Annual Report for

THE CSU-CHILL RADAR FACILITY

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DEPARTMENT OF ATMOSPHERIC SCIENCE
DEPARTMENT OF ELECTRICAL ENGINEERING
COLORADO STATE UNIVERSITY

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1. Introduction

Activities at the CSU-CHILL National Radar Facility from 1 January 1998 to 31 December 1998 are summarized in this annual report. This is the fourth report submitted under our second Cooperative Agreement with the National Science Foundation (NSF), which commenced on 1 May 1995. During this past year reliable radar operations were again performed. The facility supported another successful REU (Research Experience for Undergraduates) project in 1998, as well as a T-28 on-board data system test, both funded by NSF. Through the REU project, undergraduate engineering students from various universities participated in a two-month program. REU students learned various aspects of radar, including polarimetric techniques for remotely sensing hail. During the T-28 test project, the CHILL radar was used to identify hail shafts and direct the T-28 in real-time. The T-28 penetrated some of these hailstorms, and collected data which are currently undergoing scientific analyses. The in-situ data collected by the T-28 during these missions are being compared to the polarimetric data collected by CHILL.

Another highlight in 1998 was the establishment of a contract with Lassen Research for delivery and installation of a new digital IF dual-receiver and signal processor. This system is now being tested on one of the CSU-CHILL receiver channels. We anticipate testing on the second receiver channel to begin soon. The new digital IF dual-receiver and signal processor are expected to be fully operational by 1 March 1999. The hardware design uses high speed SHARC chips to process 3000, 50 meter deep range gates, which will be range-averaged to a 225 meter resolution. This new system will increase the antenna rotation rate by 50%, thus enabling more rapid scanning of storms to sample storm dynamics, while simultaneously collecting the full suite of multiparameter variables.

Over the past year we also brought the Pawnee 10 cm Doppler radar to full operational status. This radar was originally operated by the Illinois State Water Survey as the HOT radar; in May of this year it was renamed and installed near Nunn, Colorado. The Pawnee antenna pedestal was refurbished, and the frequency chain and receiver were rebuilt. The CHILL-Pawnee pair now provides a 48 km baseline dual-Doppler observational network along the Front Range of Colorado. The radar pair has been supplemented with a permanent, three-station flat plate antenna network for measuring total lightning flash rates over the dual-Doppler domain. This network provides a research capability that was not previously available to the community. The dual-Doppler pair began collecting data in July.

CSU-CHILL staff also spent considerable time during the summer of 1998 preparing a 10-year Strategic Plan for our facility. This Plan is included as Appendix E to this Annual Report. For the period 2000-2005, we intend to further increase the scan speed of CHILL to 18° s^{-1}, using existing CHILL hardware. During the period 2006-2010, we propose to purchase an offset Cassegrain antenna. This antenna would allow for improved sidelobe and cross-polarization performance, and when coupled with our quick scan and polarization diversity capabilities, will substantially advance the remote sensing of clouds and precipitation.

2. Summary of Activities During 1998

In general, the CSU-CHILL radar operated satisfactorily during the primary active weather months of 1998 (January through August). The radar was taken out of service in September to begin extensive hardware modifications required by the new data system installation.

As mentioned in the previous section, CSU also began dual Doppler data collection in 1998 with the installation of the Pawnee radar. The Pawnee system was obtained in 1997 as surplus equipment from the Illinois State Water Survey (where the radar was called the HOT -- Hydrometeorological Operational Tool). The Pawnee is a 10 cm wavelength, single polarization Doppler radar using a klystron-based transmitter. The data system design and radar operational procedures employed in the Pawnee radar are clones of those used at CSU-CHILL, facilitating data collection and processing.

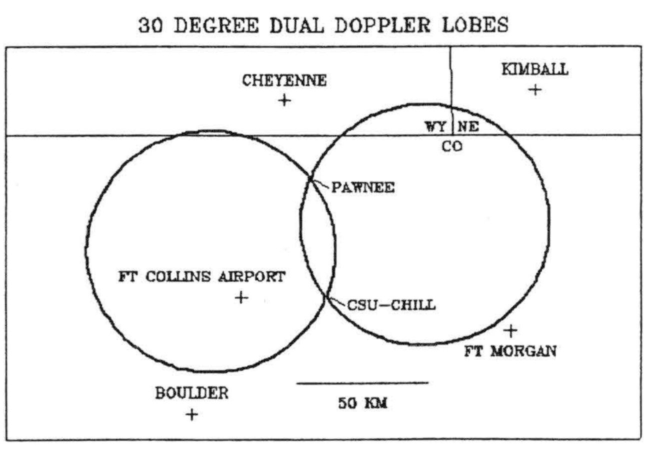

Figure 1: The CSU dual-Doppler network. The CSU-CHILL radar is located near Greeley, Colorado; the Pawnee radar is northeast of Nunn, Colorado. The baseline is 48 km long. The lobes enclose the region where the beam intersection angle exceeds 30 degrees.

Following inspection and upgrades by the CSU-CHILL technical staff (details provided in Sec. 2c below), the Pawnee radar was assembled in June on a leased site 48 km NNW of Greeley. Pawnee operations began in July; and useful dual-Doppler data sets were collected on several occasions. Table 1 summarizes both the CSU-CHILL and Pawnee radar operations conducted during 1998. Additional details may be found in the 1998 CSU-CHILL Newsletter (Appendix D), including dual-Doppler analysis of a supercell, tornadic storm on 1 July 1998, the first day Pawnee became operational!

Table 1: Chronological summary of 1998 CSU radar operations

Period	P. I.	Remarks
April	Beaver	Polarimetric data collection for aircraft icing experiment
May-Aug	Doesken	Colorado Cooperative Rain and Hail Study
June	Detwiler*	T28 new data system tests
June	Holt	Experiments with CSU-CHILL simultaneous transmissions
July	Ogden	Radar-based rainfall estimates vs. reservoir hydrology
July	Lang	Joint lightning and dual Doppler observations of storms

*NSF funded project

Analyses of data collected in 1998 (as well as from several earlier years) are ongoing. Titles of abstracts that have been submitted to the 29th AMS Weather Radar Conference to be held in July, 1999, are listed in the publications section of this report (Section 4).

b. Educational Support

The CSU-CHILL facility continued to provide various forms of educational support to both engineering and meteorological interests during 1998. On 12 May, 1998, Patrick Kennedy introduced polarimetric radar methods of hail detection and rain rate estimation to a group of approximately 100 cooperative weather observers at an organizational meeting of the CoCoRaHS (Colorado Cooperative Rain and Hail Study) project. Educational tours of the facility were conducted on several occasions, as summarized in Table 2:

Table 2: CSU-CHILL Facility Educational Tours During 1998

Date	Group	Remarks
4/10/98	75 high school students	Participants in a state-wide science fair hosted at CSU
6/15/98	4 jr. high science teachers	Teachers enrolled in the NCAR-based LEARN project
6/25/98	~30 volunteer observers	Participants in the CoCoRaHS project

Direct classroom utilization of CSU-CHILL data was made in both the Electrical Engineering and Atmospheric Science Departments at CSU. The engineering courses involved were: EE100 (Introduction to Electrical Engineering), EE342 (Electromagnetics), EE514 (Random Signals and Systems), EE521 (Satellite Communication Systems), EE541 and EE542 (Electromagnetics I and II (graduate level courses), and EE742 (Multiparamater Radar).

In the Atmospheric Science Department, real-time CSU-CHILL data were used in the classroom by Prof. Rutledge in teaching AT741, a Ph.D.-level radar course. The students in this class also wrote detailed final reports based on case studies from archived CSU-CHILL data sets. Copies of their reports are available at the following web site:

http://olympic.atmos.colostate.edu/AT741/1998/

Many students in the Atmospheric Science and Electrical Engineering departments continue to focus their thesis and dissertation topics around CSU-CHILL data. See Appendix A for details.

c. Technical Developments

i) Pawnee Radar Installation

The Pawnee radar system is similar to CHILL in that it is mounted in a semi-trailer, and utilizes an FPS-18 transmitter and a SP20 signal processor. However, the Pawnee radar differs from CHILL in that it has a smaller antenna with a 1.6-degree beamwidth, and only operates with vertical polarization. The primary function of this radar is to collect dual-Doppler data sets by scanning in coordination with CSU-CHILL.

Before the Pawnee system was fielded, the receiver was rebuilt and a new higher performance Low Noise Amplifier (LNA) was installed. The instantaneous automatic gain control (IAGC) and signal digitizer systems were also upgraded.

A 20 foot by 20 foot reinforced concrete pad was poured to support the Pawnee antenna pedestal. The radar horizon is unobstructed at the Pawnee site, so no tower was required. The antenna is protected by a fiberglass FPS-18 radome mounted on a wooden support structure. During 1998, power was supplied via a diesel generator obtained from US government surplus inventory. The installation of three phase commercial power at the site is anticipated for 1999.

ii) New Chill Processor

Colorado State University currently has a contract with Lassen Research to provide a new signal processor system for the CSU-CHILL radar. This system will consist of two digital receiver blocks (Aspen/DRX systems) and an off-the-shelf VME-DSP card. The receiver blocks directly digitize a 10 MHz IF signal. Subsequent quadrature detection and bandwidth matching filtering is done by programmable digital hardware. Five SHARC DSPs located in the receiver blocks perform the bulk of the high-speed signal processing. The signal is split into high and low sensitivity channels to extend the dynamic range of the receiver. Complete time series from both channels are saved and quickly checked to determine which of the two channels offers the optimal gain setting for each gate.

The Aspen/DRX has a demonstrated dynamic range in excess of 100 dB. The current LNAs will limit the dynamic range to approximately 96 dB with a 1 MHz bandwidth filter. The Aspen/DRX receiver blocks are interconnected to assure a precise low-jitter time reference between channels and to allow the exchange of time-series between both receivers. These modules also have a separate channel to sample the transmitter pulse. The power and average phase of each pulse will be calculated and may be used to adjust the time series for fluctuations in transmitter output. The receiver blocks will also perform the clutter filtering and covariance calculations. All data will then be passed via serial line to the off-the-shelf VME-DSP card which will calculate the meteorological moments and derived fields such as specific propagation phase shift (KDP). The end results will pass through the VME host computer and the local network where they will be archived and displayed by Sun workstations and dedicated display hardware.

The CSU-CHILL frequency chain and receivers have been rebuilt to provide the 10 MHz IF signals for the receivers and the transmitter samples (see Fig. 2). A dual-conversion approach has been adopted with the first IF at 50 MHz and the second IF at 10 MHz. This works well with the stable 10 and 40 MHz clock references available from the Aspen/DRX system. At the time this report was written, the radar modifications have been completed and the first DRX system has been delivered and is undergoing testing. Full two-channel operations are expected to begin in early March, 1999.

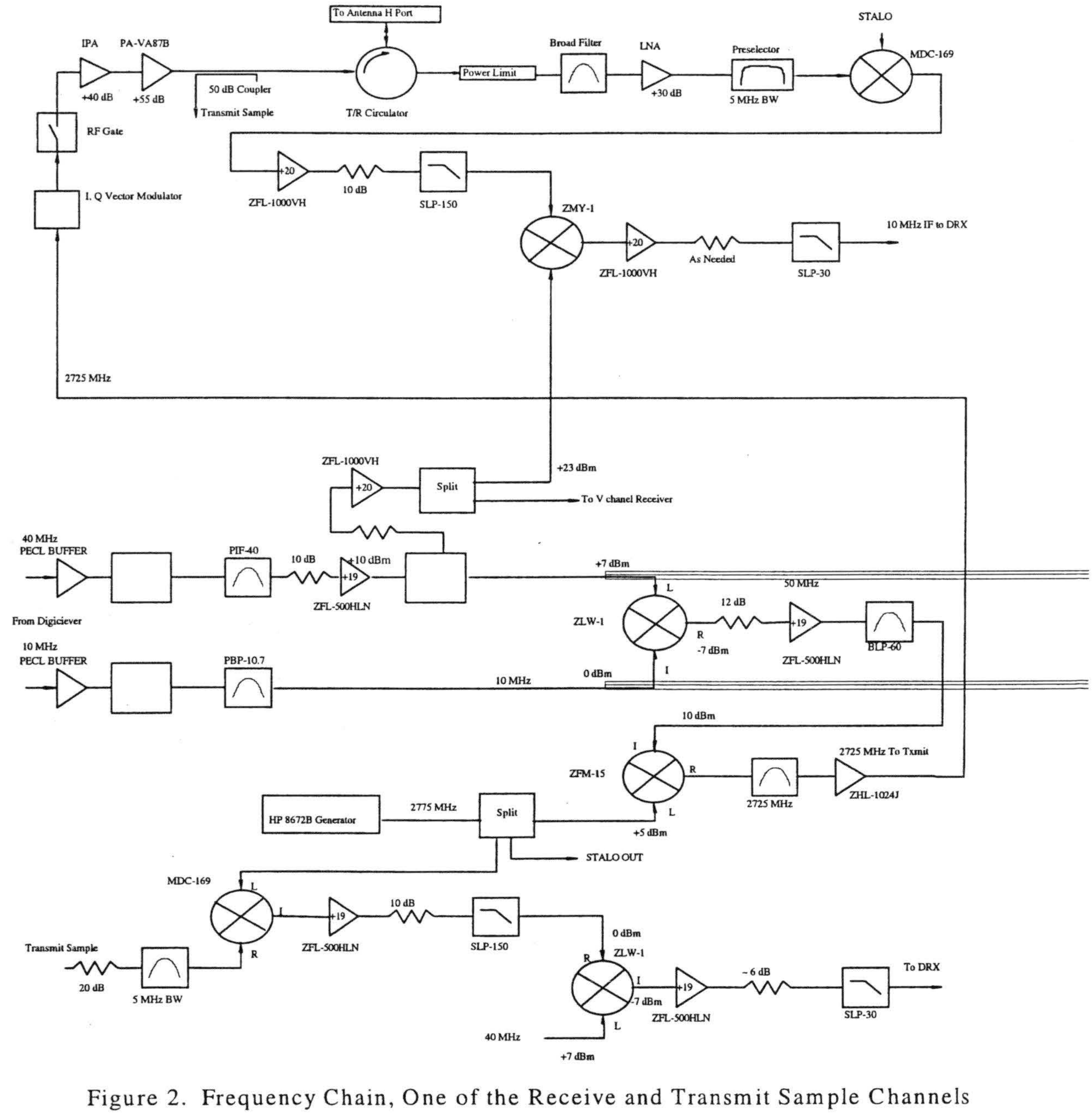

Figure 2. Frequency Chain, One of the Receive and Transmit Sample Channels

iii) Radome Repair

As summarized in the Newsletter, a radome seam opened along an approximately 8 foot length on 19 August 1998. The failure was along the final seam that was closed when the dome was built. Due to the resultant physical access limitations, this seam was assembled with adhesive instead of the fabric welding process that was used on the other seams. The failure occurred when the adhesive neared the end of its design life and began to weaken. CSU-CHILL staff installed temporary lacing as an emergency repair. Additional repair consultation was then sought from the radome manufacturer (Chemfab). The Chemfab engineers devised a pair of corset-like lace-up appliances that were to be glued onto the inside of the radome on either side of the failure. The repair appliances were installed on 31 August. Tightening of the associated lacing cord closed the majority of the seam opening and nearly brought the associated panels back to their original positions. Additional radome fabric sections were then glued on top of the laced repair to form an air-tight seal.

Additional radome inspections conducted in September revealed that another adhesive failure was in progress along the radome's horizontally-oriented "top cap" seam. This seam was reinforced by entirely overlaying it with a sequence of radome fabric patches on the dome's interior surface. On 24 November 1998, Mr. Jim Greno, a Chemfab engineering representative, visited the radar and inspected the radome repair. Mr. Greno felt that the repairs had been satisfactorily made. It is now believed that the dome can reach its designed 10 year lifetime. This still implies that the facility will need a replacement radome within the next 2 years.

d. Atmospheric Sciences Activities

Data collected by the CSU-CHILL radar was the focal point of several M.S. theses and one Ph.D. dissertation in Atmospheric Science during 1998 (all under the supervision of Prof. S. Rutledge). Also, we continued with extensive analyses of the CHILL data collected during the Ft. Collins flood in July 1997. Christine Butler completed a M.S. thesis that assessed the ability of multiparameter radar to determine microphysical characteristics of ice particles associated with winter upslope events. This research encompassed both theoretical and observational aspects. The results suggest that nearly homogeneous populations of aggregates can be distinguished from platelike crystals (i.e., dendrites, stellar crystals and plates) using a combination of co-polar and differential reflectivity observations. Furthermore, it appears possible to discern whether or not the platelike crystals are heavily rimed. Additionally, our results challenged the validity of the common assumption that aggregates always produce a differential reflectivity (Z_{dr}) of 0 db.

Rita Roberts, from NCAR, completed her M.S. thesis in the summer of 1998, focusing on the use of WSR-88D and GOES-8 data in detecting and forecasting storm initiation. Although the intent of this work was to develop algorithms for forecasting the development of thunderstorms along gust front boundaries, horizontal rolls and stationary convergence zones using NEXRAD and GOES data, CHILL data were the focus of one detailed case study. CHILL data revealed Bragg scattering off small cumulus clouds that formed on a horizontal roll, prior to the formation of precipitation. Differential reflectivity data indicated large values of Z_{dr}, indicating the presence of insects caught up in the roll convergence and associated updraft. The evolution of the small cumulus to moderate precipitating cumulonimbi was particularly well captured by the high resolution CHILL polarimetric data.

Jesse Ryan completed a M.S. thesis that examined the relationship between lightning flashes and radar observations in Colorado (using CSU-CHILL data) and in N. Australia (using data from the BMRC C-pol radar). The aim of this work was to examine the validity of the Price and Rind (PR) lightning parameterization, which is in widespread use for predicting lightning flash rates based on cloud top height. These parameterizations are used in large scale models to predict global NOx chemistry. Lightning is an important source of NOx in the free troposphere. CSU-CHILL data provided several case studies for this work. Our studies revealed that the PR parameterization, which formulates the peak lightning flash rate as being proportional to H^5, where H is cloud top height, sets a lower limit to observed lightning flash rates. CHILL data revealed that a more realistic parameterization is given by A•V, where A is the area enclosed by the 30 dBZ reflectivity contour and V is the volume enclosed by the 30 dBZ contour, above the –10 C isotherm.

A portion of Larry Carey's Ph.D. dissertation focused on the examination of CSU-CHILL data in relating radar inferred precipitation structures to electrical observations in a severe hailstorm. In particular, the relationship between large hail and the occurrence of positive cloud-to-ground lightning was examined. We found that the fallout of large hail and the occurrence of positive cloud-to-ground lightning were negatively correlated, with the fallout of large hail leading the increase in positive cloud-to-ground lightning. Furthermore, the peak positive cloud-to-ground flash rates occurred with the peak rain rate from the storm. Based on these observations we offered a new hypothesis to explain this behavior, which involves the unshielding of large amounts of positive charge in the thunderstorm due to the removal of negative charge on raindrops. The large rain rates in severe storms of this type (which can often exceed 200 mm hr^{-1}), produce a large precipitation current that may reduce the lower negative charge center. This observation is also consistent with the fact that we observe only a paucity of negative cloud-to-ground lightning in these events.

Work on the Ft. Collins flood event also continued in 1998 (we expect our main study on this flood to appear in the February 1999 issue of the *Bulletin of the American Meteorological Society*). W. Petersen, L. Carey and S. Rutledge used CSU-CHILL data to examine why this flood event produced so few lightning flashes, despite producing 10 inches of rainfall in a 5 hour period. CSU-CHILL multiparameter observations were combined with cloud modeling studies to conclude that warm rain microphysical processes, coupled with rapid accretional growth near the freezing level, led to efficient precipitation production in this storm. This efficient low-level precipitation process may have suppressed electrification processes by rapidly removing precipitation ice mass and cloud water from the mixed phase region of the convection.

e. Electrical Engineering Activities

Adaptive Neural Network for Rainfall Estimation
(V. Chandrasekar, Professor)

Recent research has shown that Neural Network techniques can be used successfully for ground rainfall estimation from radar measurements. The neural network is a non-parametric method for representing the relationship between radar measurements and rainfall rate. The relationship is derived directly from a data set consisting of radar observations and raingage measurements. The effectiveness of the rainfall estimation using a neural network can be influenced by many factors, such as the representativeness and sufficiency of the training data set, the generalization capability of the network to new data, etc. To achieve the best performance, the neural network may have to be dynamically fine-tuned based on changes in season and location, as well as on increases in the amount of data available.

The goal of this study is to develop an adaptive neural network which automatically updates the network structure and parameters by incorporating the latest rainfall information, without re-training from the beginning (Fig. 3). Therefore, the network has a "dynamic" characteristic, as it can fine-tune its relationship as a function of time. Initially, from all of the available data, the most representative values are chosen to form a training data set from which the first neural network is developed. This network begins operations in the application stage. Once new raingage data are collected, the network switches into an updating stage. By using the adaptive updating algorithm, the neural network revises its structure based on the newly received information. The scheme will not only provide a fast and efficient way to build a new neural network rainfall estimation model, it can also provide a way to gradually adjust an existing neural network model as new rainfall data are received.

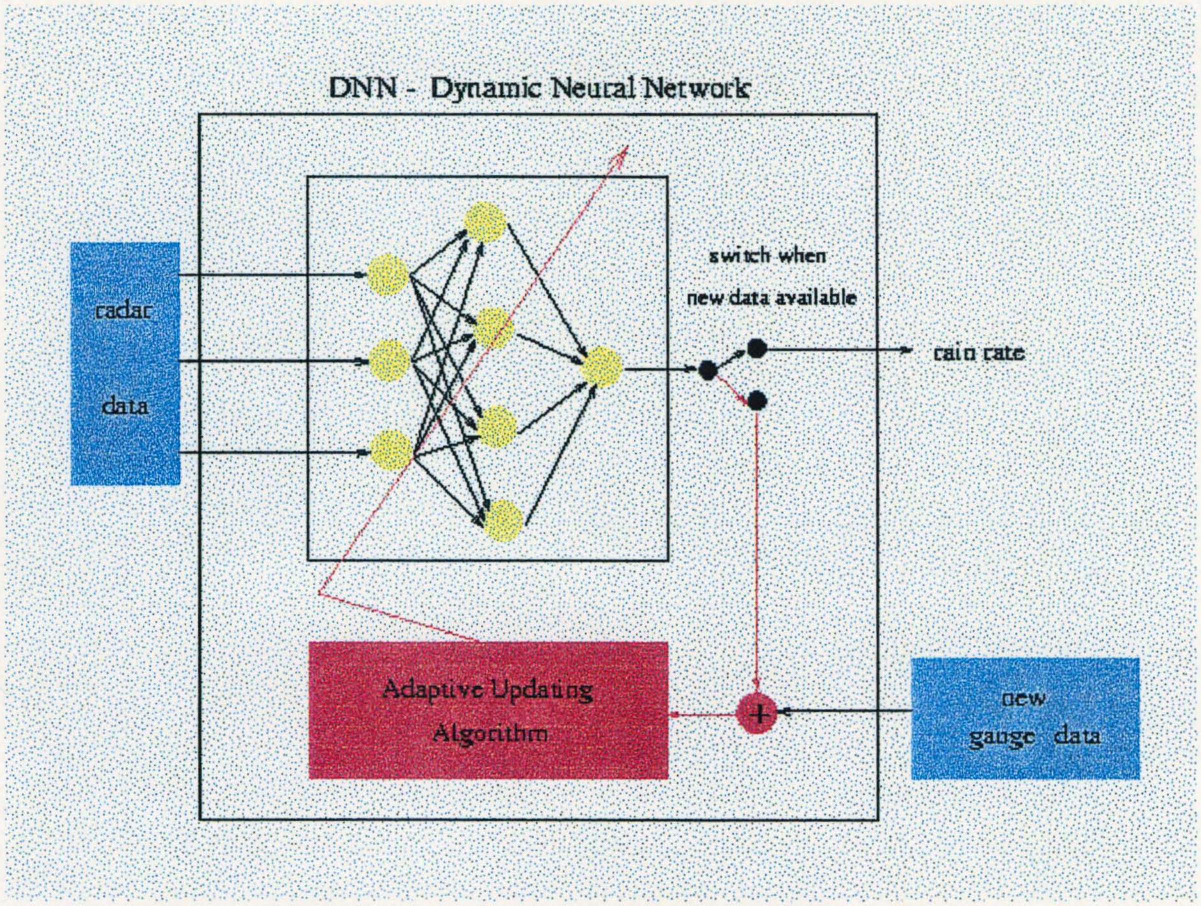

Figure 3: Schematic diagram of the rainfall estimation neural network

Case Studies of Hydrometeor Type Classification Based on Multiparameter Radar Measurements by Using Neuro-Fuzzy Systems
(V. Chandrasekar, Professor)

Mutliparameter radars have been used for discriminating between water and ice regions, and for detecting ice-crystal and hail regions in storms. These particle discriminations generally require the joint evaluation of several polarimetric radar measurements. For example, the concentrations of oblate raindrops normally found in 20-30 mmhr-1 rain rates would be associated with positive Z_{dr}'s and modest values of specific propagation differential phase (K_{dp}) and horizontal polarization reflectivity (Z_h). A Neuro-Fuzzy Hydrometeor Classification System (NFHC) has been developed in the CSU Electrical Engineering Department that ingests the various polarimetric data fields, and automatically identifies a wide variety of hydometeor types. General outlines of both the basic "Fuzzy Logic", and the more refined "Neuro-Fuzzy Logic" methods were presented in the Fall 1998 CSU-CHILL Newsletter (Appendix D). The Newsletter also presented two case studies demonstrating applications of the NFHC method to the identification of hail and graupel.

Since the publication of the Newsletter, the NFHC approach has been applied to a winter season precipitation. On February 18, 1997, there was a light snow event in the vicinity of the CSU-CHILL radar. Figure 4a-c show vertical sections through the storm of the input CSU-

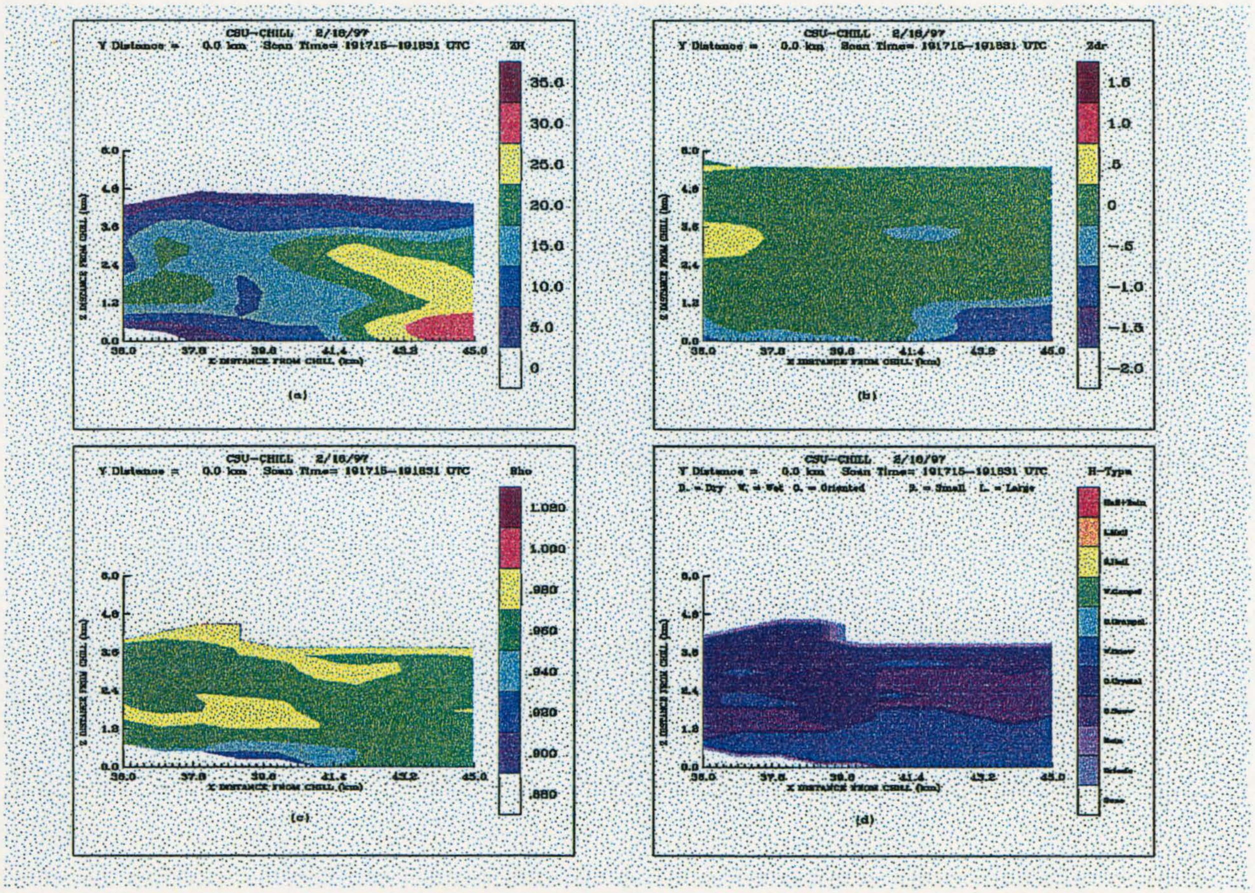

Figure 4: Z_h, Z_{dr}, ρ_{hv}, and their corresponding hydrometeor types for the 2/18/97 winter precipitation event

CHILL radar measurements. The hydrometeor classification results are shown in Fig. 4d; wet snow is indicated below 1 km, dry snow and oriented ice crystal above 1 km. 2D-Video disdrometer observations, as well as visual observations on the ground, indicate wet snow for this event, in agreement with the results of the NFHC. Thus, in both warm season convective storms as well as in winter precipitation, the Neuro-Fuzzy Hydrometeor Classifier results compare well with in-situ measurements.

Preliminary Testing of Dual Transmitter Simultaneous Firing Modes

(V. N. Bringi, Professor)

In July of 1998, several experiments were conducted during which the CSU-CHILL's two transmitters were fired simultaneously. In support of these experiments, an interactively-controlled phase modulator was installed in one of the transmitter channels. This arrangement allowed a controllable phase adjustment to be applied to the dual transmitter drive signals. Variation of the inter-transmitter phasing allowed the net polarization state broadcast from the antenna to be varied as desired (i.e., + or - slant 45 degrees; circular, etc). The actual transmitted polarization state was sampled by a pair of horn antennas and microwave power meters that were temporarily installed approximately 2 km from the CSU-CHILL site.

Collection of the simultaneous transmit mode data was done under the supervision of Prof. Anthony Holt (University of Essex, UK), and Prof. V. N. Bringi (CSU-CHILL Co-PI). On a number of occasions, the radar's firing mode was quickly changed between the simultaneous H+V and the more conventional alternating H, V sequence. This allowed data from the same echo to be observed with both transmission schemes. Initial analyses have indicated that reflectivity, Z_{dr}, and ϕ_{dp} data obtained in the simultaneous firing mode are in reasonably good agreement with those obtained under the alternate firing mode. It is also possible to extract the Circular Depolarization Ratio (CDR) values from the H+V mode data. A paper presenting these results will be presented at the 29th radar conference (Montreal) in July 1999.

3. Activities Planned for 1999

a) Project Support

The CSU-CHILL facility is currently scheduled to support one NSF-sponsored project during the present year: REU98. This is a continuation of the summer season project that Prof. V. Chandrasekar has conducted in the past. Additional investigators have expressed interest in the series of 20 hour projects summarized below:

Nolan Doesken, of the Colorado Climate Center, would like to conduct another iteration of the CoCoRaHS project. For 1999, he hopes to expand the geographical coverage of the project's cooperative observer network. The resultant data base of rainfall amounts and hailfall characteristics can provide excellent "ground truth" for evaluating various methodologies for remotely sensing precipitation characteristics using polarimetric radar observations. Dr. Erik Rasmussen, of the National Severe Storms Laboratory (NSSL) group based at Boulder, would like to collect high resolution radar observations of the Denver Convergence Zone. This is a boundary layer echo feature that appears to play a significant role in thunderstorm initiation. Dr. Rasmussen seeks use detailed, vehicle-based, mobile mesonet observations to complement mesoscale data obtained by CSU-CHILL. Finally, Prof. Steven Rutledge, of CSU, will continue to supervise the collection of additional dual-Doppler thunderstorm observations using the CSU-CHILL and Pawnee radars. These data will be used for continuing thunderstorm electrification studies, as well as for "shakedown" testing of the rapid scanning capabilities afforded by the CSU-CHILL's new data system.

b) Facility Upgrades

As noted earlier, the initial operations with the CSU-CHILL's new Lassen Aspen/DRX data system will take place during 1999. The transition to this new data system will require a variety of associated technical efforts. For example, various radar calibration methodologies, local computing network data distribution protocols, and archived data quality control and reformatting procedures must all be developed. These efforts will absorb much of the facility upgrade efforts during 1999. Improvements to the Pawnee radar's capabilities will be made as time permits.

4. Publications and Reports in 1998

Amin, I., V. Chandrasekar, V. N. Bringi, P. C. Kennedy, and R. D. Kelly, 1998: Multiparameter radar and In-situ Aircraft Observations of Winter Precipitation, *Proc. Conference on Cloud Physics*, 293-295.

Benbella, T., 1998: Multiparameter radar data analysis using Wavelets, Ph.D. dissertation, Electrical Engineering, Colorado State University, Fort Collins, CO (Advisor: Prof. V. Chandrasekar).

Bolen, S., V. N. Bringi, and V. Chandrasekar, 1998: An Optimal Area Approach to Intercomparing Polarimetric Radar Rain Rate Algorithms and Gauge Data, *J. Tech.*, Vol. 15, 605-623.

Bolen, S., V. N. Bringi, and V. Chandrasekar, 1998: An optimal area approach to intercomparing polarimetric radar rain-rate algorithms with gage data, *J. Atmos. Ocean Tech.*, Vol. 15, 605-623.

Bringi, V. N., J. Ran, and V. Chandrasekar, 1998: Polarimetric Radar and Surface Observations of Flash Flood, *Proc. IGARSS 98*, 144-146.

Carey, L. D., and S. A. Rutledge, 1998: Electrical and multiparameter radar observations of a severe hailstorm. *JGR*, 103, 13979-14000.

Chandrasekar, V., and I. A. Ibrahim, 1998: Radar remote sensing and aircraft in-situ observations of winter storms. Abstracts, *National Radio Science Meeting*, 5-8 January 1998, Boulder, Colorado, p. 211.

Hubbert, J., and V. N. Bringi, 1998: The effects of three-body scattering on differential reflectivity. Abstracts, *National Radio Science Meeting*, 5-8 January 1998, Boulder, Colorado, p. 208.

Hubbert, J., V. N. Bringi, L. D. Carey, and S. Bolen, 1998: CSU-CHILL polarimetric radar measurements from a severe hailstorm in Eastern Colorado, *J. Appl. Meteor.*, Vol. 37, 749-775.

Ibrahim, I., V. Chandrasekar, V. N. Bringi, P. C. Kennedy, and M.Shoenhuber, 1998: Simultaneous Multiparameter Radar and 2D-Video Disdrometer Observations of Snow, *Proc. IGARSS 98*, 437-439.

Kennedy, P. C., S. A. Rutledge, and V. N. Bringi, 1998: Precursor signatures of hail observed in multiparameter radar data. Abstracts, *National Radio Science Meeting*, 5-8 January 1998, Boulder, Colorado, p. 212.

Liu, H., and V. Chandrasekar, 1998: Classification of Hydrometeor type based on Multiparameter Radar Measurements, *Proc. Conference on Cloud Physics*, 253-256.

Mudukutore, A., V. Chandrasekar, and R.J. Keeler, Pulse Compression for Weather Radars: Simulation and Evaluation, *IEEE Transactions GRS*, Vol.36, N0. 1, 125-142, 1998.

Petersen, W. A., L. D. Carey, and S. A. Rutledge, 1998: The 28 July 1997 Fort Collins Flood: A multiparameter radar analysis. Preprints, *19th Conference on Severe Local Storms*, American Meteorological Society, 13-18 September 1998, Minneapolis, Minnesota.

Petersen, W. A., L. D. Carey, and S. A. Rutledge, 1998: Polarimetric Radar Observations and Cloud Modeling Studies of Low Lightning Producing Convection in the Fort Collins Flash Flood, submitted Abstract, *11th International Conference on Atmospheric Electricity*, 7-11 July 1999, Lake Guntersville State Park, Guntersville, Alabama.

Petersen, W. A., L. D. Carey, S. A. Rutledge, J. C. Knievel, N. J. Doesken, R. H. Johnson, T. B. McKee, T. Vonder Haar, and J. F. Weaver, 1998: Mesoscale and Radar Observations of the Fort Collins Flash Flood of 28 July 1997. *Bull. Amer. Meteor. Soc.*, in press.

Tawfik, B., and V. Chandrasekar, 1998: Filtering and Analysis of Multiparameter Radar Measurements in Rain Using Wavelets, *Proc. IGARSS 98*, 452-454.

Xiao, R., V. Chandrasekar, and H. Liu, Development of a Neural Network Based Algorithm for Radar Snowfall Estimation, *IEEE Transactions GRS*,1998, Vol. 36, No. 3, 716-724.

Abstracts submitted to the 29th International Conference on Radar Meteorology, 12-16 July 1999, Montreal, Quebec, Canada:

Beaver, J., V. N. Bringi, and G. Huang, 1999: Modeling of Measured Polarimetric Radar Parameters and Associated Propogation Effects.

Detwiler, A., P. C. Kennedy, and P. L. Smith, 1999: Radar and Aircraft Observations of Microphysical Evolution in Updraft Regions of a High Plains Multicellular Thunderstorm.

Holt, A. R., V. N. Bringi, and D. Brunkow, 1999: A Comparison Between Parameters Obtained with the CSU-CHILL Radar from Simultaneous and Switched Transmission of Vertical and Horizontal Polarization.

Hubbert, J. and V. N. Bringi, 1999: Comparisons of 2-D Video Disdrometer Data and S-band Radar Measurements.

Liu, H. and V. Chandrasekar, 1999: Classification from Polarimetric Radar Measurements and In-Situ Verification.

Roberts, R. D., D. W. Breed, and P. C. Kennedy, 1999: Multi-parameter Radar, Aircraft, and Satellite Signatures Associated with Precipitation Formation in Colorado Convective Clouds.

5. Report on Cost Sharing Activities

The following describes cost sharing expenditures at CSU through the fourth year of the Cooperative Agreement.

	Cumulative through 4/30/98	YEAR 4 5/1/98-1/31/99	Cumulative through 1/31/99
Materials, parts, supplies, paint	10,201	1,383	11,584
Salaries and services	163,526	31,231	194,757
Telephone and postage	3,498	1	3,499
Vehicles and fuel	844	810	1,654
Equipment	39,375		39,375
Concrete Pad (HOT radar)	0	17,222	17,222
Indirect cost @ 45%[(a)]	80,131	22,791	102,922
TOTAL	297,575	73,438	371,013
Estimate 2/1/99 - 4/30/99		28,722[(b)]	28,722
TOTAL	$297,575	$102,160	$399,735

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a) Indirect cost base excludes equipment.

b) Payment due upon shipment of the dual-channel digital signal receiver

and digital signal receiver.	$19,674
Salaries: S. Cox - .25 month	4,848
Commercial power installation – HOT radar site (est.)	4,200
Total	**$28,722**

6) Statement of Unobligated Funds

We expect no significant residual funds at the end of the current year.

7) Changes in Project Support Personnel

There are no changes in Senior Personnel.

8. Current and Pending Support

A. Current Support for Steven A. Rutledge as of 02/15/99

Agency	Project Title	K$/ YR	Role	Period Covered	Commitment (months)
National Oceanic and Atmospheric Administration (USTPO)	Further Analysis of the Shipboard Radar Data from COARE: Rainfall, Convection organization and surface fluxes.	110	PI	1/1/97 to 1/1/99	1 academic
National Science Foundation	The CSU-CHILL Radar Facility	567	CO-PI	5/1/95 to 4/30/00	1 summer 1 academic
National Science Foundation	Dynamical and Electrical Studies of Convective Cloud Systems	120	PI	2/1/98 to 1/30/01	1 summer
National Aeronautics and Space Administration	Validation Studies and Algorithm Refinement in Support of TRMM	230	CO-PI	6/1/97 to 9/30/99	1 academic
National Science Foundation	Improving Nexrad-based estimates of precipitating rates and hydrometer classification	125	PI	10/01/96 to 9/30/99	
National Oceanic and Atrmospheric Administration	Analysis and Modeling of the Transport of Lightning-Generated Nox and Other Chemical Species in Convective Cloud Systems	58	PI	1/1/97 to 6/30/00	
Colorado State University	Resident Instruction Support				7 academic

B. Current Support for V. N. Bringi as of 02/15/99

Agency	Project Title	K$/ YR	Role	Period Covered	Commitment (months)
National Science Foundation	Continuation of CaPE Radar Analysis	105	PI	4/1/95 to 8/1/98	
National Aeronautics and Space Administration	K-band Propagation Studies Usning the CSU-CHILL Radar	80	PI	5/1/93 to 3/31/98	1 summer
National Science Foundation	Improving NEXRAD Extimates of Precipitation	110	PI	9/1/96 to 8/31/99	.5 summer
National Science Foundation	The CSU CHILL Radar Facility	500	CO-PI	5/1/95 to 4/30/00	1 summer

B. Pending Support for V. N. Bringi as of 02/15/99

AFOSR	The CSU-CHILL Radar Facility for Polarimeteric Studies of Precipitation and Bistatic Methods	PI	2/1/98 to 1/31/01	1 summer
National Science Foundation	Coordinated Analysis of Fully Polarimetric CSU-CHILL Radar Signatures With Surface and Airborne Hydrometeor Images	PI	2/1/98 to 1/31/01	1 summer

Appendix A

Graduate Theses/Dissertation in 1998

Completed / in-progress graduate students:

1) Department of Atmospheric Science:

All of the following theses involve analysis of CSU-CHILL data.

Completed:

C. Butler (M.S.)	Microphysical Characteristics of Ice Crystals and Snowflakes as Revealed by Polarimetric Radar Measurements
L. Carey (Ph.D.)	On the Relationship Between Precipitation and Lightning as Revealed by Multiparameter Radar Observations
R. Roberts (M.S.)	Integration of WSR-88 and GOES-8 Data for Detecting and Forecasting Storm Initiation
T. Lang (M.S.)	Relationship Between Storm Structure and Lightning Activity in Colorado Convection Observed During STERAO-A
J. Ryan (M.S.)	Lightning and NOx production in deep convection

In-Progress:

L. Belcher (M.S.)	
M. Gauthier (M.S.)	
T. Lang (Ph.D.)	Lightning and Severe Convection
J. Staszel (M.S.)	

2) Department of Electrical Engineering:

Completed:

I. Amin (Ph.D.)	Multiparameter Radar Remote Sensing, In-Situ Observations and Modeling of Winter Precipitation
T. Benbella (Ph.D.)	Multiparameter Radar Analysis Using Wavelets

In Progress:

S. Bolen (Ph.D.)	No title as yet
G. Huang (Ph.D.)	Hybrid Mode Observations of Precipitation
I. Ibrahim (Ph.D.)	Identification and Classification of Multiparameter Radar Data in Winter and Springtime Storms

H. Liu (Ph.D.)	Hydrometeor Classification from Multiparameter Radar Observations: Development of Neuro-Fuzzy Classification Scheme
Ji Ran (M.S.)	Development of a Neural Network for Multiparameter Radar Rainfall Estimation
J. Tang (M.S.)	Intercomparison of Multiparameter Radar Observations and Microphysical Modeling
G. Xu (Ph.D.)	No title as yet

Appendix B

Letters Associated with Radar Users

1 September 1998

Dr. Andy Detwiler
Institute of Atmospheric Sciences
South Dakota School of Mines and Technology
501 East St. Joseph Street
Rapid City, South Dakota, 57701-3995

Dear Andy:

This note marks the completion of your T-28 instrumentation flight test project (8 June to 26 June 1998) in the CSU-CHILL facility records. It seemed that much useful experience was gained during this program. According to my field notes, test flights were conducted in conditions ranging from clear air, through benign stratiform rain, to a hail-bearing thunderstorm. I look forward to our continuing joint analyses of the aircraft and radar data collected during the 22 June 1998 thunderstorm flight. If you are also interested in radar data from any of the other test flights, please let me know.

Feedback from radar facility users is always of interest A brief summary addressed to me of your impressions of the radar support for this project (i.e. conduct of operations, performance of the radar equipment and staff, data quality, etc.) will be quite useful. If you prefer, such a summary may be sent directly to Dr. Ken Van Sickle at the NSF.

Sincerely,

Pat Kennedy
CSU-CHILL Facility Manager
(970) 491-6248

SOUTH DAKOTA
SCHOOL OF MINES
AND TECHNOLOGY

INSTITUTE OF
ATMOSPHERIC SCIENCES
(605) 394-2291
(605) 394-6061 (FAX)

December 14, 1998

Pat Kennedy
CSU-CHILL Radar Facility
30750 W.C.R. #45
Greeley, CO 80631

Dear Pat:

I want to acknowledge the support given to our June T-28 airborne instrument test exercise by you and your colleagues at the CSU-CHILL radar facility. You, Dave, and Bob provided superb support for our test operations at a time when you were already busy trying to bring a second 10-cm Doppler radar on-line during the same period. We received a royal welcome at your Greeley field site and all the help we needed to get our telemetry and radio equipment installed. Through your workstations connected to the Internet we could find the weather guidance we needed to forecast and nowcast for our operations. Your staff is expert at interpreting the multiparameter CHILL display in real-time to guide our aircraft to updrafts, precipitation shafts, hail swaths, and other storm features of interest for our testing. The radar equipment was available to us on a 7-day-a-week basis for 3 weeks, enabling us to take advantage of every weather opportunity that came our way during the period.

It has been interesting to review with you some of the radar and aircraft data obtained during the flight on 22 June 1998. On that flight we had finally gotten almost all of our instrumentation working and nature provided us with an excellent storm to sample. This review has allowed us to develop, test, and extend our software for microphysical data analysis to make it more suitable for use in comparing radar and aircraft microphysical signatures.

I hope it is not long before we are back in another collaborative effort with your facility.

With best wishes,

Andy

Andy Detwiler
cc: P. L. Smith

501 E. ST. JOSEPH STREET, RAPID CITY, SD 57701-3995 USA

1 September 1998

Mr. Nolan Doesken
Colorado Climate Center
Foothills Campus
Colorado State University
Ft. Collins, Colorado 80523

Dr. Harold Duke
USDA-ARS Water Management Research
107 AERC Annex
Colorado State University
Ft. Collins, Colorado 80523

Dear Nolan and Harold:

This note marks the completion of your joint 20 hour CSU-CHILL radar project conducted during the summer of 1998 (Colorado Collaborative Rain and Hail Experiment (CoCoRaHS)). My field notes indicate that radar data were collected on several occasions when convective storm activity crossed your respective surface measurement networks. Some of the primary operational days were as follows:

Date	Remarks
17 June	Widespread, small hail at Loveland
22 June	Heavy rain,, hail documented at Wiggins site
1 July	Heavy rain event at Wiggins site
21 July	Wet microburst with hail near Wellington

We have already exchanged preliminary data sets for some of these days (i.e., 22 June 98 tipping bucket data from the Duke site, and hail maps derived from CSU-CHILL polarimetric data and posted on the internet). I look forward to continuing future collaboration.

I believe that this project was an overall success. Notable advancements were made in the use of internet technology for the rapid exchange and display of observed data. Feedback from radar facility users is always of interest A brief summary addressed to me of your impressions of the radar support for this project (i.e. conduct of operations, performance of the radar equipment and staff, data quality, etc.) will be quite useful.

Sincerely,

Pat Kennedy
CSU-CHILL Facility Manager
(970) 491-6248

2 September 1998

Dr. John Beaver
Department of Electrical Engineering
Colorado State University
Ft. Collins, Colorado 80523

Dear John:

This note marks the completion of your 20 hour CSU-CHILL radar project conducted during the early spring of 1998 (Simultaneous Radar Measurements with Airborne Radar and Cloud Particle Probes). My field notes indicate that there was only one day on which potentially useful data were collected by both the SPEC aircraft and the CSU-CHILL radar. This took place during the early afternoon of 2 April, when a gradual snow to rain transition was documented in the vicinity of the Ft. Collins - Loveland Airport. Perhaps this single case will prove to be adequate for some preliminary analyses. We would welcome the opportunity to collect additional data sets in future projects of this sort.

Sincerely,

Pat Kennedy
CSU-CHILL Facility Manager
(970) 491-6248

2 September 1998

Dr. V. Chandrasekar
Department of Electrical Engineering
Colorado State University
Ft. Collins, Colorado 80523

Dear Chandra:

This note marks the completion of the 20 hour CSU-CHILL radar project that you and Prof. Fred Ogden conducted during the summer of 1998 (Radar estimates of rainfall over Horsetooth Reservoir). While the radar observed precipitation over Horsetooth Reservior on a number of occasions, the best conditions for your project took place on 30 July. Pre-dawn thunderstorms on this day may have increased the soil moisture in the general Horsetooth area. Then, between 1400 and 1930 MDT, the radar observed the passage of several episodes of convective rain over the reservoir. Hopefully, this overall precipitation pattern will provide an input of adequate magnitude for your reservoir response model. We would welcome the opportunity to collect additional data sets in future projects of this sort.

Sincerely,

Pat Kennedy
CSU-CHILL Facility Manager
(970) 491-6248

20 July 1998

Professor Anthony Holt
Department of Mathematics
University of Essex
Wivenhoe Park, Colchester CO4 3SQ, UK

Dear Anthony:

I'm glad to hear that your return trip was satisfactory. The basic purpose of this letter is to acknowledge for our files the CSU-CHILL radar support that was provided to your research project. Beyond this simple formality, I would also like to acknowledge the obvious personal effort that you put forth in the conduct of this project. In my experience, it is rare for an investigator to so immediately begin a detailed examination of the radar data. This is unfortunate, since the interactions that directly result from these immediate data examinations can be highly useful to the radar facility staff as well as to the research investigator. It has been our pleasure to work so directly with you (and your son) during this project.

Dave Brunkow should be able to supply you with additional data sets via ftp. Please let us know of difficulties that arise during you analyses.

Feedback from radar facility users is always of interest A brief summary addressed to me of your impressions of the radar support for this project (i.e. conduct of operations, performance of the radar equipment and staff, data quality, etc.) will be quite useful. If you prefer, such a summary may be sent directly to Dr. Ken Van Sickle at the NSF.

Sincerely,

Pat Kennedy
CSU-CHILL Facility Manager
(970) 491-6248

Appendix C

Summary of Greeley Data Collection Activities Through 01/15/98

Project	Period	Outcome
1991		
WISP91 (NSF)	January-March	Nick Powell - CSU Atmospheric Science M.S. thesis completed.
Kostinski (20 hr)	April	Subsequently funded NSF proposal.
Srivastava (20 hr)	April-June	Profiler-radar intercomparison.
University of Nevada-Reno/ DRI (NSF)	May	Summary to appear in BAMS.
Julien (20 hr)	May-July	Fred Ogden CSU Ph.D. Civil Engineering dissertation completed.
McKee (20 hr)	June-August	Dave Speltz CSU Atmospheric Science M.S. thesis completed.
Hartley (20 hr)	May-August	Summary in Ag. Res. Svc. article.
(Rutledge; Class-room cases)	January-August	Data base for CSU Atmospheric Science radar class, summary to appear in BAMS. Antenna patterns, sphere calibrations, etc., for Ashok CSU Electrical Engineering (M.S. thesis completed).
1992		
Turk (20 hr)	March	Support of NASA ER2 over flights.
Srivastava (20 hr)	April-May	Continuation of 91 program.
Dixon (20 hr)	May - June	Ph.D. dissertation in progress.
Chandra REU (NSF)	June-August	Several senior year electrical engineering projects in progress.
T-28 tests (NSF)	June	Support data during T-28 test flights.
Cotton 92 (20 hr)	July-August	Observational data for NSF funded modeling study.
Connell (20 hr)	July-August	Exploratory data.

Rauber	October	Cloud water sampler test on Sabreliner.

1993

Kennedy	Feb - April	Aircraft ground icing study.
Chandra (WISPIT)	Feb - March	In-situ aircraft / multi-parm radar comparison.
Roberts (WISPIT)	Feb - March	Combined dual-Doppler and multi-parm radar analyses.
Carey	May - June	Multiparameter radar and storm electrification study.
Holtzer	May - June migration.	Radar observations of insect .
Aydin	June	Multi-parameter radar hail detection.
Bringi	July	" "
McAnelly	July - August	Upscale evolution of mesoscale convective systems.

1994

WISP94	Jan - March	Winter storms and icing project (NSF supported NCAR project).
ACTS	Beaver et al	Meteorological effects on microwave propagation (Ph.D.).
ANVIL	Hallett	Evolution of anvil airflow fields.
APHID94	Holtzer et al	Migration patterns of Russian Wheat Aphids.
DEN94	Clement and	Multiparameter obs of storms over Denver/McKee urban flood district (MS).
RAIN94	Bringi	Comparison of WSR-88D and multiparameter based rainfall estimates.

REU94	Chandrasekar	Research experience for EE undergraduates.
MCS94	McAnelly	Observations of MCS genesis.

1995

Carey and Rutledge	May-July	Combined electric field / multi- E-FIELD parameter radar observations of thunderstorms.
Chandrasekar	June-August	Exposure of undergraduate REU95 students to weather radar research project field activities.
Straka, Zrnic et. al	June	Aircraft collection of in-situ T28 cloud observations to validate multiparameter radar data.
Bringi	June-August	Use of mobile hydrometeor PRECIP VAN95 measuring systems to verify multiparameter radar data.
Breed	June-August	Sailplane observations of the SAILPLANE 95 early electrification stages of cumulus clouds.
Metcalf	June	Radar detection of cloud ICE ORIENTATION electrification through ice particle orientation signatures.
Bedard et. al.	June-August	Correlations between low LF SOUND frequency sound waves and convective storm life cycle.
Browning	July-August	Relationship between boundary PBL95 layer echo evolution and later convective development.
Heymsfield	July-August	Multiparameter radar REPLICATOR observations of convective cloud systems penetrated by a balloon-borne particle replicator.

1996

Kennedy and	Feb-April	Combined multiparameter

Chandrasekar FNL		radar and surface observations of winter season precipitation.
Cifelli PLATTEVILLE	May-June	Joint CSU-CHILL / NOAA profiler study of precipitating cloud systems.
Chandrasekar and Bringi REU96	June-August	Exposure of undergraduate students to weather radar research project activities.
Rutledge, Dye, and Tuck STERAO-A	June-July	Coordinated multiparameter radar, aircraft, and lightning study of deep convective storms.
Bedard LF SOUND	July-August	Correlations between low frequency sound waves and convective storm life cycle.

1997

Rasmussen et. al. PROWS97	Jan - March	Combined multiparameter radar and surface observations of winter season precipitation.
Chandrasekar REU97	June-August	Exposure of undergraduate students to weather radar research project activities.
Duke RAIN MAP	June-August	Multiparameter rainfall estimation over dense rain gage networks.
Carey POS CG	June-July	Evolution of + CG producing thunderstorms using radar and lightning detection data.
Petersen FIRST LTG	July-August	High time resolution radar observations of initial stages of storm electrification.

1998

Beaver SPEC FLIGHT	April	Radar support of an aircraft icing project.

Detwiler T28 TEST98 (NSF)	June	Test flight project for new SDSMT T28 data system.
Doesken / Duke CoCoRaHS	June-August	Radar rain and hail mapping Over ground observation networks.
Ogden RESERVOIR	July	Radar rain estimation over Horsetooth Reservoir.
LANG FLAT PLATE98	June-August	Joint storm electrification and dual-Doppler studies.

Appendix D

1998 CSU-CHILL Newsletter

CHILL RADAR NEWS

from

Colorado State University

Eighth Edition
October 1998

Overview

(Steven Rutledge, Professor and Scientific Director)

This is the eighth edition of the Colorado State University (CSU)-CHILL newsletter which we distribute on an annual basis, near the start of the academic year. The newsletter is intended to provide information to the community regarding research, education, and refurbishment activities of the CSU-CHILL facility. In April 1995, Colorado State University was awarded a second five-year Cooperative Agreement from the National Science Foundation (NSF) for operation and maintenance of the CSU-CHILL, a 10 cm, dual polarized Doppler radar. The radar is presently operational near Greeley, CO (located approximately one mile north of the Greeley-Weld County Municipal Airport), situated on an eighty acre agricultural site owned by CSU.

The use of the CSU-CHILL radar is granted by the National Science Foundation after review by the NSF Facilities Advisory Council (FAC) and Observing Facilities Advisory Panel (OFAP). We supported two NSF-reviewed projects during 1998: a Research Experience for Undergraduates (REU) project directed by Prof. Chandrasekar in the Department of Electrical Engineering, and a T-28 data system test. In the REU project, several undergraduate engineering students from a variety of universities participated in a two month long program. For a portion of the program, REU students learned various aspects of radar, including polarimetric techniques for remotely sensing hail. The T-28 flew multiple missions in the vicinity of CHILL to test its new on-board data system. Several hailstorms were penetrated. The data collected during these missions are now undergoing scientific analyses. CHILL was used to identify hail shafts and direct the T-28 in real-time. Polarimetric data from CHILL are now being compared to the in-situ data collected by the T-28.

For projects requiring less than about 20 hours of radar operational time, the Scientific Director of the CSU-CHILL facility awards the use of the radar without OFAP/FAC review. In projects of this nature, radar operational costs are provided by the Cooperative Agreement. These projects encourage use of the radar for highly focused experiments; as such, these projects continue to be very productive. We supported three 20-hour projects over the past year, which are detailed in the next section.

Another major highlight of this past year's activities has been bringing the HOT radar (acquired from the Illinois State Water Survey) to full operational status. Renamed the Pawnee, this radar is located near Nunn, CO, providing a 48 km dual-Doppler baseline with CHILL. Numerous outstanding cases were collected by the dual-Doppler pair during June-August, 1998. This dual-Doppler network has been supplemented with a permanent, three-station flat plate antenna network for measuring total lightning flash rates over the dual-Doppler domain. The CHILL-Pawnee pair are now available to the community.

The CSU-CHILL radar facility continues to play a central role in formal education classes here and beyond CSU. Students studied real-time CHILL data in the classroom during AT741, a Ph.D.-level radar class taught by Prof. Rutledge. Students in the class also analyzed data collected by the CHILL and developed detailed, final project reports. Their reports have been placed on the Worldwide Web at:
http://olympic.atmos.colostate.edu/AT741/1998/
Numerous M.S. and Ph.D. theses have also been completed in the past year in Atmospheric Science and Electrical Engineering.

Our new digital IF dual-receiver and signal processor, developed by Lassen Research (their *Digiceiver®*), is on schedule, and will be delivered during late October, 1998. This new system will be tested during the coming winter. The hardware design uses high speed SHARC chips to process 3000, 50 meter deep range gates, which will be range-averaged to a 225 meter resolution. As a result of the new processor, we expect the antenna rotation rate to increase by 50%.

Radar Operations Summary

(Pat Kennedy, Facility Manager)

Operations Summary:

The highlight of the 1998 convective season was the initiation of data collection by the CSU Pawnee radar (formerly called the HOT -- Hydrometeorological Operational Tool -- radar when it was operated by the Illinois State Water Survey). The Pawnee is an 11 cm wavelength, 1.6 deg beamwidth, single polarization Doppler radar. The transmitter is a military surplus FPS-18 system using a VA-87B klystron tube final power amplifier. The inherently high pulse-to-pulse phase stability of this transmitter allows the Pawnee radar to collect high quality Doppler velocity measurements. The Pawnee's data system is a direct clone of that currently used at the CSU-CHILL facility, which helps standardize both real-time radar operational procedures, and subsequent data processing.

During May of 1998, the Pawnee was installed at a site 48 km NNW of the CSU-CHILL (Fig. 1). This radar site offers an excellent radar horizon. Operational testing was done during June, and data collection began in July. Radar operations were directed from the CSU-CHILL user van. The general operational plan centered on identifying areas of significant convection that were either entering or developing within the dual-Doppler coverage area of the two radars (defined by beam intersection angles greater than 30 degrees). Once the target storm(s) were identified, synchronized PPI sector volume scan coverage was started. The volume scan cycle times varied with the solid angle required to fully scan the storm; in most cases the volume times were between 3 and 6 minutes. Furthermore, during most of these events, Tim Lang, a Ph.D. candidate in the CSU Atmospheric Science Department, operated a local network of electric field sensors. Data from these "flat plate" systems, in combination with records from the National Lightning Detection Network (NLDN), will document the lightning characteristics of the storms observed by the dual-Doppler network.

As shown in the following summary, dual-Doppler data sets were collected during a variety of convective storm regimes:

Date	Remarks
7/1/98	Tornadic supercell storm (see analysis in later section)
7/11	Evolving multicell storms in the east lobe
7/15	Squall line evolution, including development of the trailing stratiform precipitation region.
7/21	Pulse-type storm producing a wet microburst with hail.
7/24	Monsoon-related storms generating heavy (>10 cm) rainfall.

30 DEGREE DUAL DOPPLER LOBES

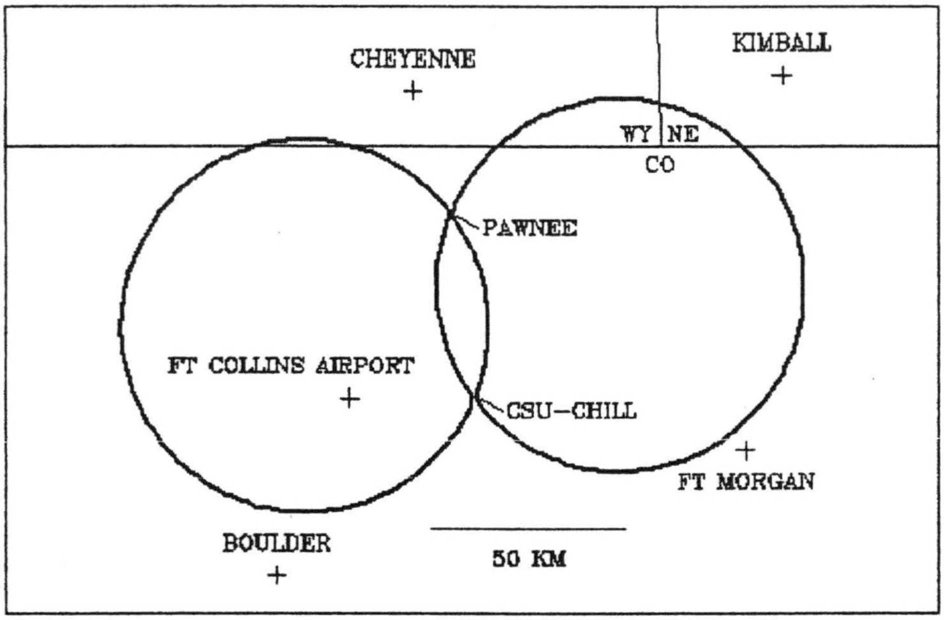

Figure 1: The CSU dual-Doppler network. The CSU-CHILL radar is located near Greeley, Colorado; the Pawnee radar is northeast of Nunn, Colorado. The baseline is 48 km long. The lobes enclose the region where the beam intersection angle exceeds 30 deg.

Several technical upgrades to the Pawnee radar are to be made during the upcoming cool season. As circumstances permit, efforts will be made to collect additional dual-Doppler data sets when specific precipitation situations of interest are expected (i.e., frontal passage during widespread upslope precipitation, rain/snow transitions, etc.).

In addition to the Pawnee radar test activities, the CSU-CHILL Facility supported several research programs within the last year.

An NSF-sponsored project was directed by Dr. Andy Detwiler of the South Dakota School of Mines and Technology (SDSMT). This project was designed to test a major upgrade of the SDSMT T28's onboard data recording system that had been completed earlier in 1998. Specifically, the T28 was to penetrate a variety of echo systems while under real time guidance from the CSU-CHILL radar. During the three week long project, flights were conducted in conditions varying from clear air to active thunderstorms. The most vigorous storm, which contained a significant amount of hail, was encountered on 22 June 1998. Comparative analyses of the aircraft and radar data collected during this flight are in progress.

Three 20 hour projects were supported during 1998:

1) r. John Beaver (CSU EE Department) sought CSU-CHILL polarimetric data taken in the vicinity of a cloud physics research aircraft operated by the Boulder Colorado-based SPEC company. The aircraft flights were conducted in the vicinity of the Ft. Collins-Loveland Airport (FNL) when significant inflight icing conditions were expected. The primary radar operation for this project took place on 2 April 1998, while a snow to rain transition took place in the general FNL area. The SPEC aircraft collected in-cloud data during two low approaches to FNL during the precipitation transition period.

2) Nolan Doesken (Colorado State Climate Center) devised the Colorado Cooperative Rain and Hail Study (CoCo RaHS); a project that enlisted over 100 volunteer cooperative observers in the greater Ft. Collins area. These observers kept detailed records on rain and hail events affecting their locations. Their observations were rapidly posted by way of a web page developed as a part of the project. As an adjunct to the volunteers' observations, hail swath maps based on CSU-CHILL reflectivity and differential reflectivity data were generated and posted on the web within a day or two of hail events. Additional usage of the volunteer observations as ground truth for the polarimetric radar signatures is expected.

3) Prof. Fred Ogden (University of Connecticut) and Prof. V. Chandrasekar (CSU EE) ran a project in which hydrological measurements taken at Horsetooth Reservoir (located immediately west of the city of Ft. Collins) were used to estimate convective storm rainfall amounts. The most useful data for this project were collected on 30 July 1998, when a series of rainshowers and thunderstorms were observed by the radar as they passed over the reservoir.

Prof. Anthony Holt, of the University of Essex in the UK, visited Prof. V. N. Bringi (CSU EE) and the CSU-CHILL radar facility during a three week period in June and July. Profs. Holt and Bringi were interested in test data collected while the radar was operated in a variety of modes in which the two transmitters were fired simultaneously. For the purposes of this experiment, a PC-controlled phase modulator was added to the final amplifier drive hardware in one of the transmitter channels. This permitted an adjustable phase delay to be added between the firing times of the transmitters. Phase delay adjustments allowed the overall transmitted phase to be altered as desired (i.e., electric field vibration in the + or - 45 degree planes; circular polarization, etc.). Test data were successfully collected from convective precipitation echoes while the radar was operated in several polarization states. (Please see the Electrical Engineering section of this Newsletter for additional details.)

Initial CSU-CHILL and Pawnee dual-Doppler Analysis: 1 July 1998

As noted earlier, the Pawnee Doppler radar became fully operational on 1 July 1998. Remarkably, a tornadic thunderstorm developed within the east dual-Doppler lobe while both radars were operating during the early evening hours of July first. Prior to tornadogenesis, the storm tracked southeastward from southern Wyoming into northern Colorado. The storm core passed immediately south of the Pawnee radar site shortly before 00 UTC, producing rainfall totals of approximately 30 mm (1.2 in), and hail diameters of 19 mm (.75 in) in under 30 minutes. Synchronized 6 minute long dual-Doppler scans by the CSU-CHILL and Pawnee radars were started after the storm exited the baseline connecting the radars. By 0050 UTC, the storm was well located in the eastern dual- Doppler lobe, and had assumed a hook echo configuration.

A preliminary dual-Doppler analysis has been done from the volume scans starting at 0050 UTC. The data from both radars were converted to Universal Doppler Exchange Format (UF), and were interactively edited to eliminate signal artifacts (i.e., noise, antenna sidelobe contamination, velocity aliasing, etc.) using NCAR RDSS software. A Cressman-weighted interpolation of the edited UF data to a common three dimensional grid was done using the NCAR REORDER program. The gridpoint intervals were 1 km in X and Y, and .75 km in Z. A dual-Doppler wind field synthesis based on the gridded radial velocity values was done via NCAR's CEDRIC software package. Vertical air velocities were based on a single downward integration of the smoothed convergence field diagnosed at each grid plane height.

The hook echo configuration is apparent in the 2.25 km AGL reflectivity pattern (Fig. 2). Peak reflectivities exceeding 65 dBZ (X=19, Y=18), and a well defined mesocyclone (centered near X=21, Y=13) were present at this height.

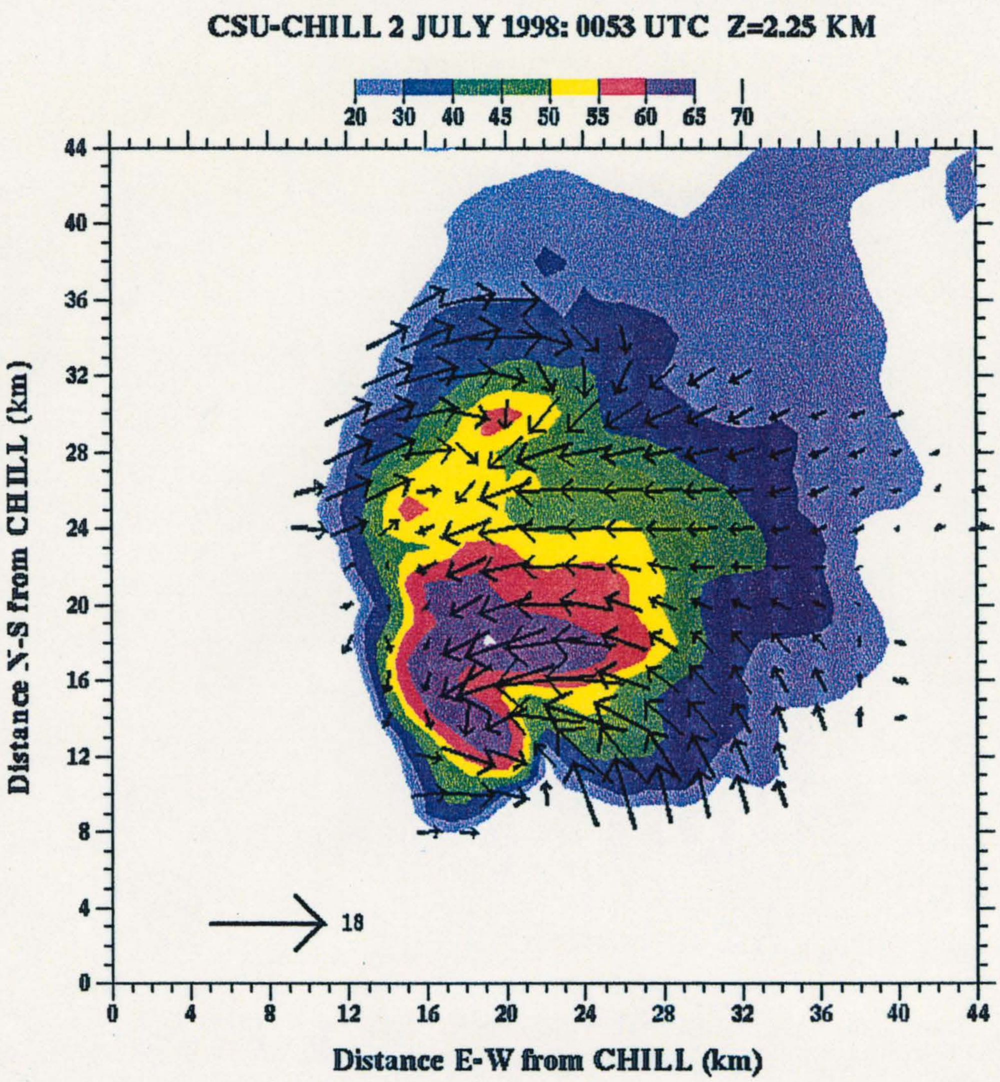

Figure 2: CSU-CHILL - Pawnee radar dual- Doppler CAPPI plot at 2.25 km AGL, 0053 UTC on 2 July 1998. Color filled contours are CSU-CHILL reflectivity levels. Wind vectors are earth relative in mps. (Plot courtesy of Dr. Walt Petersen, CSU ATS).

A north-south oriented vertical cross section along X=20 is shown in Figure 3. This cross section plane intersects the hook echo feature, as indicated by the low altitude reflectivity minimum centered near Y=15 km. An intense (peak values of approaching 40 mps), updraft is found in the right (south) flank of the storm.

Solid contours of the CSU-CHILL differential reflectivity (Z_{dr}, black lines) and Linear Depolarization Ratio (L_{dr}, light blue lines) are also shown in the cross section. The largest positive Z_{dr}'s are found in the rain area well north of the main updraft (Y=28), and in the insect-laden hook echo inflow region (Y=15). Near 0 dB Z_{dr} values descend to the surface near Y=20 km where a significant fraction of the precipitation is tumbling /quasi-spherical hailstones (vs. oblate raindrops which generate positive Z_{dr}'s). A column of enhanced (> -25 dB) L_{dr} values slopes along the lower regions of the strong updraft from low altitude inflow area (Y=14), upwards to the reflectivity core aloft (X=17, Z=7). These enhanced L_{dr}'s are probably due to the increased wetness experienced by hailstones that are intercepting the intense updraft's rich moisture supply.

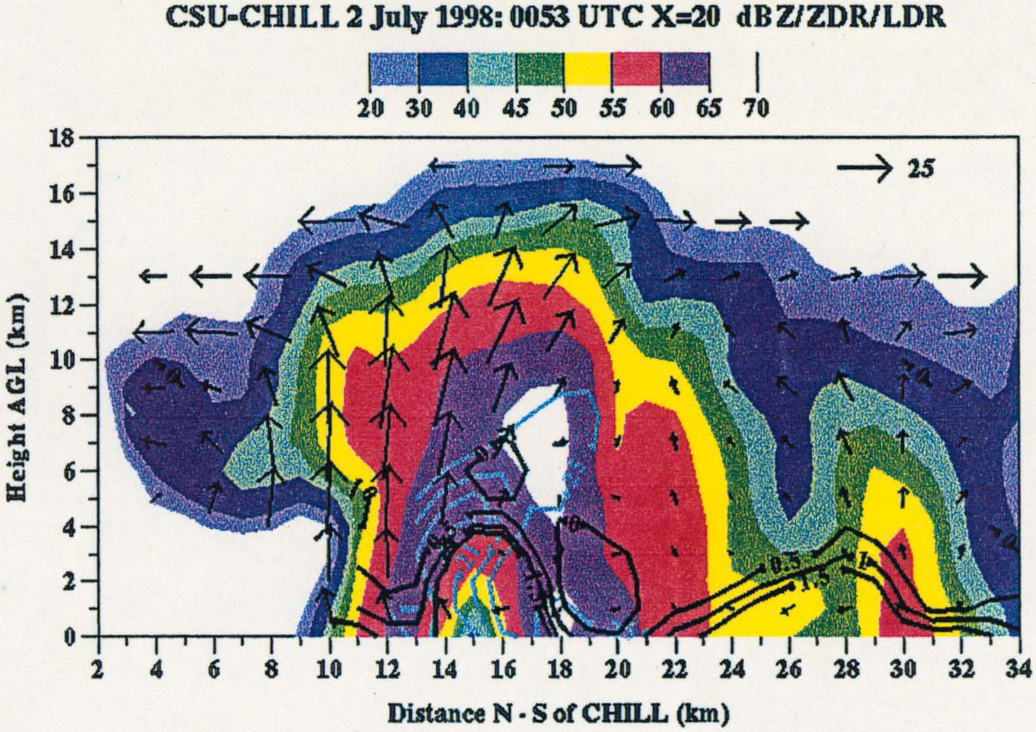

Figure 3: North-south oriented vertical cross along X=20 km, 0053 UTC on 2 July 1998. Reflectivities and wind vectors as in Fig. 2. Solid black contours are differential reflectivities (Z_{dr}); light blue contours are linear depolarization ratios (L_{dr}), both in dB. (Plot courtesy of Dr. Walt Petersen, CSU ATS).

This initial analysis illustrates the great utility of radar data sets that permit polarimetric data fields to be analyzed in the context of dual- Doppler synthesized airflow fields. Such data sets can now routinely be collected by the CSU-CHILL/Pawnee radar network.

Electrical Engineering

(V. N. Bringi, Professor)

CSU collaborates with the National Severe Storms Laboratory (NSSL) to evaluate polarimetric schemes for a possible future upgrade of the operational WSR-88D radars. A scheme suggested by Seliga and Bringi (1976)†, employing simultaneous transmission of horizontally (H) and vertically (V) polarized waves with matched power, has been tried. This approach eliminates a high power waveguide switch. Both alternate reception, using a single receiver (termed the STAR-mode), and simultaneous reception with two receivers (termed the STSR-mode), have been tried with the CSU-CHILL radar. The STAR-mode has been implemented on NASA's S-band radar, located in Kwajalein, Marshall Islands, and data are being evaluated.

Fig. 4 shows range profiles of radar observations acquired in the conventional mode(HV-mode) and the new STAR-mode. The agreement in reflectivity and ϕ_{dp} is excellent. The offset in ϕ_{dp} is related to system offsets. The agreement in Z_{dr} is also good, but a systematic bias in the STAR-mode is likely due to a slight mismatch in the transmitted power, which can be corrected in post-processing. The greatest disagreement is in the STAR-mode ρ_{hv}, which is biased low due to backscatter depolarization effects. A substantial amount of data in the STSR

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†Seliga, T. A. and V. N. Bringi (1976): Potential use of radar differential reflectivity measurements at orthogonal polarizations for measuring precipitation, *J. Appl. Meteor.*, **15**, 69-76.

(simultaneous transmit, simultaneous receive) mode were collected last summer. Prof. Anthony Holt, of the U.K., spent three weeks at CSU and is involved in the data analysis. CSU's collaboration with Drs. Srnic and Doviak of the NSSL is supported by the U.S. Weather Research Program.

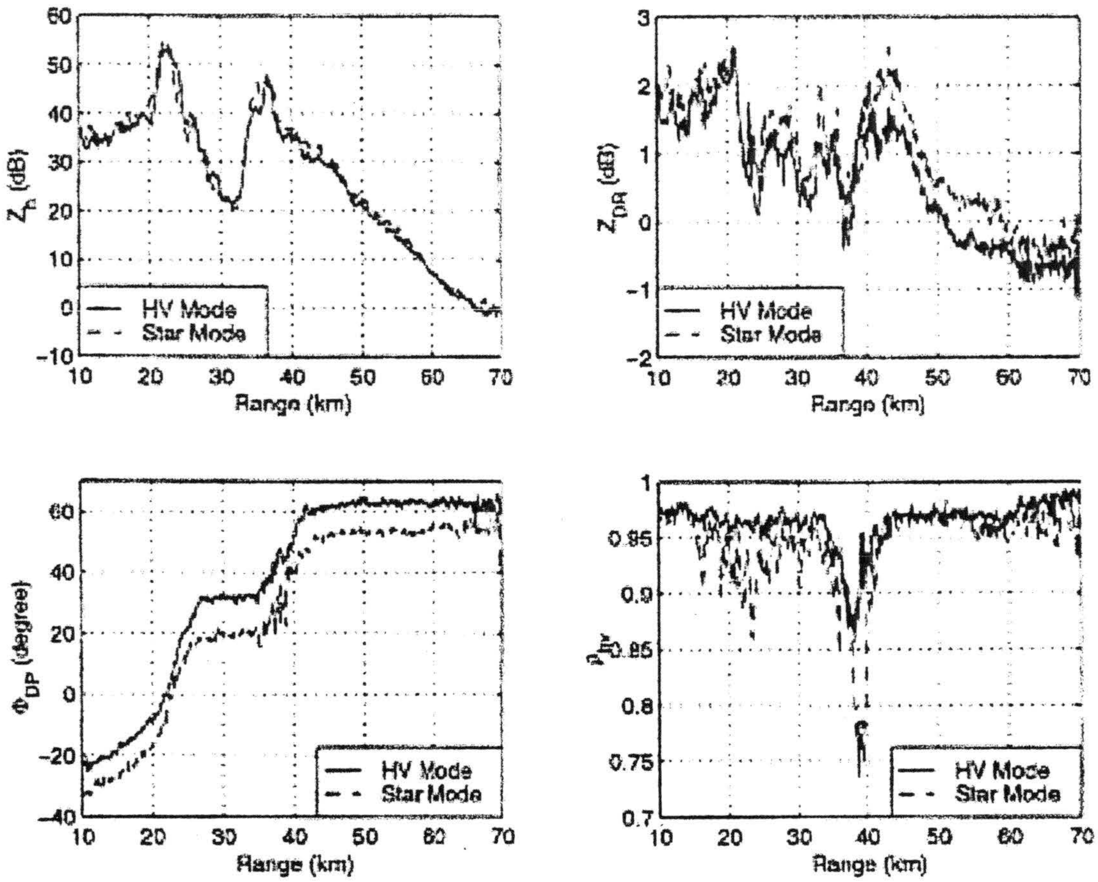

Figure 4: Range profiles through a convective storm: the conventional (HV-mode) and STAR-mode.

Fuzzzy Logic and Neuro-Fuzzy Classification ofHydrometeor Type Based on Multiparameter Radar Measurements
(V. Chandrasekar, Professor)

1. Introduction

One of the important applications of polarimetric radar is hydrometeor classification, which can help in the study of precipitation formation and life cycle. Based on the existing polarimetric radar measurements and the current knowledge about the hydrometeors, a Neuro-Fuzzy system for automatic classification of hydrometeor type has been developed at CSU.

Five radar measurements, namely, horizontal reflectivity (Z_h), differential reflectivity (Z_{dr}), differential propagation phase shift (K_{dp}), correlation coefficient ($\rho_{hv}(0)$), and linear depolarization ratio (L_{dr}), and the corresponding altitude, have been used as input variables to the Neuro-Fuzzy network. The output of the Neruo-Fuzzy system is one of the many possible hydrometeor types, which are:

1) drizzle,
2) rain,
3) dry and low density snow/crystal,
4) dry and high density crystals,
5) wet and melting snow/crystals,
6) dry graupel,
7) wet graupel,
8) small hail,
9) large hail, and
10) mixture of rain and hail.

The inputs and output of the Neuro-Fuzzy Hydrometeor type classifier is shown in Fig. 5.

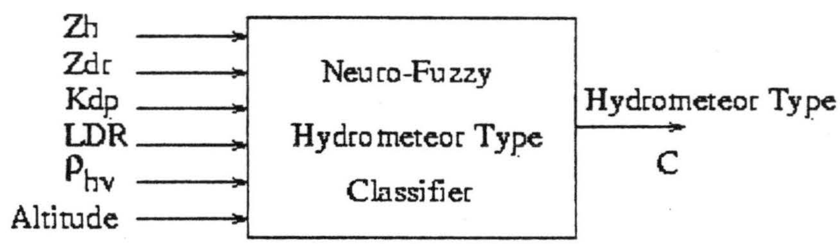

Figure 5: Scheme of the fuzzy logic classifier.

Appropriate fuzzy rules are defined according to prior knowledge; an initial fuzzy set is defined first, in which the membership functions of the input fuzzy variables are also chosen (1-Dimensional, or 2-Dimensional). The Neuro-Fuzzy classifier has advantages over the Neural Network classifier, by appearing as more transparent instead of as a "black box". The Neuro-Fuzzy classifier also has advantages over the Fuzzy Logic classifier (shown in Fig. 6), because it is able to learn the parameters of the system according to radar data samples and their corresponding hydrometeor types.

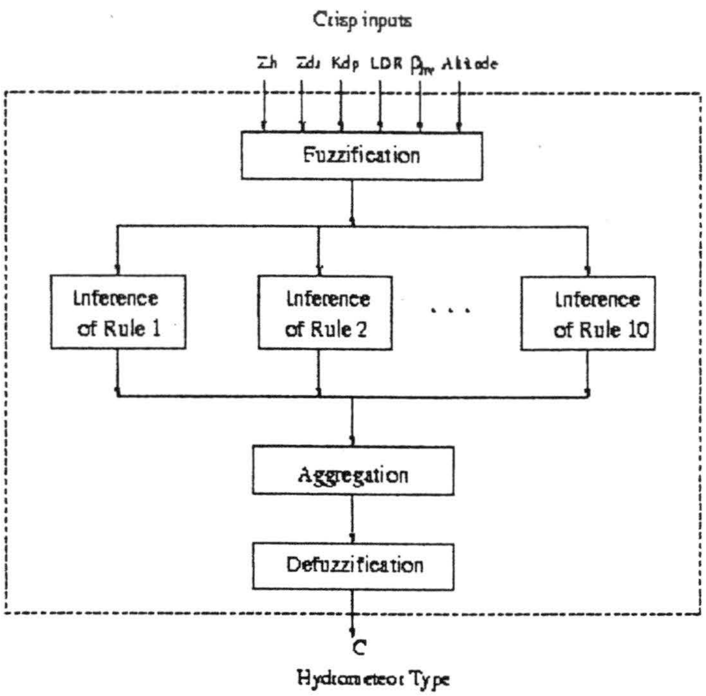

Figure 6: The fuzzy logic classifier.

2. Neuro-Fuzzy Hydrometeor Type Classifier

The performance of the Fuzzy system classifier depends critically on the specification of the membership functions, which are set manually according to empirical and prior knowledge. It is necessary to fine tune these parameters based on the radar data and the corresponding hydrometeor types observed. Manually adjusting these parameters is very tedious, inefficient, and inaccurate. We have developed a Neural Network to adjust its membership functions automatically. The Neuro-Fuzzy system, which combines the learning capability of a Neural Network with the transparency and interpretability of the rule-based fuzzy system, can improve the classifier's performance greatly. The combination between neural network and fuzzy logic system is called hybrid Neuro-Fuzzy model, shown in Fig. 7. In this model, the Fuzzy system can be viewed as a multilayer feedforward neural network. The Neuro-Fuzzy system can perform much better than the fuzzy logic system.

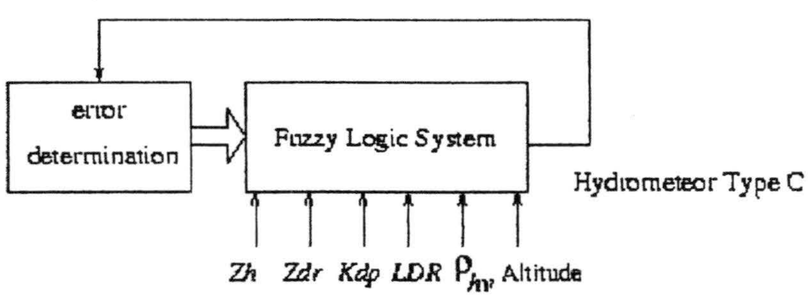

Figure 7: Neuro-Fuzzy Hydrometeor type classification.

3. Performance Evaluation

The performance of the Neuro-Fuzzy classifier for hydrometeor types was evaluated based on CSU-CHILL radar data from many summer and winter storms associated with in-situ observations. The two cases discussed here are: a) a severe hail storm on 7 June 1995, and b) a convective storm with graupel on 20 June 1995.

Case 1: The severe hail storm - 7 June 1995

On 7 June 1995, the CSU-CHILL radar observed a supercell structure, and a chase van with a roof-mounted hail collector net was sent to intercept the storm core and collect in-situ measurements. The 7 June 1995 storm turned out to be a severe hail storm. The classification result for a vertical profile of the storm through the core of the storm is shown in Fig. 8. In this figure, the radar measurements shown are Z_h, Z_{dr}, and K_{dp}, respectively. Panel (d) is the classification result from the Neuro-Fuzzy classification system. We can see from the classification result that hail and rain mixture, small hail, wet graupel, and rain are found on the ground and at low altitude, and small hail and graupel are found at the altitude between 2km to 6km. Ice crystals are found at regions above 6 km. The Neuro-Fuzzy Hydrometeor classifier results were consistent with ground observations by the hail chase van.

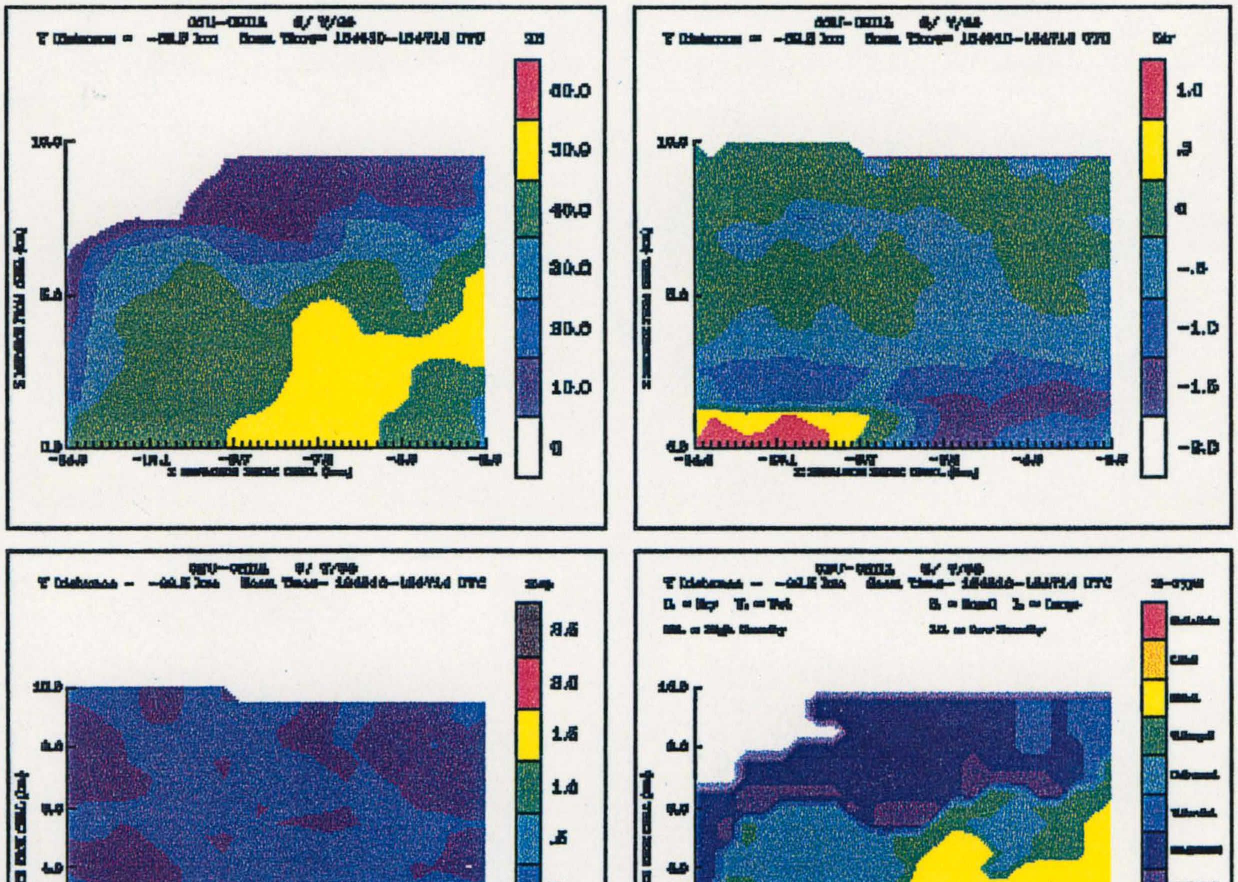

Figure 8: Z_h, Z_{dr}, K_{dp} and their corresponding Hydrometeor Type

Case 2: The Convective Storm with graupel - 20 June 1995

On 20 June 1995, the CSU-CHILL radar observed a storm cell that formed 20 km east of the radar. A T-28 aircraft carrying an HVPS probe penetrated through the core of the storm to collect in-situ observations. Most of the aircraft flights through the storm were made at a constant altitude of 4 km above ground. During the flight, the HVPS collected samples of hydrometeors along the path. Fig. 9 shows the classification result from the Neuro-Fuzzy scheme at the altitude of the aircraft. The solid line is the aircraft track. From Fig. 9, it can be seen that the observation area consisted predominantly of graupel particles, and a small region of small hail in the core of the storm. This inference is supported by the T-28 aircraft observations obtained from the HVPS probe. Sample images of hydrometeors from HVPS for the flights are shown in Fig. 10. We can see the signature of conical graupel particles in the images.

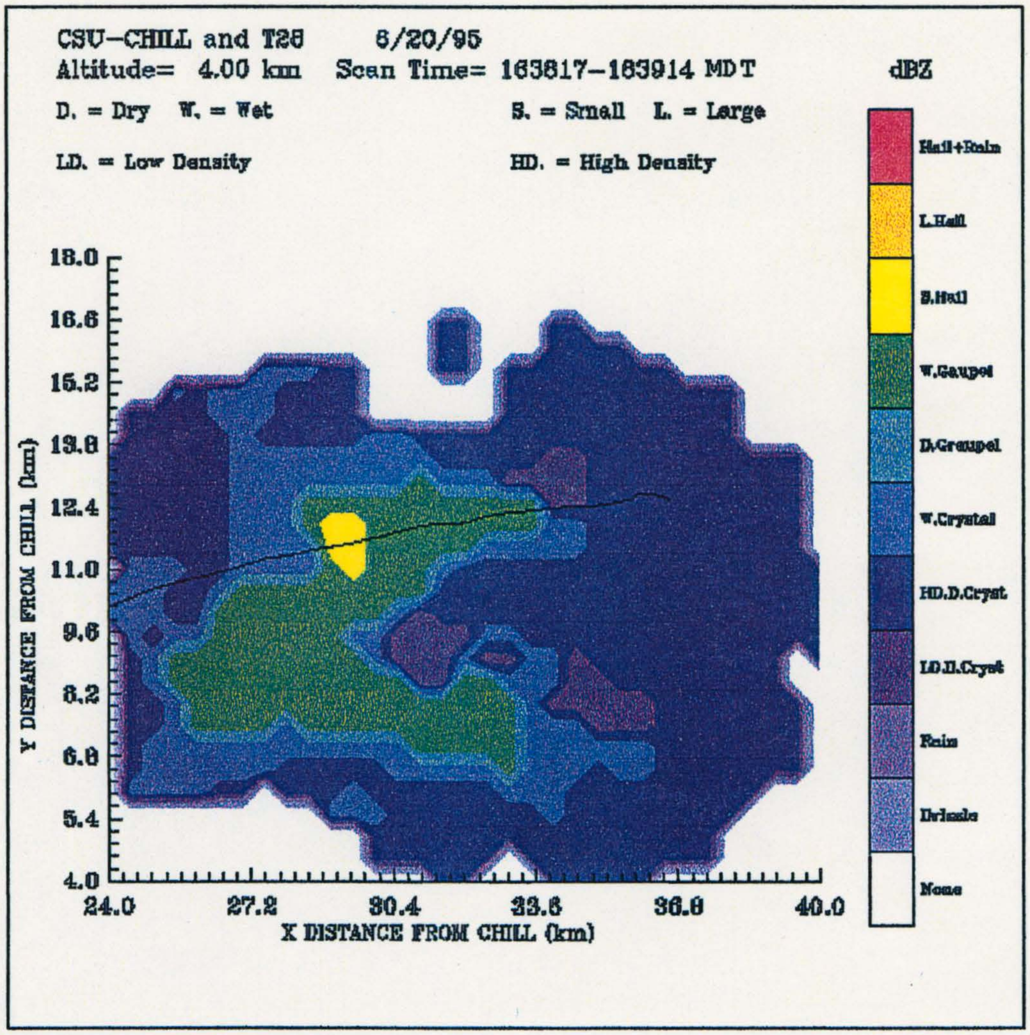

Figure 9: Classification result for Case 2.

4. Summary

A comprehensive automatic hydrometeor classification system using both Fuzzy Logic and a Neuro-Fuzzy network has been developed at CSU. The Fuzzy logic and Neuro-Fuzzy system developed through this work is robust and not affected by measurement errors. The Fuzzy Logic and Neuro-Fuzzy system has been applied to radar data and successfully compared against in-situ measurements. The fuzzy logic classification is currently being implemented in the product display at the CSU-CHILL radar. Similar to any newly introduced system, the Fuzzy Logic and Neuro-Fuzzy system will be fine-tuned and improved over time, when more observations are made. However, the basic framework is very conducive to improvement and/or adjustment.

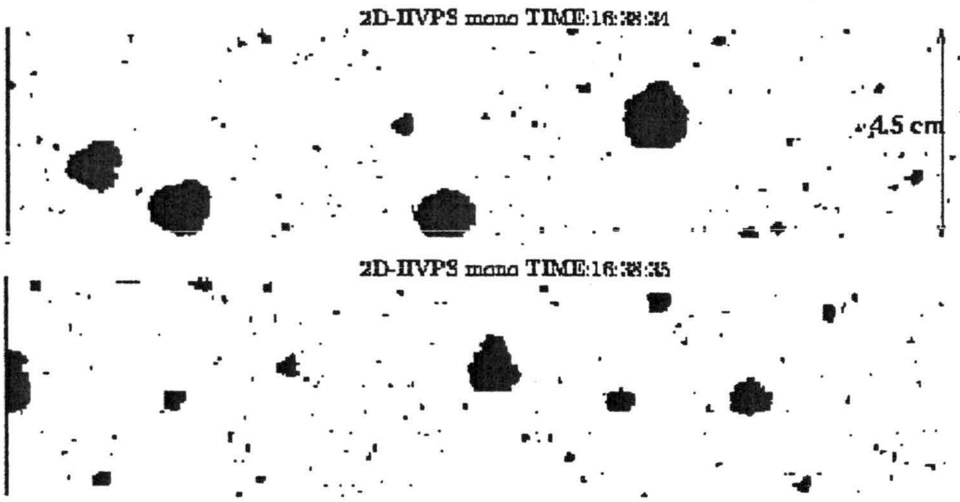

Figure 10: HVPS Images of hydrometeors in 20 June 1995 storm.

Radar Engineering
(Dave Brunkow, Senior Engineer)

<u>Technical Improvements</u>

a) Pawnee Radar Installation

A single channel Doppler radar (formerly referred to as the HOT radar) was acquired from the Illinois State Water Survey and installed 48 km NNW of CSU-CHILL. This system is similar to CHILL in that it is mounted in a semi-trailer, utilizes a FPS-18 transmitter and an SP20 signal processor. The main difference is that the Pawnee radar has a smaller antenna with a 1.6-degree beamwidth and only operates with vertical polarization. The primary function of this radar is to function in a dual-Doppler scan mode coordinated with the CSU-CHILL. This dual-Doppler configuration affords a good view of the storms, which frequently move southeast off the Cheyenne ridge.

Bob Bowie of the CHILL staff traveled to Illinois to dismantle the system and supervise the removal of the antenna pedestal from its tower. Bob also refurbished the transmitter and installed of a solid-state IPA. The receiver was rebuilt with the addition of a new LNA and an instantaneous automatic gain control (IAGC) system and digitizer. The new Colorado location offers an excellent radar horizon and does not require the use of a tower. A fiberglass FPS-18 radome was installed on a wooden structure to protect the antenna from winds and hail damage. A surplus diesel generator supplied power for the 1998 operations; however, three-phase commercial power is available at the site and will be installed during this fall if funds are available. After a few initial problems were solved, the Pawnee proved to be a reliable system during the months of July and August. After the new signal processor is installed at CSU-CHILL, the more powerful SP20 will be moved from the CHILL to the Pawnee radar. This will add a better digitizer and clutter filtering capability. Additionally, a substantial new privy will be installed at the site in accordance with the Weld County Zoning laws.

b) New Chill Processor

The CSU-CHILL has used a Lassen SP20 signal processor since 1987. Although this system has preformed reliably, its computational capability is not adequate to process all of the gates available with a dual receiver system.

To overcome this restriction, a new Lassen Digiciever signal processor is scheduled for installation late in 1998. The Digiciever system uses IF digitizing to simplify and improve receiver performance by replacing the IAGC system currently in use. A 10 MHz IF signal will be digitized, then converted to band-pass filtered I and Q values. These functions will be performed in a pair of receiver channels separated in sensitivity by 25 dB. When all samples are complete for a given integration period, the set which offers the most sensitivity without excessive saturation will be selected for processing. The transmitters will be modified to obtain a high quality sample (12-bit accuracy) of the transmitted pulse. The signal processor will sample this pulse and these results will be used to correct the samples from each pulse for slight variations in phase and magnitude. These corrections are expected to produce mean phase estimation accuracy of better than 0.1^{o}. A series of Analog Devices SHARC DSP chips will perform this correction, apply clutter filtering, and do the covariance processing. A third party SHARC based processor board will be used to calculate the meteorological moments. The data stream will be passed to a workstation for archiving and further distribution. The SHARC digital signal processing chips offer an optimal computational capability with a convenient software development environment.

The enhanced computational capability of the new processor will allow the testing of a faster scanning mode for the acquisition of the polarization parameters. The antenna scan rate is a function of the rate at which independent samples can be acquired, and the number of independent samples required for a given accuracy. The polarization parameters such as Z_{dr} and $_{dp}$ require high accuracy which implies a large number of independent samples and typically slow scan rates. By reducing the transmitted pulse width and the receiver gate size, the number of independent range samples can be quadrupled which would allow the scan rate to approximately double while maintaining the same accuracy in the meteorological fields.

c) Radome Repair

Near the end of the 1998 storm season, one of the seams in the side of the 72 foot diameter air-inflated radome opened up over a distance of about 10 feet. Although this was a substantial leak, the dome stayed up and functioned normally. Within two days, the tear was reinforced with emergency lacing. After consulting with Chemfab, the manufacturer of the dome, a more permanent repair was conducted. This involved the gluing of a corset-like lace-up appliance on the inside of the radome. This allowed the opening in the fabric to be closed by pulling the two panels back nearly to their original positions. The laces were left in place and made air-tight by gluing an overlay on the entire area. The seam that failed was the closing seam, that is, the last seam joined during the manufacture of the dome. This seam was different from most in that it was glued rather than welded. After 8 years of use, the glue was beginning to fail. Upon inspection, it was found that two of the three glued seams in the radome showed at least initial signs of glue failure. Gluing overlays on the inside of the radome reinforced all of the glued seams. It is hoped that these repairs will hold until a new radome can be provided for the facility.

Acknowledgments:
The CSU-CHILL facility is supported by NSF Cooperative Agreement ATM-9500108, supplemented by cost sharing funds from Colorado State University.

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------ End of Newsletter --------

Appendix E

CSU-CHILL Strategic Plan

Ten Year Strategic Plan

for the

CSU-CHILL National Radar Facility

Prepared by

Departments of Atmospheric Science and Electrical Engineering

Colorado State University

Submitted to

Dr. Kenneth Van Sickle

Program Director, Lower Atmosphere Facilities

National Science Foundation

21 September 1998

Table of Contents

1. OVERVIEW

Herein we submit a Strategic Plan for the CSU-CHILL National Radar Facility, for the period 2000-2010, as requested by the National Science Foundation/Division of Atmospheric Sciences. Through the stable and excellent support provided by the National Science Foundation and Colorado State University over the past eight years, we have moved the CSU-CHILL radar to the forefront of ground-based meteorological radar research. During this period we have upgraded the radar to a full dual-channel system, operating two transmitters and two receivers. A new antenna was acquired, which is a state-of-the-art, center-fed, parabolic reflector antenna. We have carried out numerous improvements and calibration procedures to allow us to constantly produce high quality data from this highly reliable radar system. We are about to install a new, dual-digital IF receiver and signal processor. Upgrades described under this Strategic Plan build on these significant improvements to the radar system.

Our 10-year plan is broken into two segments: 2000-2005 and 2005-2010. Our broad intentions for the first period are to carry out modifications to the radar that will allow quick scan capabilities, achieving typical scan speeds of $18^{\circ}s^{-1}$. This upgrade, when combined with our new, fully operational, S-band Doppler radar (the Pawnee radar), will allow for unprecedented observations of the dynamical structure of storms, placed in the context of microphysical observations via CHILL's polarimetric capabilities. With the addition of permanent instrumentation to monitor the electrical behavior of storms being viewed by the dual-Doppler network, a unique, low-cost field network would be available to the meteorological community. As a great benefit to users of this network, we plan to provide real-time dual-Doppler analyses from the CHILL-Pawnee radars. Costs for implementation of this upgrade are included in this Strategic Plan. Real-time dual-Doppler analyses would be displayed at CHILL.

During the second five-year period, we propose to acquire an offset Cassegrain antenna. This antenna would allow for improved sidelobe and cross-polarization performance, and when coupled with our capabilities to transmit various polarization states, will substantially advance the remote sensing of clouds and precipitation. We would also like to replace the existing FPS-18 transmitters with surplus 88D transmitters which have superior spectral characteristics. We believe this new radar system would play a pivotal role in future field experiments intended under the U.S. Weather Research Program and other related programs. We also see the CHILL radar system serving as a developmental testbed for the nation's operational NEXRAD radars, including testing transmit schemes and algorithms for the proposed polarimetric upgrade of the NEXRAD radars. These upgrades will not decrease the portability of the CSU-CHILL radar. Therefore, CHILL should still be viewed as a portable radar during the next decade. We stand ready to deploy the radar for any project.

As an additional component of our plan, we also intend to fully develop real-time dissemination of CHILL data via the Internet. This upgrade would allow for remote users to rapidly interrogate the datastream, make real-time decisions, and select scan strategies to study evolving storm structures. We envision this capability allowing students in classrooms, both nationally and internationally, to effectively conduct field programs from their home bases. In this way, the CSU-CHILL radar will continue to play a lead role in educating future radar meteorologists and radar engineers. We also intend to develop and implement a sophisticated, real-time, fuzzy logic based hydrometeor identification scheme as a first step towards quantitative precipitation forecasting.

2. TECHNICAL UPGRADES

a. 2000-2005

i) Quick Scan Capability: The new Lassen digital IF receiver and signal processor will enable the acquisition of polarimetric variables at quick scan rates of approximately 10-12° s^{-1}, which is a factor of two increase over our current scan rates. Our goal is to further increase the scan rates to 18° s^{-1} by the year 2002. This scan rate will be compatible with WSR-88D scan rates while still maintaining high accuracy for the polarimetric variables. This increase will involve using frequency agility over a bandwidth of approximately 10 MHz, since it is well-known that a change in source frequency by $1/\tau$ will decorrelate successive samples (here τ is the pulse width which will be 300 ns). The current Klystron-based FPS-18 transmitters are suitable for operation over a 10 MHz bandwidth and planned frequency shifts of 3 MHz will yield 3 source frequencies.

We note that the NASA SPANDAR radar and the Austrian C-band radar have used frequency diversity to increase the number of independent samples. In particular, the Austrian system (e.g., see Bringi and Hendry, 1990; their Fig. 3.10) uses two magnetron transmitters, one for H-polarization and one for V-polarization, which are fired alternately. In their scheme, the source frequencies for the H-pulses are different from those of the V-pulses, in effect, causing the standard deviation of Z_{dr} to be substantially worse as compared to using no frequency agility (Bringi and Hendry, 1990). However, estimates of reflectivity and linear depolarization ratio are greatly improved. The Austrian scheme, for purposes of Z_{dr},, is comparable to the SPANDAR scheme, in which successive block transmissions at H and V states are used, with frequency agility used on each block of pulses, and where slow switching between blocks is incorporated. Sachidananda and Zrnic (1985) have simulated the effects of frequency agility on the standard deviation of Z_{dr}. They considered two schemes based on conventional alternate transmit mode and on the simultaneous transmit mode. In the alternate mode, the frequency is changed after every two pulses, so that subsequent pairs are uncorrelated, i.e., the sequence (H1, V1), (H2, V2), (Hn, Vn) where (Hi, Vi) are at the same source frequency but lagged by one PRT, and the successive pairs are uncorrelated because of frequency agility. While this scheme is superior to the Austrian scheme, the standard error in Z_{dr} was found to be worse than without using frequency agility. Thus, care must be used when combining alternate transmit mode with frequency agility so as to improve the estimates of Z_{dr} rather than degrading them!

We propose an alternate-mode scheme which should make full use of frequency agility (over a bandwidth of 10 MHz) in improving the accuracy of Z_{dr} (and ϕ_{dp}, or ρ_{hv}). The simultaneous transmit scheme (as described in Sec. 2c) is optimal when combined with frequency agility based on the simulations of Sachidananda and Zrnic (1985). This scheme will also be evaluated. The combination of frequency agility as described here, using our existing two FPS-18 transmitters over a 10 MHz bandwidth, coupled with 300 ns transmit pulse widths and range averaging over 5 samples (to yield 225 m range resolution) as discussed under the quick scan scheme, will enable us to scan at WSR-88D compatible rates of 18 sec^{-1}.

The scientific goal of the quick scan modification is to use these faster CSU-CHILL scan rates in dual-Doppler configuration with the Pawnee radar (formerly the Illinois State Water Survey HOT radar), so that convective storms can be scanned with cycle times of $\leq$2 minutes. Pawnee is also a S-band Doppler radar, and is located 48 km NNW of CHILL. The combined study of retrieved kinematics and bulk microphysical fields from full polarimetric measurements with such high time resolution has been a long-standing goal in radar meteorology. *This "rapid" dual-Doppler capability, coupled with polarimetric data from CHILL, further supplemented by a permanent network to determine total lightning flash rates, will provide a low-cost, permanent field* *network to the entire meteorological community.* We expect this network to be used extensively by the meteorological community in the future, to study both winter and warm-season precipitation systems. This use would range from the study of cyclonic upslope storms and flood events, to supercell storms. The network can be easily supplemented by aircraft observations and ground-based instrumentation (e.g., a lightning interferometer) to provide a low-cost, comprehensive experimental design to study a wide range of precipitation systems.

ii) Polarization diversity studies: Because we have two transmitters on the CHILL system, we have the capability to radiate any state of polarization. Currently, we are evaluating slant 45 and circular (right hand/left hand) polarization bases. The goal here is to evaluate additional microphysical information obtainable with circular polarization based on the extensive experimental and theoretical framework provided by previous studies (McCormick and Hendry, 1975; Hendry et al., 1987; Antar and Hendry, 1987). One advantage of the circular basis is that the mean tilt angle of the propagation medium can be determined and the specific differential attenuation and phase along the principal axes can be estimated for homogeneous propagation sections. Both raindrops and ice crystals form an anisotropic propagation medium. In particular, the mean tilt angle of the ice crystals changes from horizontal orientation to vertical orientation in the presence of in-cloud electric fields, and orientation changes caused by lightning discharges can be detected in real-time (Metcalf, 1995; Krehbiel et al., 1996). *We believe that it is time to combine the best aspects of conventional linear polarization (horizontal/vertical) and circular polarization (RHC/LHC) to enhance hydrometeor classification and quantitative microphysical retrievals.* Long wavelengths (i.e. S-band) are best for this application because of reduced Mie scattering effects. It is also desirable to radiate linear and circular polarizations with full polarization agility because of statistical considerations.

While theoretical and experimental results are available for transforming from linear to circular basis (e.g., Jameson and Dave, 1988; Holt, 1988), they are based on assumptions of the mean tilt angle of the propagation medium being zero, and on certain symmetry properties of the individual particles as well as of the ensemble as a whole (i.e., mirror reflection symmetry). In addition, the differential attenuation is assumed to be negligible, which while generally considered to be a good assumption at S-band, is now known to be non-negligible when the differential propagation phase in rain exceeds around 150 degrees (Ryzhkov and Zrnic, 1995). Thus, we believe that we can optimize retrieval of quantitative rainfall amounts, and enhance hydrometeor classification in regions above and below the 0° C level using a combination of linear and circular polarizations with polarization agility. Our goal is to achieve this capability by 2004.

b. 2005 - 2010

Our goals for the longer term are to upgrade the CSU-CHILL radar with a new antenna and to acquire surplus NEXRAD transmitters to replace the aging FPS-18 transmitter technology. The cleaner output pulse of the 88D transmitters would also be an advantage in our circular/slant 45 polarization work. Furthermore, the entire radar system will be significantly easier to maintain with more modern transmitter technology.

Currently we are at the limit of antenna accuracy provided by prime-focus fed reflector antenna technology. In regions of homogeneous precipitation, this technology is sufficient for polarization measurements (system linear depolarization ratio limit of -32 to -34 dB), but copolar sidelobe levels along the plane of the feed support struts (45/135 degree planes) are relatively high (-27 dB) and do not fall sufficiently fast with angle deviation from boresight. This type of reflector design limits the polarization accuracy when precipitation is non-homogenous, and in particular, when cross-beam precipitation gradients exceed around 20-30 dB km^{-1} (depending on range). Cloud models and high resolution (e.g., vertical pointing) radar data show that much larger spatial gradients exist in storms, especially near the updraft/downdraft interface. To reduce errors, the copolar sidelobe levels must be as low as possible (in any plane) and this necessitates an offset-fed reflector design, which eliminates feed and strut blockages, yielding an improvement of around 8 - 10 dB in close-in, worst-case copolar sidelobe levels (to around -35 to -37 dB) compared to prime-focus fed reflectors.

The offset-fed antenna was chosen for the early Canadian research, and several research C-band systems in Europe (Germany and Italy) use this design with great success. For linear polarizations, the offset design (even with an ideal feedhorn) does generate cross-polarized lobes with peaks up to -27 dB in one plane. This will limit the LDR system limit to what can be achieved in center fed reflectors, though using a circular polarized feedhorn, depolarization ratio limit can be much lower (around -38 to -40 dB in homogeneous precipitation), as established by the Canadians. Since we contemplate transmitting linear (horizontal/vertical) in combination with circular polarizations, an offset Cassegrain design is desirable. The Italians have an offset Cassegrain antenna at C-band manufactured by Alenia that yields excellent copolar sidelobe levels, as well as excellent linear cross-pole lobe levels that are both 8 - 10 dB lower than our center-fed design (e.g., see Wilkinson and Burdine, 1980). We are not aware of any S-band offset Cassegrain radar antennas in existence, but Alenia has a S-band design. *The acquisition of a new offset Cassegrain antenna will meet the scientific needs of the meteorological community until 2010 and beyond, in terms of providing the highest possible accuracy of radar measurements from a ground-based system at S-band.*

We realize that the new offset Cassegrain antenna is a very expensive item (estimated at $750K). However, if funded, this configuration will yield a superb, ground-based S-band radar for cloud physics and precipitation research, employing proven technology with high spatial and temporal resolution, and with full polarimetric capabilities. Scientists will have considerable flexibility in waveform design, i.e., full polarization agility (including radiation of elliptical polarizations) and choice of range resolution and frequency agility. Such a meteorological radar does not exist today, and our long range plan is to make such an advanced facility available to the cloud physics and radar meteorology community. When combined with the Pawnee radar, a unique, dual-Doppler/polarimetric observational platform would be realized. We would expect many field programs take advantage of this network's unprecedented observational capabilities. While plans are not firm, we plan to seek significant cost-sharing from Colorado State University for all equipment purchases.

c. *Relevance to NEXRAD Polarimetric Upgrade*

The National Severe Storms Laboratory (NSSL) is currently engaged in adding a polarimetric upgrade to the WSR-88D radar for improving rainfall measurements (Doviak and Zrnic, 1998). They propose transmitting essentially slant 45° linear polarization state (termed simultaneous transmission with equal power at H and V polarizations), and receiving the horizontal and vertical components of the backscattered ellipse in a two-channel receiver. The 2 x 2 coherency matrix will be measured on reception. The differential reflectivity (Z_{dr}), differential phase (ϕ_{dp}) and copolar correlation coefficient (ρ_{hv}) will be directly obtained from the coherency matrix elements. Because the receive basis (H,V) is not the same as the transmit basis (slant 45° linear), cross-coupling due to scattering and propagation can potentially bias the estimates, especially for ρ_{hv}, and to a smaller extent for Z_{dr} and ϕ_{dp}. These potential biases have been simulated by Bringi et al. (1998), and by Doviak and Zrnic (1998). Note that simultaneous transmission only implies equal power at H and V polarizations, and the phase difference can be arbitrary (zero phase difference implies slant 45° linear, while 90° implies circular polarization).

The CSU-CHILL radar, because of its two transmitters, was recently used to test this scheme in a slight variant of the above mode whereby the received H and V components were alternately received via the same receiver (to permit greater accuracy in Z_{dr}, ϕ_{dp} and ρ_{hv}). This mode is termed simultaneous transmit-alternate receive or the STAR-mode (Brunkow et al., 1997). Sample data were collected in a stratiform event, and in a convective storm with hail. These data showed that ϕ_{dp} and Z_{dr} could be retrieved accurately, whereas ρ_{hv} was biased low because of cross-coupling in the bright-band and the hail-bearing regions of the precipitation shaft (Bringi et al., 1998). These initially promising experimental results and theoretical simulations lead Doviak and Zrnic (1998) to conclude that ... "simultaneous transmission of H, V waves is a sound method and should be tested".

The CSU-CHILL radar facility can play an important role in the experimental testing phase for the polarimetric upgrade of NEXRAD. We believe that the polarimetric upgrade to the WSR-88D system is an important one for the National Weather Service, since improved rainfall estimation is vital for hydrologic application (e.g., flash-flood forecasting). Indeed, one of our recent studies, Petersen et al. (1998), demonstrated markedly improved rain estimates for the 1997 Ft. Collins flood using polarimetric radar vs. NEXRAD-based estimates. This is just one of many examples that can be cited demonstrating the improvements in estimating rain rates (even in the presence of hail) and in detecting hail via polarimetric radar. We also believe that the flexible CSU-CHILL configuration can play an important role in evaluating future polarimetric upgrade schemes and algorithms. We are currently engaged in experimental and theoretical research related to the WSR-88D polarimetric enhancements, and expect to be so engaged during the period 2000-2005. We also expect to participate in robust polarimetric-based algorithm development for the WSR-88D, and to use the CSU-CHILL facility as a test-bed for refinement of algorithms. The WSR-88D system upgrades are potentially of enormous importance to the nation. The CSU-CHILL facility can continue to play an important role in this effort.

3. EDUCATION AND OUTREACH

The CSU-CHILL radar facility plays an important role in various levels of education. Such activities include:

i) Providing data for graduate research at M.S. and Ph.D. levels,

ii) Radar hardware and signal processing methods for graduate classes,

iii) Undergraduate projects (Capstone courses) and Research Experience for Undergraduates,

iv) Undergraduate class demonstrations, and

v) Junior High and High School visits and Regional Science Fair participation.

Thus, the CSU-CHILL facility participates in a broad spectrum of educational and outreach activities from grade 8 through Ph.D. programs. CSU-CHILL data have been used by graduate students from many universities around the U.S. Similarly, undergraduate students from around the country have participated in summer research projects.

During our existing cooperative agreement, we have developed an excellent infrastructure in terms of courses, programs, and projects related to the educational aspects of the CSU-CHILL facility. In the future we are ready to launch a major initiative towards what we call ``Knowledge Networking of the CSU-CHILL Facility," which will lead to new levels of interactivity, and flow of information and knowledge among researchers and students from across the entire country, or world, for that matter. This initiative will require funds for hardware upgrades in order to establish a high-bandwidth network between the CSU-CHILL facility and Colorado State University main campus. Two levels of network connectivity are proposed, namely:

i) high speed real-time data to sites that can control the radar, and

ii) lower speed, radar based product information such as rainfall rate, rainfall accumulation maps, locations of hail, and rain/snow transition regions etc., for general purpose and scientific use.

a. Signal and Data Flow from the CSU-CHILL Radar

As discussed in Sec. 1, a new state-of-the-art signal processing and radar control system is being installed on the radar. The salient features of the new system are ease of programming, large and efficient internal memories, unsurpassed communication bandwidths and good isolation between data transfers and core digital signal processing activity. The new signal processing/receiver system will have a dynamic range of 100 dB, with a 0.05 degree RMS phase error within an integration cycle. The processor has a peak computation power of 2.8 GFLOPS and communication bandwidth of 240 Mbytes/sec without affecting DSP core operations. Total communications capacity in the base unit is approximately 2.88 Gigabytes/sec (sustained). The radar is completely computer controlled, including range gate selection and trigger, as well as transmitter phase control.

The radar data will be archived at the radar site and will be simultaneously transmitted to Colorado State University (CSU) radar lab. This path is currently incomplete. The radar site is physically close to the University of Northern Colorado (UNC). As part of this initiative we plan to install a microwave link between CSU-CHILL and UNC, since UNC is well-connected to the CSU campus. Once the data reaches the CSU radar lab, the network servers will process them and then route it to two types of destinations, namely:

i) Real-time display of base data and web images of product maps such as rainfall, location of hail, snowfall rate, etc., and real time video of radar operations.

ii) Destinations with products only.

The generation of products from raw radar data will be done at the radar lab.

The network configuration to be developed will be an efficient low-latency link between the CSU-radar lab and the radar facility. The development will be based on the Integrated Network Communication Architecture (INCA) research at CSU.

b. Scope of the Initiative

The proposed initiative includes a multitude of tasks including:

i) hardware upgrade,

ii) development of software for network applications,

iii) development of radar algorithms, and

iv) installation and training at remote sites.

The hardware installation and radar algorithm development work must precede much of the other tasks envisioned. Though several algorithms are available for radar applications such as rainfall rate, rainfall accumulation, hail location, etc., the algorithms have never been developed for robust performance under the real-time applications of the type discussed here. Thus, significant effort will be spent on generating robust algorithms for networking applications. Once the hardware upgrade from CSU-CHILL to the EE radar lab is in place, the network protocol development to transfer data to the radar lab can be initiated in parallel. Subsequently, a single site remote operation of the radar with real time data transmission will be developed and tested. Once this part of the project is in place, then web-based products at lower data rate (frame-by-frame or volume-by-volume upgrade) will be developed with specific software for monitoring targeted regions of interest to the audience.

The specific plan is itemized as follows:

2000-2002

i) Install microwave (or other high speed) link to UNC from the CSU-CHILL radar.

ii) Upgrade servers at the radar facility, CSU radar, and INCA laboratories.

iii) Implement high level protocols for retrieving and staging CSU-CHILL radar data at the CSU main campus.

iv) Development of radar data processing and algorithm testing for radar products and quality control.

2002-2005

i) Algorithm development and testing for multiparameter radar real time products.

ii) One prototype of remote control of radar including parameters such as pulse repetition time, (PRT), scan rate, and integration cycle will be developed.

iii) Development of Internet plug-in software for accessing data from the web.

iv) The software will allow users to customize the access of data.

2005 - 2010

During this time frame we expect to have the real-time data networking as well as remote control working. Part of the effort will also involve developing documentation and field testing the developed products in field experiments in collaboration with other projects.

c. Potential Impact of the Initiative

This initiative will have substantial impact on radar operations by bringing the facility much closer to scientists in a virtual sense. In addition, since it has the potential to increase simultaneous observation/monitoring by many scientists, there is a good chance for collecting unique data sets and making significant progress scientifically, thus reducing the overall cost of research. A large component of this CSU-CHILL education and outreach objective resides in a proposal submitted to the Knowledge and Distributed Intelligence program at NSF. If this KDI proposal is funded, costs for the initiative, as outlined in this Strategic Plan, would be considerably reduced.

4. FUZZY LOGIC-BASED CLASSIFICATION OF HYDROMETEOR TYPES

One of the important applications of polarimetric radar is hydrometeor classification, which is the first step towards quantitative precipitation forecasting. Based on the existing polarimetric radar measurements and the current knowledge about these hydrometeors, a Neuro-Fuzzy system for automatic classification of hydrometeor type is currently being developed at CSU.

Five radar measurements, namely, horizontal reflectivity (Z_h), differential reflectivity (Z_{dr}), specific differential phase (K_{dp}), correlation coefficient (ρ_{hv}), and linear depolarization ratio (LDR), have been used as input variables to the Neuro-Fuzzy network. The output of the Neuro-Fuzzy system is one of the many possible hydrometeor types, which are:

i) drizzle,

ii) rain,

iii) dry and low density snow,

iv) dry and high density crystals,

v) wet and melting snow,

vi) dry graupel,

vii) wet graupel,

viii) small hail,

ix) large hail, and

x) mixture of rain and hail.

Appropriate fuzzy rules are defined according to prior knowledge.

The Fuzzy Logic and Neuro-Fuzzy system have been applied to radar data and successfully compared against in-situ measurements. We plan to implement this fuzzy logic classification in the product display in real-time using the new signal processor. This real-time hydrometeor identification, coupled with real-time kinematic information via dual-Doppler analyses, will provide new insights into storm dynamics and microphysics. Furthermore, having real-time access to these resources will allow for effective decision-making in field programs.

5. TIMELINE, EQUIPMENT BUDGET DETAIL, AND BUDGET PROJECTIONS

10/98-5/99 CSU-CHILL Modulator upgrade: This upgrade would involve the replacement of the hydrogen thyratron modulator tubes and trigger amplifier chassis. The trigger amplifier chassis is currently a complex system consisting of a delay circuit, a small thyratron and pulse forming network. The replacement of this assembly by a solid state module will significantly improve the stability of the modulator delay. The overall reliability of the transmitters would also be improved through the elimination of the trigger amplifier chassis as well as the elimination of the 300, 800, and 5,000 volt power supplies. The instability of the modulator delay is believed to be the major source of drift in the ZDR calibration. This improvement may also reduce the intra-pulse phase shift thought to be the limiting factor in the polarization purity in the current circular/slant 45 operation. Cost: $8,000

10/98-5/99 Improved Circular/Slant 45 upgrade: This upgrade would consist of waveguide modifications which would allow the transmission of a single high purity polarization basis which could be tuned for either circular or slant 45. In this mode, the output from a single transmitter would be split equally and fed to both ports on the antenna. A mechanically tuned high power phase shifter would trim the phase of one channel to provide the desired output polarization. These polarization bases would offer improved cross-polarization signal strength which would be of particular advantage in winter precipitation situations. It has the disadvantage of limited agility since it would take 30-60 minutes to restore the waveguide to the normal VH configuration. Cost: $2000 if Canadian phase shifter is available for use.

1/2000 Faster Scan Operation I: This would involve the use of the short pulse operations provided by the new Lassen Digiceiver processor. The 45-meter samples would be range averaged back to provide 225-meter samples with a scan rate of 12 degrees per second, double the current scan rate. This upgrade will require no hardware modification other than the new signal processor, scheduled for installation in the fall of 1998. This mode will likely be tested during the 1999 summer operations. Cost: N/A

5/2001 Faster Scan Operation II: This upgrade would add a frequency-hopping mode, which would triple the rate of independent sample acquisition. It would add two STALO oscillators and a high-speed selector switch. This would raise the scan rate to approximately 18 degrees per second at 225-meter range resolution. It is not clear whether this mode of operation would be permitted, but hopefully it would be allowed at least on an experimental basis. Cost: $4,000

5/2002 Real-Time Dual Doppler: This upgrade would involve the addition of a high-speed data link to the CSU-Pawnee Radar near Nunn, CO. The radar control circuits and signal processor would also be upgraded to facilitate reliable remote operations. Conversion to a rectangular grid would be done by a workstation at the remote site. This would reduce the required data rate to the level of a switched phone line or spread spectrum radio modem. The addition of radar control circuits would allow unattended operation of the system. Raw data files would be archived on local disk storage and transferred to CSU-CHILL in a post-operations mode. Cost: $100,000

2005-2010 Transmitter Upgrade: This would involve replacing the existing FPS-18 transmitters with surplus 88D transmitters that may be available though the Department of Defense. It is not clear when these might be available, hence the broad time frame. These transmitters would be more reliable and more maintainable than the FPS-18 units. The cleaner output pulse of the 88D would likely be an advantage in the circular/slant 45 mode of operation. When the transmitters become available, they could be installed in a new shipping container without interrupting operations of the current radar configuration. Cost: $60,000

2005-2010 Offset Cassegrain Antenna: The current prime-focus reflector antenna on the CSU-CHILL system, while a big improvement over the original antenna, is still limited because of feed and support strut blockages, especially in the sidelobe performance in the plane of the struts (45/135 deg planes). We believe we are at the limits of performance that can be achieved with the current design. Elimination of feed and strut blockage is essential to improve the sidelobe performance in all planes. The offset Cassegrain design enables the attainment of vanishingly small sidelobe levels (about 10 to 15 dB better than prime-focus reflectors), and with a well-designed feed can give outstanding cross-polar performance. Such high performance is needed to eliminate gradient-induced artifacts in the polarization measurements and is vital for accurate cloud physics studies. The offset Cassegrain antenna is currently used by NOAA/ETL 35 GHz cloud radar and by the Italian C-band research radar. Cost estimated at: $750,000

CHILL New Equipment Budget

(10 year projection)

EQUIPMENT	COST
<u>Radar Facility Equipment Purchase</u>	
2001: STALO oscillators	4,000
2002: Real-time dual-Doppler	100,000
2005-2010: Transmitter upgrade	60,000
2005-2010: Offset Cassegrain Antenna	750,000
<u>Outreach Initiative: Hardware rqmts.*</u>	
3 high-end workstations	60,000
Hardware for building links	10,000
Microwave (or other) link cost	30,000
Disk farm (data storage/distribution)	30,000
Network upgrade @ radar lab	30,000
UNC link costs	5,000
2 high end user (remote) terminals	20,000
2 low data rate user (remote) terminals	10,000
TOTAL COST:	**$1,109,000**

*These costs would be borne by NSF/KDI and CSU if NSF KDI proposal is funded.

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