearby homes (*31*). Value-added output to the model data gives emergency personnel valuable demographic and routing information.

SUMMARY

A new radar network is being designed that explicitly meets the needs for improving analysis and forecasting of surface weather conditions. The system of CASA radars will provide dense, rapid scanning between 0 and 3 km AGL, collaboratively and adaptively sensing wherever and whenever end-user needs are greatest.

With rapid advancements in computing, telematics, data assimilation, and numerical modeling, development of a dynamic, networked approach to remote sensing of the near-surface atmosphere is now both feasible and cost-effective. Many technical limitations have now been solved, and the first demonstration test bed of CASA technology will be operational by the spring of 2006. The next step is to integrate the meteorological network with emerging state-of-the-art VII and telematic infostructure. Such an integrated system will undoubtedly reduce accidents, save lives, and improve the efficiency and safety of today's transportation systems.

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