Annual Report for

THE CSU-CHILL RADAR FACILITY

Cooperative Agreement No. ATM-8919080

Submitted to

The National Science Foundation

Division of Atmospheric Sciences

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Colorado State University

DEPARTMENT OF ATMOSPHERIC SCIENCE
DEPARTMENT OF ELECTRICAL ENGINEERING
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

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1. Introduction

Activities at the CSU-CHILL National Radar Facility from 1 January 1994 to 31 December 1994 are summarized in this annual report. This report is the last report to be submitted under our Cooperative Agreement, which expires in April 1995. A proposal is presently under review at the National Science Foundation for a second, five year Cooperative Agreement.

Highlights during this past year included installation and operation of our new antenna (feed horn and reflector), installation of a new low noise amplifier (which has decreased our minimum detectable signal to -119 dBm), and first estimates of Linear Depolarization Ratio by the CSU-CHILL system. Numerous 20 hour projects and educational activities were also supported during the past year, as detailed below. The CSU-CHILL facility also supported two projects that received formal funding from the NSF, the Winter Icing and Storms Project (WISP 94) and a Research Experience for Undergraduates project (funded by the Engineering Directorate at NSF).

The new antenna is performing up to all design expectations. Low sidelobes and matched patterns between horizontal and vertical polarization states result in much less ground clutter at low elevation angles, low noise in the polarization variables, and fewer artifacts. First-of-the-kind polarization data were collected in several WISP 94 cases which showed large values of differential reflectivity in pristine ice clouds (4-5 dB, consistent with ice crystal measurements made by the NCAR Electra aircraft; co-polar reflectivities of about -10 dBZ), and near-zero values of differential reflectivity associated with ice aggregates. Numerous severe storms were also observed with the new antenna with all polarization variables showing consistent patterns with rain and hail locations (confirmed on several occasions by spotters or follow-up investigations). Overviews of these data collections were presented during the Spring and Fall Observing Facilities Advisory Panel meetings.

This spring marked the first measurements of Linear Depolarization Ratio, Ldr, by the CSU-CHILL facility. The first data collections of Ldr were in an extended bright band situation. Measurements of Ldr, reflectivity, differential phase and co-polar correlation were analyzed in the vertical and found to be consistent with previous studies and microphysical melting models. We continue our Ldr observations at this time.

At present, we are well on our way towards completing our dual-channel system. The second channel obtained from the National Severe Storms Laboratory has been installed in the radar trailer. Testing of the high power components will be done over the next few months. We expect to have the dual-channel system available for research in late spring, 1995. All major components to complete the dual-channel installation have been acquired, or will soon be received. Our new user trailer came on line this past summer and provides nearly 30 feet of comfortable, conditioned scientist work space as well as nearly 20 feet of machine room space.

A formal meeting of the CSU-CHILL Radar Advisory Committee was held in April 1994, at the CHILL site. Our detailed plans for the dual-channel system were presented to this committee along with a presentation of data collected with the new antenna and a review of all research and educational activities. The RAC recommended that we proceed ahead with our dual-channel installation.

2. Summary of Activities During 1994

a. Radar Operations Summary: 1994

During 1994, operations were conducted at the CSU-CHILL Facility in support of 8 research projects. Two of these projects were funded by the NSF, while the remaining 6 were of the "20 hour" variety. The radar remained at its home base in Greeley, Colorado during all of these activities.

The first NSF sponsored program was the 1994 version of NCAR's Winter Icing and Storms Project (WISP94). The field phase of WISP94 took place between 25 January and 31 March. Results from earlier WISP field campaigns had shown that the concentration of supercooled water (and the associated aircraft icing hazard) was significantly reduced in areas where ice particles were actively growing. To explore this depletion of supercooled water, the 1994 data collection efforts were focused on the nucleation and early growth of ice particles in winter season precipitation systems. Multiparameter data were collected by the CSU-CHILL (S band) and NOAA (X band) radars. More generalized mesoscale radar observations were made by the NCAR CP-4 and NWS WSR-88D fixed polarization Doppler systems. The NCAR King Air and Electra aircraft were used to collect in situ data. A variety of winter precipitation systems were probed during the project, and the resultant data sets have already proven to be highly useful. CSU-CHILL radar operations were highly successful during WISP94.

The second NSF program was the Research Experience for Undergraduates (REU) project directed by Prof. V. Chandrasekar of the CSU Electrical Engineering Department. In this program, 8 students from 6 states spent the summer of 1994 at CSU and participated in a variety of radar-related research activities. The REU students received a series of introductory lectures at the CSU-CHILL facility on various aspects of the design and usage of meteorological radar systems. A number of the students will be able to use their REU CSU-CHILL activities as the basis for their senior year electrical engineering project. Additional details regarding the REU project are presented in the educational support section.

As has been true in the past; this year's 20 hour project activities encompassed a wide range of research topics. All of the 1994 projects were conducted during the spring through summer months. The following is a brief chronological summary:

John Beaver, a Ph.D. candidate in the CSU Electrical Engineering Department, collected multiparameter radar data when precipitation occurred along the beam path between CSU-CHILL and the NASA Advanced Communications Technology Satellite (ACTS). This satellite is in geosynchronous orbit; two on-board microwave beacons transmit test signals on frequencies of 20 and 27 GHz. Beaver is using the CSU-CHILL data to relate the microphysical characteristics to the associated attenuation effects noted in the transmissions received from the satellite. Two cases of particular interest were recorded: In one, stratiform rain containing a radar bright band was present. In the second case, fairly intense convective rain intruded into the ACTS beam path. In both cases, excellent agreement was obtained between the observed satellite signal attenuation and that predicted from the radar data.

For the second year, Prof. Tom Holtzer, head of the CSU Entomology Department, directed a study of the annual spring migration of Russian Wheat Aphids into the Colorado high plains. A specially instrumented helicopter from the University of Illinois was once again used to make in flight captures of live insects. Weather conditions were favorable during this year's efforts, and successful insect captures were made on a number of flights. On two occasions, the helicopter made insect collections while transiting precipitation - free fine line echoes observed with CSU-CHILL.

Prof. John Hallett, of the University of Nevada Desert Research Institute (DRI), sought radar observations of evolving thunderstorm anvils. He was interested in using a sequence of RHI scans to make inferences about the flux of precipitation particles from the updraft region of a thunderstorm into the divergent anvil outflow. Extended sequences of RHI data were collected for Prof. Hallett during several thunderstorm events of varying intensity levels.

Peter Clement, an Air Force-sponsored M.S. student in the CSU Department of Atmospheric Science, collected multiparameter radar data during thunderstorm passages over a network of raingages in the greater Denver area. The combined multiparameter radar and raingage data sets will be used to evaluate various rainfall estimation algorithms used in the NWS WSR-88D radars. Data analysis is well underway and a M.S. thesis will be completed by June 1995.

V. N. Bringi supervised another project related to WSR-88D products. Prof. Bringi's interests lay in comparing rain rates deduced from CSU-CHILL propagation differential phase (ϕ_{dp}) data to rain rates derived from conventional reflectivity observations recorded by the Denver WSR-88D. It should be noted that some of the data collected in this project have been used by Prof. Bringi to refine the calibration constant for the CSU-CHILL system. This calibration alteration was based on the reflectivity adjustment needed to bring the rain rate estimations from co-polar power measurements (Z_h, Z_{dr}) into agreement with those based on ϕ_{dp} data.

A secondary thrust of Prof. Bringi's project was hail identification and size characterization using multiparameter radar data. CSU-CHILL data were collected during 3 episodes of confirmed, damaging hail. These data are currently being jointly analyzed by Prof. Bringi, Ph.D. student Scott Bolen, and members of the CSU-CHILL staff.

Finally, Mr. Ray McAnelly, a research associate in the CSU Atmospheric Science Department, continued his efforts to document the evolution of groups of individual thunderstorm cells into larger scale convective systems. Unfortunately, the desired "upscale" evolution only took place during a single operation when a squall line developed within 100 km of the CSU-CHILL radar.

b. Educational Support

As noted earlier, a major aspect of the facility's education support in 1994 was in connection with the Research Experiences for Undergraduates (REU) project conducted by Prof. Chandrasekar of the CSU Electrical Engineering Department. The majority of the 8 students in this group were between their junior and senior years. To provide a common introduction to a number of fundamental aspects of meteorological radar systems, the following sequence of lectures were presented at the CSU-CHILL facility during the initial weeks of the REU program:

Presenter	Introductory Topic
P. Kennedy (CSU-CHILL)	general applications of radar meteorology
E. Mueller (CSU-CHILL)	overview of the CSU-CHILL system
C. Frush (NCAR)	radar hardware design considerations
J. Keeler (NCAR)	digital signal processing
F. Pratte (NCAR)	radar system calibration considerations
J. Turk (CSU EE)	mwave propagation, passive remote sensing
D. Breed (NCAR)	airborne cloud physics instrumentation
C. Mueller (NCAR)	Doppler radar nowcasting applications
M. Politovich (NCAR)	radar detection of wind shear hazards
M. Randal (NCAR)	digital technology in radar receivers

Each of the REU students participated in a research project during the course of the summer. Also, each student was assigned to an Electrical Engineering Department faculty member who served as a research mentor. The research projects in which the students participated were:

Student(s)	Project Title
D. Arko	Radar data visualization using Matlab
M. Padialla	Analysis of ACTS and CSU-CHILL data
X. Le	Neural network usage with radar data sets
R. Russel and R. Etcitty	Introduction to multiparameter radar
B. Preston	Design and testing of a mobile raingage
D. Gunderson and T. Velaquez	Visualization of multiparameter data

During 1994, the facility continued to provide classroom support for both the CSU Atmospheric Science and Electrical Engineering Departments. In the spring semester, Prof. Rutledge taught AT 741 (Radar Meteorology) to a class of 8 graduate students. Pairs of these students analyzed four cases from the facility's data archive; their results were presented at the end of the course in a mini-conference format. Through these efforts, the students gained familiarity with various radar data manipulation software packages including RDSS, REORDER and CEDRIC. The class also visited the radar site on two occasions to learn about radar operations and radar engineering principles. During the Fall semester, Prof. Rutledge taught AT

652 (Remote Sensing). The twenty-five students enrolled in this class visited the CSU-CHILL site to obtain a technical overview of the radar system. The interpretation of a sample of CSU-CHILL multiparameter data was used as the basis for part of their final examination.

In the Electrical Engineering Department, the CSU-CHILL facility provided educational support in several ways. During the spring semester, Prof. V. N. Bringi taught a course entitled Time Harmonic Electromagnetics (EE 642). A number of radar-related topics were covered in this course, including Doppler and dual polarization theory and computational algorithms used in the CSU-CHILL signal processor. The three students in the class were introduced to various hardware components of the radar system during a tour of the site. They also worked with several samples of CSU-CHILL data recordings.

Radar-related research activities by Electrical Engineering students at both the graduate and undergraduate levels continued throughout 1994. Scott Bolen is examining several techniques for using multiparameter radar data to characterize convective storms. As noted in the earlier discussion of 20 hour projects, John Beaver is correlating various 20 and 27 Ghz attenuation effects noted in the ACTS beacon data to CSU-CHILL multiparameter observations of precipitation along the ACTS beam path. Both Scott and John are Ph.D candidates. At the undergraduate level, Chad Wangsvick completed a senior project in which he used CSU-CHILL reflectivity measurements to predict the expected magnitude of ACTS signal attenuation. Two additional senior projects are currently underway utilizing CSU-CHILL data collected during a pair of June 1994 severe storm events.

c. Technical Developments

i. Dual Channel Upgrade

As has been mentioned in various reports, the primary radar upgrade currently proposed for the CSU-CHILL system is the addition of a second transmitter and receiver, along with a dual channel rotating joint. This system will allow full utilization of the superb electrical properties of our new antenna, such as superior isolation of the two orthogonal linear polarizations. Previously, with the switchable ferrite circulator, it was only possible to maintain about 20 to 23 dB of channel isolation. In this new system, the channel isolation exclusive of the antenna will be on the order of 60 dB and thus the full isolation capability of the antenna will be utilized.

A second channel from a FPS-18 military radar was acquired last May from the National Severe Storm Laboratories (NSSL). This channel has been modified by changing the high voltage rectifiers (tubes) to solid state. The receiver has been completely modernized. A circulator duplexer has replaced the former system of ATR/TR duplexers. In addition, the low noise amplifier, first mixer, intermediate frequency amplifiers, and second detectors have been replaced. A new input board for the SP-20 processor has been purchased and modified to support the second mixer, video amplifiers and analog to digital conversion functions in the second channel. The new transmitter channel has been installed, wired, and is currently being checked out.

To provide space for the second transmitter and receiver, the area of the electronics van previously devoted to the signal processing and control computers has been vacated. The computers have been moved to a new 48 foot semitrailer user van. Additional information on the new user van is provided in the following section of this report.

A new dual channel rotary joint was purchased in conjunction with NCAR, who also bought the same joint for their S-pol radar. The old horizontal rotary joint has been removed and will be reused as a vertical axis joint. Installation of the dual channel joint is nearly complete. Once this joint is installed, the radar will be operational on an interim basis in its former configuration while the remainder of the dual channel conversion is completed.

The waveguide runs for the new system, including the sections within the transmitter van, between this van and the radome, and on the antenna proper, have not yet been installed. The present schedule calls for the second channel to be transmitting into a dummy load by the end of January, and operating through the antenna by the middle of February. Both of these schedules assume that no large unknown complications arise.

The CSU-CHILL's prototype pulse compression capabilities have been modified for use in the dual channel configuration. The modulator which develops the phase encoding sequence has been altered to permit different codes to be used on alternate transmitter pulses. Under this scheme, the effects of echo obscuration due to range folding will be reduced since the phase code of the second trip returns will differ from that used in the most recent transmitter pulse.

Another pulse compression option that is under consideration is the use of complementary codes and the same polarization on consecutive transmitter pulses. By using complex addition between the two returned signals after decoding, the range sidelobes will be

On 22 August 1994, time-series data was collected over a storm to the northeast of the CSU-CHILL radar. The antenna position was pointed at the core of the storm. The attenuators were set to 36 dB and samples were taken for a 1 *ms* long transmit pulse with and without phase-coding.

Figure 2 shows the standard deviation in estimates of 10 log $\overline{P}$ as a function of number of samples per estimate at a range of 51.75 km. The solid-line represents standard deviation at 150 *m* range-resolution (no pulse-compression) and the dotted-line represents the standard deviation at 150 *m* spacing with pulse-compression (5 gate averaging was performed to bring the range-resolution to 150 *m*). Note the lower values for standard deviation for the data derived from pulse-compression. This allows for accurate measurement in a short data acquisition time.

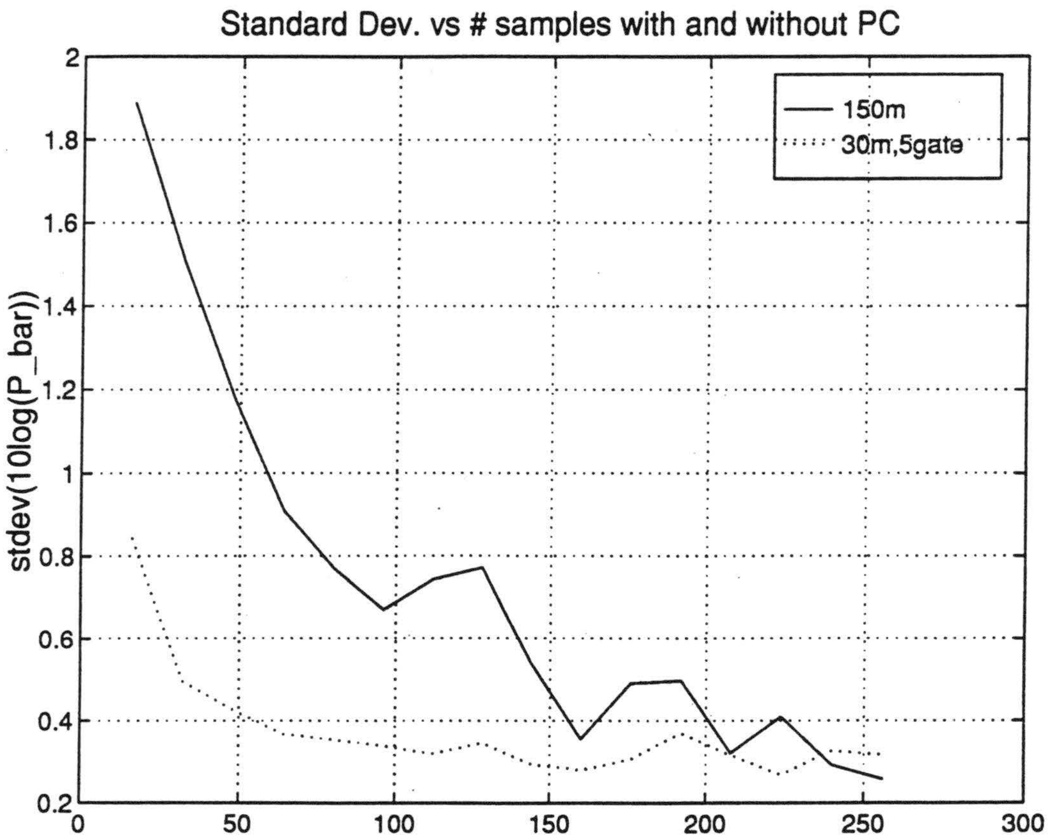

Figure 2

ii. Dual Channel Signal Processing and Upgrades to the Radar User Environment

A second Analog Input card for the SP20 signal processor was acquired. This will allow the independent digitization of the second receiver's data stream. A fast transfer switch just after the LNA's will allow the two receivers to function either as Horizontal and Vertical receivers or as copolar and crosspolar receivers. This switch will be under control of the SP20 program. The second receiver will double the data rate into the SP20 as approximately twice the number of covariance calculations are desired. This will place a duty cycle calculation limit which means that in the near term, only about half the normal number of gates will be processed (~500). A general upgrade to the signal processing system is planned over the next 2 years. Under the next generation signal processing system, this gate number restriction will be removed.

A new 48 foot semi-trailer was acquired to serve as a new computer room and operations area. The interior of the trailer was completely redone to provide 28 feet of office quality space for the operations area and 19 feet of machine room. Four to six inches of insulation are provided on all sides. A raised floor was installed throughout to allow additional insulation and concealed wiring and heating/cooling ducts. Separate all weather heater/cooling units were installed, one for each room in the trailer. Ambient noise was minimized through the use of acoustical treatments on the ceilings and walls. The receiver, signal processor, and computer systems were moved into the machine area to make room for the second transmitter which was installed in the radar trailer. This new arrangement was first tested in the Fall of 1994, and was found to work well.

3. Publications and Reports:

Aydin, K., V. N. Bringi, and L. Liu, 1994: Rainrate estimation in the presence of hail using S-band specific differential phase and other radar parameters. Accepted for publication in *J. Appl. Meteor.*

Bringi, V. N., L. Liu, P. C. Kennedy, V. Chandrasekar and S. A. Rutledge, 1994: Dual multiparameter radar observations of intense convective storms: The 24 June 1992 case study. *J. Meteor. Atmos. Physics,* in press.

Carey, L. D., and S. A. Rutledge, 1994: Multiparameter and dual-Doppler radar study of the kinematic and microphysical evolution of lightning producing storms in northeastern Colorado. *Preprint, 1994 Global Circuit-Lightning Symposium,* AMS Annual Meeting, Nashville, TN, January, 1994.

Carey, L. D., and S. A. Rutledge, 1994: A multiparameter radar case study of the microphysical and kinematic evolution of a lightning producing storm. *J. Meteor. Atmos. Phys.*, in press.

Kennedy, P. C., and S. A. Rutledge, 1994: Dual-Doppler and Multiparameter Radar Observations of a Bow Echo Hailstorm. *Mon. Wea. Rev.*, in press.

Kennedy, P. C., N. E. Westcott, and R. W. Scott, 1995: Reply to Comments on "Single Doppler radar observations of a mini-supercell tornrnadic thunderstorm. Mon. Wea. Rev., 123, 235-238.

Liu, L., V. N. Bringi, V. Chandrasekar, E. A. Mueller, and A. Mudukotore, 1994: Analysis of the copolar correlation coefficient between horizontal and vertical polarizations. *J. Ocean. Atmos. Tech.*, in press.

McAnelly, R. L., J. E. Nachamkin, and W. R. Cotton, 1994: The development of an MCS in a quasi-tropical environment in northeastern Colorado. AMS Sixth Conference on Mesoscale Processes, 17-22 July 1994, Portland, OR.

Mudukotore, A., V. Chandrasekar, and E. A. Mueller, 1995: The differential phase pattern for the CSU-CHILL radar antenna. Submitted to *J. Atmos. and Oceanic Tech.*

Nachamkin, J. E., W. R. Cotton, and R. L. McAnelly, 1994: Analysis of the early growth stages of a High Plains MCS. Submitted to the AMS Sixth Conference on Mesoscale Processes, 17-22 July 1994, Portland, OR.

Rauber, R. M., M. K. Ramamurthy, and A. Tokay, 1994: Synoptic and Mesoscale Structure of a Severe Freezing Rain Event: The St.Valentine's Day Ice Storm. *Wea. and Forecasting*, **9**, 183-208.

Paper presented at the COST-75 International Seminar on Advanced Weather Radar Systems, held at Brussels, Belgium, 20 -23 September, 1994:

Bringi, V. N., E. A. Mueller, D. A. Brunkow, V. Chandrasekar, S. A. Rutledge, and A. Mudukotore: The CSU-CHILL S band dual polarization Doppler weather radar system: Recent improvements and planned enhancements.

Papers presented at the National Radio Science Meeting, held at Boulder, Colorado, 3 - 7 January 1995:

Beaver, J., J. Turk, and V. N. Bringi: K_a-band propagation studies using the ACTS propagation terminal and the CSU-CHILL multiparameter radar.

Bringi, V. N., L. Liu, K. Aydin, and S. Bolen: Multiparameter radar measurement of rainfall in hailstorms: A case study".

Dobaie, A., and V. N. Bringi: Dual Multiparameter observation of precipitation.

4. Report on Cost Sharing Activities

The following describes cost sharing expenditures at CSU for the five years of the Cooperative Agreement.

	Cumulative through 4/14/94	YEAR 4 4/15/94-2/1/95	Cumulative through 2/1/95
Building and site prep.	$188,275	$0	$188,275
Freight, Transport, ins., crane	15,940	0	15,940
Furniture and grounds	17,722	556	18,278
Materials, parts, supplies, paint	27,082	6,612	33,694
Salaries and services	126,398	29,733	156,131
Telephone and postage	5,839	23	5,862
Vehicles and fuel	2,990	464	3,454
Equipment	156,553	58,051	214,604
CSURF lease (equipment)	351,543	35,245	386,788
Indirect cost @ 45%[a]	64,473		64,473
Indirect cost @ 44.7%[a]	15,635	16,464	32,099
TOTAL	$972,450	$147,148	$1,119,598
Estimate 2/1/95 - 4/14/95	0	18,441	18,441
TOTAL	$972,450	$165,589	$1,138,039

(a) Indirect cost base excludes building, furniture, equipment and CSURF lease.

Appendix A

Letters Associated with Radar Users

22 July 1994

Prof. Tom Holtzer
Head, Department of Entomology
C134 Plant Science
Colorado State University
Ft. Collins, CO 80523

Dear Tom:

The purpose of this letter is to close out our files regarding the 20 hour project that you recently completed using the CSU-CHILL facility. According to our records, radar operations in support of the Russian Wheat Aphid project were conducted on the following dates:

May 1994:
25, 26, 27, 28, 29, 30 ,31
June 1994:
1, 2, 3, 7

As you know, members of your research group took 35 mm slide photographs of the radar display as the data were being collected. Also, the digital radar data recorded on magnetic tape during these operations have been archived and are available for re-display or additional post analysis.

Thank you for utilizing the CSU-CHILL facility in your research activities. Feel free to contact me with any questions that may arise regarding the radar data.

Sincerely,

Patrick Kennedy

Patrick C. Kennedy
CSU-CHILL Facility manager
(303) 491-6248

22 July 1994

Prof. John Hallett
Desert Research Institute
University of Nevada-Reno
5625 Fox Avenue
Reno, NV 89506

Dear John:

The purpose of this letter is to close out our files regarding the 20 hour project that you recently completed using the CSU-CHILL facility. According to our records, radar operations in support of the Thunderstorm Anvil Outflow project were conducted as follows:

Date	Remarks:
5/19/94	Small storm just N of CHL moving off to the N. Small anvil present at start of recording. Interesting boundary layer echo "stairsteps" on S flank of the storm. At least one photograph taken of this storm from the radar site.
5/23/94	Approximately 1 hr of data on storm near Sterling CO (~100 km range from CHL).
6/3/94	Fairly good RHI coverage over ~1 hr period of rapidly developing severe storm NE of CHL. Several cloud photographs taken of the storm from the radar site.

I propose that we place the data from these 3 operations onto a single 8mm tape written in UF. Please advise if this approach will suit your needs; if so we will prepare the tape and mail it to you.

Once you have the opportunity to examine the data, feel free to contact me if any questions arise. Also, we are always interested in our user's evaluation of the CSU-CHILL facility's ability to meet their data needs. We greatly appreciate receiving "feedback" letters from users regarding data quality as well as the general performance of the radar and it's staff.

Sincerely,

Patrick Kennedy

Patrick C. Kennedy
CSU-CHILL Facility manager
(303) 491-6248

4 January 1995

Mr. Peter Clement
Department of Atmospheric Science
Colorado State University
Ft. Collins, Colorado, 80523

Dear Pete:

I'm in the process of closing out our files on the 20 hour projects which were conducted at the CSU-CHILL facility during 1994. According to our joint records, the operations chronology for your project was as follows:

Date	Remarks
2 June	Storms over DEN network, ~1" totals; possible case study day
3 June	Damaging hailstorm in Boulder, under .5" in DEN network
20 June	Heavy rain, flooding, hail in Ft. Collins area; case study day
21 June	Storms stayed in mountains, case study day with -88D data
22 June	No event case
15 July	Storms too far south to be of interest
27 July	Surveillance of Cu line; no storm development
1 August	Storm too far southwest to be of interest
3 August	Isolated storms, all rain totals under .5"
8 August	Very isolated storms under .25" totals
11 August	Storm in W DEN, ~.5" totals; under 1" in Boulder area
12 August	Very isolated storms, under .25" totals
31 August	Some small hail, ~.75" total in parts of DEN area

I believe that UF tapes for the cases of primary interest have been supplied to you since the end of your project. Please let me know if there are additional data sets that should be converted to UF, or if any data questions in general arise. Finally, we are always interested in receiving feedback from the users of the CSU-CHILL facility. A short letter summarizing your perceptions of the performance of the radar system and its staff, as well as any thoughts on the quality of the data recordings, will be most welcome.

Sincerely,

Patrick Kennedy

Patrick Kennedy
CSU-CHILL Facility Manager
(303) 491-6248

4 January 1995

Professor V. N. Bringi
Department of Electrical Engineering
Colorado State University
Ft. Collins, Colorado, 80523

Dear Dr. Bringi:

I'm in the process of closing out our files on the 20 hour projects which were conducted at the CSU-CHILL facility during 1994. According to my records, the primary radar operations conducted in support of your Summer 1994 project were as follows:

Date	Remarks
3 June	Damaging hailstorm in northeastern Boulder
24 July	Damaging hailstorm at Raymer, Colorado
25 July	~Golfball sized hail fall confirmed by the mobile raingage crew near Brush Colorado

Field format copies of the radar data recorded during these three hail events have been supplied to your research group (Scott Bolen). I look forward to our collaborative analyses of these data sets.

Sincerely,

Patrick Kennedy

Patrick Kennedy
CSU-CHILL Facility Manager
(303) 491-6248

4 January 1995

Mr. Ray McAnelly
Department of Atmospheric Science
Colorado State University
Ft. Collins, Colorado, 80523

Dear Ray:

I'm in the process of closing out our files on the 20 hour projects which were conducted at the CSU-CHILL facility during 1994. According to our joint records, the operations chronology for your project was as follows:

Date	Remarks
25 July	Small cluster of severe storms near Ft. Morgan
1 August	Generally disorganized storms associated with a cold front
8 August	Developing squall line
12 August	Widely scattered storms over eastern Colorado

I know we have already supplied you with a UF version of the data from the case of primary interest (8 August). Please let me know if there are additional data sets that should be converted to UF, or if any data questions in general arise. Finally, we are always interested in receiving feedback from the users of the CSU-CHILL facility. A short letter summarizing your perceptions of the performance of the radar system and its staff, as well as any thoughts on the quality of the data recordings, will be most welcome.

Sincerely,

Patrick Kennedy

Patrick Kennedy
CSU-CHILL Facility Manager
(303) 491-6248

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
RESEARCH APPLICATIONS PROGRAM
P.O. Box 3000 • Boulder, Colorado 80307-3000
Telephone: (303) 497-8488 • FAX: (303) 497-8401

6 May 1994

Dr. Stephen Rutledge
Department of Atmospheric Sciences
Colorado State University
Fort Collins, CO 80523

Dear Dr. ~~Rutledge~~ Steve:

WISP94 ended up being very successful with all the scientific objectives being achieved, with over 15 wave clouds and 20 winter storms being studied during the two month field effort. A large part of our success can be attributed to the excellent support provided by the CSU CHILL radar facility. Pat Kennedy and the rest of your support staff worked hard to make the project successful. CHILL was was ready for operations on the requested date, and collected data on nearly every storm studied during the project.

Thanks for your excellent support and I look forward to working with your staff in future field programs.

Best regards,

Roy M. Rasmussen

Roy M. Rasmussen
Chairman, WISP Scientific Steering Committee

Colorado State University

Department of Entomology
Fort Collins, Colorado 80523
(303) 491-7860
FAX: (303) 491-0564

July 06, 1994.

Pat Kennedy
CHILL Radar Site
Colorado State Univ.

Dear Pat

I'd like to thank the crew at CHILL for your asssistance with this year's Russian Wheat Aphid helicopter sampling. We've started to evaluate the insect material, and this year has turned out to be a sucess. We recovered RWA from a variety of altitudes and many of the atmospheric layers identified by the CHILL site. We have yet to complete the lipid anaylsis on all of the sampled individuals, but so far the results are quite promising with regard to publication.

We were impressed by the preformance of both the radar and the crew. We also greatly appreciate the CHILL crew coming in over the wekends, especially the Memorial Day Weekend. As you know, we were limited in the time we had for sampling, and the availability of the CHILL crew and equipment was very much appreciated.

The data from the radar runs was interesting for a number of reasons, and I'll be out this fall to further review some of it. I believe we may find some strong correlations between insect captures and certain atmospheric conditions we observed with the CHILL, especially the strong thermals we saw in the afternoons. I plan to present some of the data on the relationship of the observed atmospheric layers and aerial insect distribution at the National meeting of the Entomological Society of America this December. There will be at least two other presentations by CSU and University of Illinois researchers at the same meeting utilizing some aspects of the CHILL radar data.

Thanks again for all you assistance this year.

Sincerely,

Ian MacRae
Research Associate
Dept. of Entomology

Colorado State University

Department of
Atmospheric Science
Fort Collins, Colorado 80523
(303) 491-8360
FAX: (303) 491-8449

(303) 491 8341

January 9, 1995

Dr. Pat Kennedy
CSU-CHILL Facility Manager
Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado 80523

Dear Pat:

This letter is in response to your letter of 4 January 1995 concerning your closing of files on our 20-h CSU-CHILL project for 1994 and your request for "feedback" letters. As you indicated, we collected data for four days in 1994: 25 July, and 1, 8, and 12 August. The 8 August 1994 case ended up being the only one of high interest to us. We have performed a case overview using the CSU-CHILL UF dataset you provided for this case, and we found no problems with the data (please let us know if a velocity correction should be applied as in the previous seasons). This case features the growth of a multi-cellular convective ensemble into a broken, curved squall line. During this evolution, the ensemble undergoes an apparent meso-β-scale convective cycle prior to its primary development into the mature MCS stage. Since documenting this type of evolution was the primary field objective, we are quite satisfied with the operations. We will proceed with in-depth dual-Doppler analysis of this case in conjunction with WSR-88D data from Denver, which we have also obtained. We see little chance of needing data for the other three days.

Our 1994 season completes the third and final season of these 20-h projects. In total, we have five good cases of MCS development, one from 1992, three from 1993, and the case described above from 1994. Although we hoped for at least one good case of full upscale development into a mesoscale convective complex (MCC) within dual-Doppler range, such development never occured quite within range. Nevertheless, the datasets collectively cover developing MCSs of less-than-MCC scale, with a wide variety of convective substructures, and they all display early meso-β-scale convective cycles. Our primary research objective is in documenting the dynamic link between the burst of latent heating associated with the β-scale convective maximum and the subsequent upscale development to mature MCS stage. We are currently writing a manuscript for *Monthly Weather Review* which focusses on the 1992 case and includes preliminary results from one of the 1993 cases. The other three cases are under ongoing investigation by myself and Jason Nachamkin. Jason also will investigate the dynamics of upsacale development in these cases with the RAMS numerical model.

In summary, we are very pleased with the opportunity to participate in the 20-h CSU-CHILL projects over the last three years. The datasets are of high quality, meet most of our primary field objectives, and are undergoing continued dual-Doppler analysis in conjunction with Mile High and WSR-57 radar datasets from Denver. As was the case in 1992 and 1993, we found the CSU-CHILL staff to be most cooperative in all phases of our 1994 project.

Sincerely,

Ray L. McAnelly

Ray L. McAnelly
Research Associate

Colorado State University

Department of
Atmospheric Science
Fort Collins, Colorado 80523
(303) 491-8360
FAX: (303) 491-8449

(303) 491-8545
January 13, 1995

Dr. Steve Rutledge
Director, CHILL Radar
Atmospheric Science Department
Colorado State University
Fort Collins, CO 80523

Dear Dr. Rutledge:

This letter is in reference to our use of the CSU-CHILL facility for a 20-hour project from June to August 1994. I would like to provide feedback on the quality and performance of the facility's operations for our project, the performance of the radar, and special acknowledgment to the facility's staff.

Operations for our project. The facility's staff had to juggle a number of different projects, with each customer pursuing areas of study, resulting in different scan strategies and modes of operation. However, the staff continually sought and provided the ever elusive win-win arrangement, which could appease all customers' concerned. This necessary flexibility did not interfere with our particular project, but I would recommend caution in accepting larger number of diverse projects. Most of our periods of data collection extended beyond the normal operating hours. To alleviate the long summer hours, you may want to consider summer shifts to cover the most likely times of convection 1400-1900L.

Performance of the radar. The radar met or exceeded all of our expectations. The radar's unique multiparameter capabilities, specifically Zdr and Kdp, enabled the use of additional techniques to determine rain rates and indicate presence of frozen hydrometeors. The recent improvement in the radar antenna has increased the quality and confidence in the data provided. As an aside, one interesting case, we observed this summer, was the locating of an ongoing forest fire using the Zdr field – an interesting case for the forest service.

The facility's staff. We thoroughly enjoyed working with the CSU-CHILL's staff. Their knowledge of the radar operations, multiparameter variables used, radar data format, and programs used to process the data, was absolutely essential for us to collect, process, and interpret the data necessary for our research. I would like to acknowledge both Pat Kennedy and Dave Brunkow for their assistance and patience throughout our 20-hour project.

Sincerely,

Thomas B. McKee
Professor

opb
cc: Peter Clement, Capt.

Appendix B

Letters From Members of the CSU-CHILL Radar Advisory Committee

UNIVERSITY OF CALIFORNIA, LOS ANGELES UCLA

BERKELEY · DAVIS · IRVINE · LOS ANGELES · RIVERSIDE · SAN DIEGO · SAN FRANCISCO · SANTA BARBARA · SANTA CRUZ

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April 9, 1994

Professor Steve Rutledge
Dept. of Atmospheric Sciences
Colorado State University
Fort Collins, CO 80523

Dear Steve,

This is my own follow-up letter concerning our recent RAC meeting at the CHILL site on 8 April 1994. It was a pleasure to hear and evaluate your accomplishments during the past year and over the entire duration of the Cooperative Agreement with NSF. CSU's record in maintaining and upgrading the radar as well as overseeing its implementation in research and education is a modern day success story. I have been especially impressed with the mileage you have attained with the 20-hr research projects. As a member of a competing university, I have to admit to be envious of your success. In fact, compared with NCAR, your facility has better served the university community as an educational tool. Moreover, you will soon have **the state-of-the-art multiparameter radar** that will be in exceedingly high demand as a research tool.

The following comments merely serve as minor suggestions that you should consider over the next few months:

1. In assessing CHILL's impact on education, I believe some attempts should be made to quantify its effectiveness There are various ways to do this -

    i. Soliciting written comments by the students during course evaluations specifically addressing the impact of the radar.

    ii. Tracking your graduate students to see if exposure to the CHILL radar made an impact in future job opportunities. This may be too early to implement now since your students have only recently used the radar.

    iii Comparing your graduate applications over the past few years to see if the quality (GRE and GPA scores) and quantity of entering students wishing to work in the area of radar meteorology has increased.

2. In the future, you should consider inviting high school teachers

to a workshop. This may be fairly simple if you coordinate with various UCAR programs. I believe Project LEARN invites teachers to Boulder, accordingly, you would only need to bus them up to Greeley for an all-day session.

I would also suggest that you advertise your 20-hr research projects at the upcoming UCAR Members' Reps/Heads & Chairs meeting in the Fall. You may also want to submit a short article to the UCAR Newsletter.

3. I agree with the rest of the RAC that an effective case has been made for a renewal of the 5-year Cooperative Agreement with NSF. I strongly endorse continued funding by NSF at approximately the same levels for the next 5-year agreement. NSF must be pleased with the commitment by CSU for significant cost-sharing (cash support estimated to be $100,000/year).

   For this next proposal, I recommend that the CHILL radar continue to collect high quality research and educational case studies in Colorado. However, to truly be a national facility and also to indoctrinate the radar as part of the fleet of high-quality research radars, future deployments in other geographic locations should be considered. In particular, I think there will be a growing demand by the microphysical community wishing to see the radar deployed in a semi-tropical climate to study warm-rain processes. Although the radar is more difficult to deploy, its unique capabilities should be tested at other sites.

I, again, wish to compliment you and your staff for the excellent job as caretakers of the CHILL radar. The joint efforts of the Departments of Electrical Engineering and Atmospheric Science are truly exemplary. You have convinced the community (and responded to any critics) that a national facility can be successfully maintained as a research and education tool at a major university. Good luck in your future endeavors.

Sincerely,

Roger

Roger M. Wakimoto
Professor of Meteorology

Colorado State University

Engineering Research Center
Foothills Campus
Fort Collins, Colorado 80523

April 11, 1994

Dr. Dusan Zrnic, Chairman
CSU-CHILL Radar Advisory Committee

Dear Dr. Zrnic:

Upon your request, it is my pleasure to report on the CSU-CHILL activities in the past four years, as we discussed last Friday in Greeley. I am very impressed with the on-going and past activities of the CSU-CHILL radar since it is located near Greeley.

The radar is operated by competent personnel. At least three faculty, Profs. Rutledge, Bringi and Chandrasekar, are working in close collaboration for the development and use of the facilities. Several post-docs and research associates complement the research programs. Hardware and software problems are also tackled by competent scientists such as Dr. Muller and Kennedy.

Most projects lead to refereed journal publications, which reflects on the top quality of the research. Several Ph.D. dissertations also centered on radar use and developments. The 20 hour projects are helpful for testing new initiatives and attract outside scientists.

The new antenna and upcoming dual channel capabilities should lead to significant technological improvements. The radar is a unique platform for testing Dr. Bringi's ϕ_{DP} precipitation algorithm. At Greeley, the radar is also uniquely located for the analysis of winter storms, severe thunderstorms in complex terrain, melting layer, and possibly tornadoes.

The budget is well-distributed among personnel, hardware and software. The CSU matching contribution is substantial and expected to be maintained. The resources are carefully used to optimize the scientific output of each component purchased.

In summary, I am impressed with the on-going and planned activities at the CSU-CHILL radar facility. There are true feelings of competence and friendly collaboration among research scientists that can only foster significant contributions to radar technology and atmospheric sciences.

Sincerely,

Pierre Julien

Pierre Y. Julien, Ph.D.
Assoc. Prof. of Civil Engineering

cc. S. Rutledge

Appendix C

Summary of Greeley Data Collection Activities Through 01/15/95

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	Radar observations of insect migration.
Aydin	June	Multi-parameter radar hail detection.
Bringi	July	" "
McAnelly	July - August	Upscale evolution of mesoscale convective systems.

<u>1994</u>

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 McKee	Multiparameter obs of storms over Denver 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

Appendix D

1994 CSU-CHILL Newsletter

CHILL RADAR NEWS

from

Colorado State University

Fourth Edition
September 1994

Overview
(Steven Rutledge, Scientific Director)

This is the fourth 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 activities of the CSU-CHILL facility, including research, education, and refurbishment activities. In April 1990 Colorado State University was awarded a five-year Cooperative Agreement from the National Science Foundation 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 Colorado State University. Co-Principal Investigators for the cooperative agreement are Profs. Steven Rutledge and Stephen Cox in the Department of Atmospheric Science and Prof. V. N. Bringi in the Department of Electrical Engineering. Recently, we have submitted a proposal to the NSF for a second five year Cooperative Agreement, to begin in April 1995.

The past year has been a busy period for both research and education projects. The use of the CSU-CHILL radar is granted by the National Science Foundation after review by the NSF Facilities Advisory Committee and Observing Facilities Advisory Panel. We supported two formal NSF projects during the past year as discussed below. For projects not needing more than approximately 20 hours of radar operational time, the Scientific Director of the CSU-CHILL facility can award the use of the radar for such projects, without OFAP/FAC review. In these projects, radar operational costs are provided by the Cooperative Agreement. We supported five 20 hour projects in the past year, as detailed in the following section. These small projects allow investigators to conduct highly focused research with the CSU-CHILL radar.

In December 1993, the new CSU-CHILL antenna, built by Radiation Systems, Inc. of Sterling, VA was installed. The antenna has performed flawlessly, and has met or exceeded all performance criteria. The new antenna has much lower sidelobes compared to the previous antenna, and matched beam patterns between horizontal and vertical polarization states, and very high cross-polar isolation. The latter quantity is critical to the measurement of LDR (linear depolarization ratio), which is now being recorded by the CSU-CHILL radar. Presently, the system limit on LDR is about -20 dB, being limited by the cross polar isolation of the fast ferrite polarization switch. To take full advantage of the isolation offered by the new antenna, which is about -35 dB, a second transmitter/receiver chain is presently being installed. By summer 1995, we expect to be operational with the dual channel system. Not only will this development increase the dynamic range of LDR, but will for the first time yield information on the full covariance matrix at a non-attenuating wavelength. We then expect to embark on a series of exploratory studies to investigate the additional insights into cloud microphysics afforded by the off-diagonal elements in this matrix.

Radar Operations Summary
(Pat Kennedy, Facility Manager)

The first program in which radar operations were funded by NSF was the Winter Icing and Storms 94 (WISP94). This year's efforts focused on the formation of ice particles in winter cloud systems. *In situ* data were recorded by the University of Wyoming King Air and NCAR Electra aircraft. Multiparameter observations of these cloud systems were made by the CSU-CHILL and NOAA K radars. CSU-CHILL also coordinated with NCAR's CP4 radar in the collection of dual Doppler data. A variety of winter precipitation situations developed during the 25 January - 25 March field season and the project ended with a useful data set.

The second NSF project was a Research Experience for Undergraduates (REU) program directed by Prof. V. Chandrasekar of the CSU Electrical Engineering Department (CSU EE). Twelve engineering students from 5 different states participated in this summer project. A series of introductory lectures and demonstrations for the students were held at the CSU-CHILL site. The lecture sequence was as follows:

1) Intro. to Radar Meteorology
   P. Kennedy (CSU-CHILL)
2) Intro. to CSU-CHILL Radar
   E. Mueller (CSU-CHILL)
3) Weather Radar Equation / Radar Design
   C. Frush (NCAR)
4) Intro. to Digital Signal Processing
   J. Keeler (NCAR)
5) Calibrations of Weather Radar Systems
   F. Pratte (NCAR)
6) Passive Microwave Remote Sensing
   J. Turk (CSU EE)
7) Instrumentation on the NCAR Sailplane
   D. Breed (NCAR)
8) Nowcasting with Doppler Radar
   C. Mueller (NCAR)
9) Doppler Radar and Air Safety
   M. Politovich (NCAR)
10) Design of Digital IF Receivers
   M. Randall (NCAR)

Along with the lectures, the students participated in real time radar operations at CSU-CHILL. During the later portion of the summer, the students returned to the main CSU campus to pursue individual projects under the supervision of Electrical Engineering Department faculty members.

The past year's 20 hour project activities covered a wide range of research interests. RHI data were taken through evolving thunderstorm anvils for Prof. John Hallett (University of Nevada Desert Research Institute). Prof. Hallett's study centered on the characterization of the flux of precipitation particles from the main storm updraft into the anvil outflow region. At least 2 of the 3 events observed in this project appear to hold analysis possibilities. For the second year, Prof. Tom Holtzer of the CSU Department of Entomology directed a project in which the insect-laden boundary layer was monitored by the CSU-CHILL radar. The target of interest was the annual spring migration of the Russian Wheat Aphid into Colorado. As before, a specially equipped helicopter from the University of Illinois captured airborne samples of the insect population. Successful catches of Russian Wheat Aphids were made on several occasions. Peter Clement, an Air Force MS student in the CSU Atmospheric Science department under the supervision of Prof. Tom McKee, designed a project to collect radar data during several heavy rain events in the greater Denver area. Pete's thesis work involves comparing several radar techniques for rainfall estimation, including multiparameter methods, to actual rain accumulations collected by a gage network operated by the Denver Flood Control District. Ray McAnelly, a Research Associate working with Prof. W. Cotton in the CSU Atmospheric Science Department, continued to direct an investigation into the early evolutionary stages of Mesoscale Convective Systems (MCS). Unfortunately, this year's late July - early August period provided relatively few days of organized convective activity at suitably close ranges to CSU-CHILL, so Ray ended up with only a single candidate case study day. Finally, John Beaver is studying the impacts of various atmospheric attenuation effects upon earth to satellite microwave communication paths as his Ph.D. thesis topic at CSU EE. He used CSU-CHILL data to characterize various forms of precipitation that passed through an experimental microwave link maintained between a geostationary satellite and a ground receiver located at the CSU-CHILL site.

Dual Channel Upgrade
(Gene Mueller, Senior Engineer)

The major advances in radar meteorology in the last decade and a half have been in the emergence of polarization variables. Such variables as differential reflectivity, differential propagation phase, and the correlation of horizontal and vertical polarization returns are called copolar variables. These variables use only the values of power return having the same polarization as the transmitted wave. Compared to copolar work, there has been some limited work in using depolarization, or cross polar information, like LDR. In theory, the scattering matrix and related matrices involving copolar and cross-polar variables provide all of the information in the radar return. It is believed that further advancement in meteorological radar will be found in these matrices and variables related to individual terms of these matrices. Thus it becomes important for a National Radar Facility like the CSU-CHILL, to have high quality capabilities in the area of polarization diversity.

The staff of the CSU-CHILL system, believing that the best possible implementation of a polarization radar is necessary, have embarked on radar upgrade which replaces the switchable ferrite circulator, which had an isolation limit of about 20 dB, with a dual transmitter/receiver system, which has an isolation exclusive of the antenna of 50 dB, for improved polarization capability, system characterization, and reliability. These dual channel plans have been extensively reviewed by the CSU-CHILL Radar Advisory Committee (RAC) and a positive recommendation has been made by the RAC to move ahead on this system.

The new antenna has an isolation between horizontal and vertical channels of 35 dB, and the measurement of cross-polar parameters becomes practical if the remainder of the system isolation can be made comparably large. The CSU-CHILL Facility is presently proceeding with the transition to the dual-channel configuration. A second FPS-18 transmitter, high-voltage power supply, and cooling system have been obtained from the National Severe Storms Laboratory. This transmitter is currently being updated with a solid state Intermediate Power Amplifier (IPA), and solid state rectifiers. A new transmit/receive circulator will be installed in place of the original FPS-18 TR/ATR system. The existing solid state frequency chain will be shared by both transmitters with minor additions to modulate the second channel. The two transmitters will be triggered independently by the signal processor.

A number of additional advantages will also be obtained by using this dual transmitter/receiver configuration. For example, it becomes possible to simultaneously transmit both horizontally and vertically polarized signals and to simultaneously receive the returns from both polarizations. This in turn allows better estimates of the copolar variables, such as differential reflectivity (Z_{dr}), zero lag correlation ($\rho HV(0)$), and differential propagation phase (ϕ_{dp}) to be made. In particular, a more direct estimate of the correlation between the signal returns in the two channels will be possible. It is probable that the $\rho HV(0)$ magnitudes calculated with the simultaneous H and V transmission scheme will increase from the estimates currently being made by the lag correlation algorithm.

Multiparameter Developments
(V. N. Bringi, CSU-CHILL Co-PI, and Pat Kennedy, Facility Manager)

New Antenna

The new antenna manufactured by Radiation Systems, Inc. was installed in December 1993. The reflector is identical to the 7.6m reflector manufactured by RSI for the TDWR program with additional 0.9m extension panels. The surface accuracy was specified to be better than 0.5 mm (rms) which was validated by RSI. The dual-polarized horn is a scalar horn with excellent rotationally symmetric primary patterns and very low cross-polar levels. The far-field copolar and cross-polar patterns were measured at RSI's test range in four ϕ-planes (0^o, 45^o, 90^o and 135^o) and at three frequencies (2.725, 2.8 and 2.875 GHz). The $\phi = 45^o$ and 135^o planes contain the four feed-support spars and the two waveguide runs. Fig. 1 shows the copolar and cross-polar patterns in the $\phi = 45^o$ plane. Note the excellent main lobe pattern match for excitation at the two ports, as well as the low sidelobe and cross-polar levels.

The integrated two-way cross-polar ratio (ICPR2) in the worst-case $\phi = 45^o$ or 135^o planes, defined as,

$$ICPR_2 = \frac{\int_{45^\circ \text{ plane}} F_{hh} F_{vh} \sin\theta d\theta}{\int_{45^\circ \text{ plane}} F_{hh} \sin\theta d\theta}$$

was computed to be ≤-35dB. Note that F_{hh} is the normalized copolar pattern while F_{vh} is the cross-polar pattern. In the principal ϕ planes (0^o, 90^o), the $ICPR_2$ was much less, as expected, by an additional 5 to 10 dB. We expect the new antenna to yield excellent linear depolarization ratio data for cloud physics applications.

The copolar correlation coefficient (ρ hv) measurement has improved significantly due to improved phase matching between the H and V polarizations across the main lobe. This was measured by the CSU-CHILL radar using a test horn transmitting a slant 45^o linear polarized signal, with the radar alternately measuring H and V-returns. Fig. 2 shows the phase difference

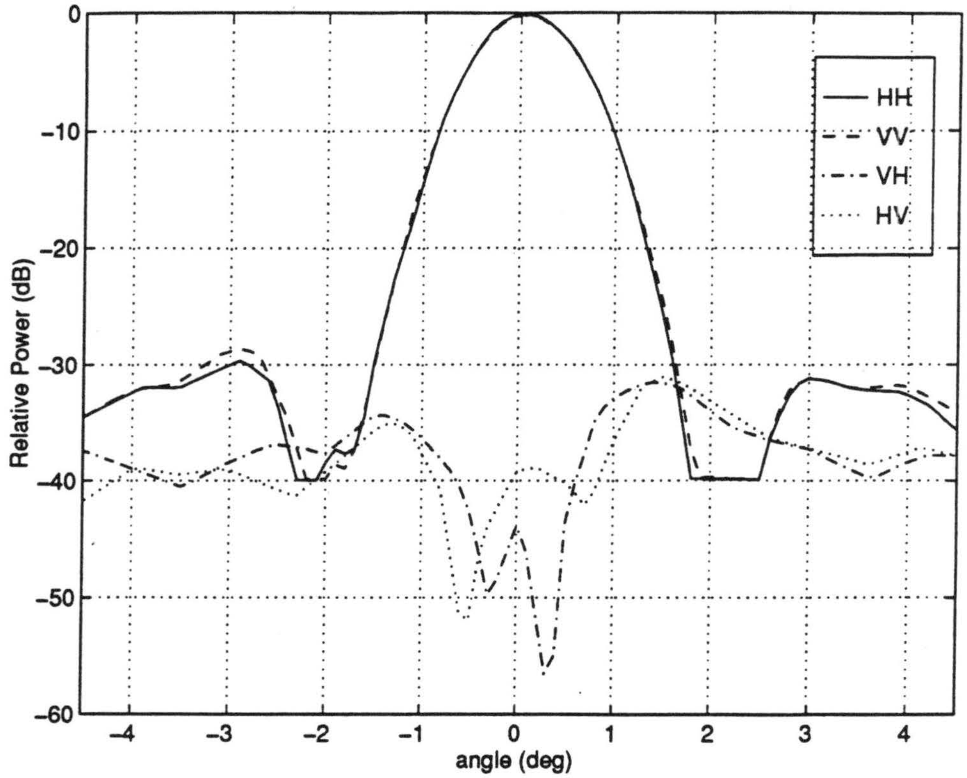

Figure 1: Co-polar and Cross-polar patterns in the $\phi = 45^o$ plane.

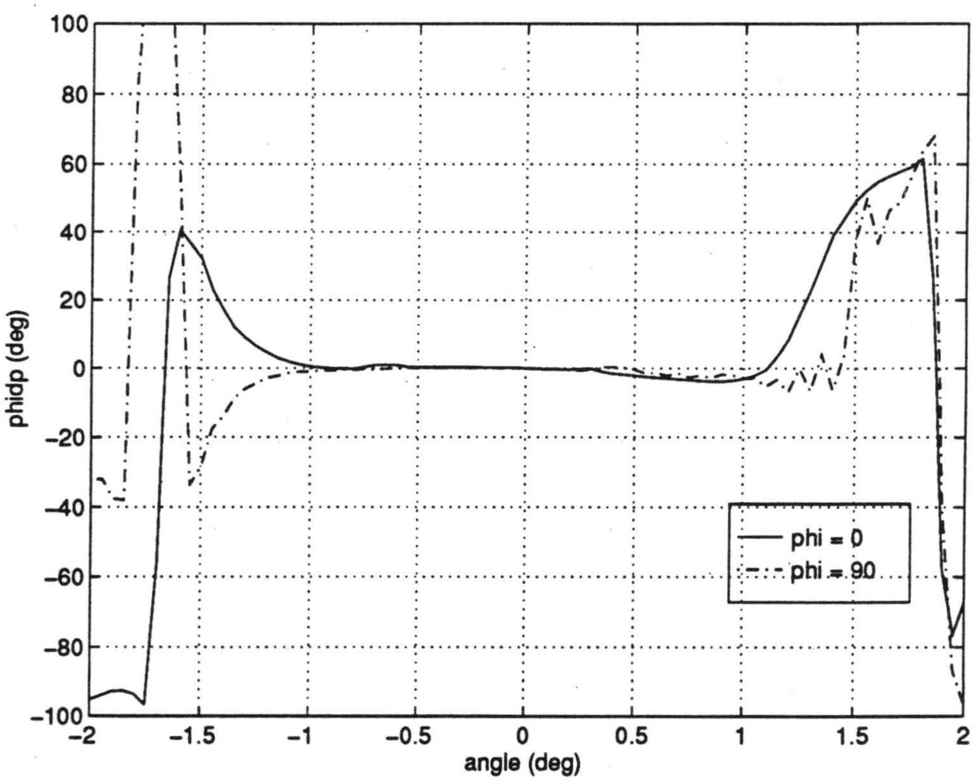

Figure 2: Phase difference pattern of the new antenna in the $\phi = 0$ and 90^o planes.

pattern in the $\phi = 0^{o}$ and 90^{o} planes. Note the nearly constant phase difference within the main lobe (|angle|<1.3^{o}), a notable improvement over the old antenna. The ρ hv data is useful for identifying clutter, anomalous propagation, partial beam blocking, three-body "hail" flares, and side-lobe generated artifacts in very strong gradient regions, all of which cause ρ hv to be generally <0.8. In most precipitation ρ hv is generally >0.9, and is particularly useful in identifying, for example, the base of the melting layer, and regions of rain mixed with hail.

For highly accurate Z_{dr} measurements, the copolar difference pattern within the main lobe should equal zero (dB) in all the ϕ-planes. The patterns measured at RSI indeed show that the pattern matching is excellent (|difference| < 0.1 dB) within the main lobe in all the 4 ϕ-planes (angular extent defined by |angle| $\leq 1.3^{o}$, power level down by 20 dB). In spite of excellent mainlobe matching, close-in sidelobe mismatches (near |angle| $\approx$ 1.75,^{o} power level down by ~27 dB) occasionally produce artificial Z_{dr} signatures in high gradient regions (spatial gradients $\geq$30 dB km^{-1}, near hail cells for example) which are easily identified by ρ hv which rapidly falls to below 0.5 in such side-lobe contaminated regions.

Time Series Analysis

For every transmitted pulse, the complex video sample (I+jQ) can be recorded in the time series mode of data acquisition. This mode is useful to evaluate signal fluctuations, and at times can be used to identify radar system problems which often bias the statistical estimators or cause unduly high fluctuations compared to theory. Here, we compare the standard deviation of the ρ hv estimator based on analysis of time series data and based on simulations, versus the number of complex video sample pairs (each pair consists of one H and one V-polarized sample). Time series records were collected in stratiform rain with the antenna stationary. Data were selected from light rain and in bright-band. Since the ρ hv fluctuations depend on Doppler spectral width (σ_v) as well as the true ρ hv, these were estimated from the data itself using very long time averaging. Fig. 3 shows the results of the standard deviation in ρ hv (termed "stdv Rohv") versus number of sample pairs. The time series simulations are based on classical Gaussian statistics (see, Liu et al. J. Tech., 11, 1994). In Fig. 3a, the light rain case is shown where the "true" ρ hv was estimated to be 0.9928 and σ_v = 1.385 ms^{-1}. The simulations were done assuming two values for "true" ρ hv as shown, and are compared with data. Fig. 3b shows the bright-band case where the "true" ρ hv = 0.945 and σ_v = 1.08. Simulations were again performed for two values of "true" ρ hv as shown. The excellent agreement between simulations and data analysis gives confidence in both the theoretical assumptions as well as radar system performance.

Hailstorm Observations

One of the first opportunities to observe a significant hailstorm with the new CSU-CHILL antenna occurred during the evening hours of 3 June 1994. During this event, a small cluster of thunderstorm cells developed along the eastern slopes of the Rocky Mountains and moved northeastward over portions of Boulder, CO. Hail damage occurred as the strongest of these cells crossed the extreme northeastern districts of Boulder.

Figure 4 presents data collected in a 0.4^{o} elevation angle PPI sweep at 1826 MDT. The contours are based on individual range gate data values; the data have not been interactively edited or gridded. Considerable damage to roofs and automobiles took place within some 3 km of point B (x = -46.2, y = -42.8 km). At 1826, the region near point B was experiencing the passage of a >60 dBZ echo core (Fig. 4a). Due to the presence of quasi-spherical, tumbling hailstones, the differential reflectivity (Z_{dr}) in much of this core was near 0 dB (Fig. 4b). Further insights into the horizontal distribution of the hail are presented in Figure 4c. Relatively low copolar correlation (ρ hv(0)) was found in an elongated area immediately north of the reflectivity core. Balakrishnan and Zrnic (J. Atmos. Sci., 47, 1525 - 1540) have associated such ρ hv(0) reductions with the combined presence of rain drops and hailstones within the radar pulse volume. Additionally, specific differential propagation phase (K_{dp}, not shown), was used to estimate the reflectivity component due to rain (Balakrishnan and Zrnic, J. Atmos. Sci., 47, 565 - 583). The hail fraction was then obtained from the difference between the rain and total (observed) reflectivities. As shown in Fig. 4c, the primary area with a high hail component was in the southwest portion of the reflectivity core

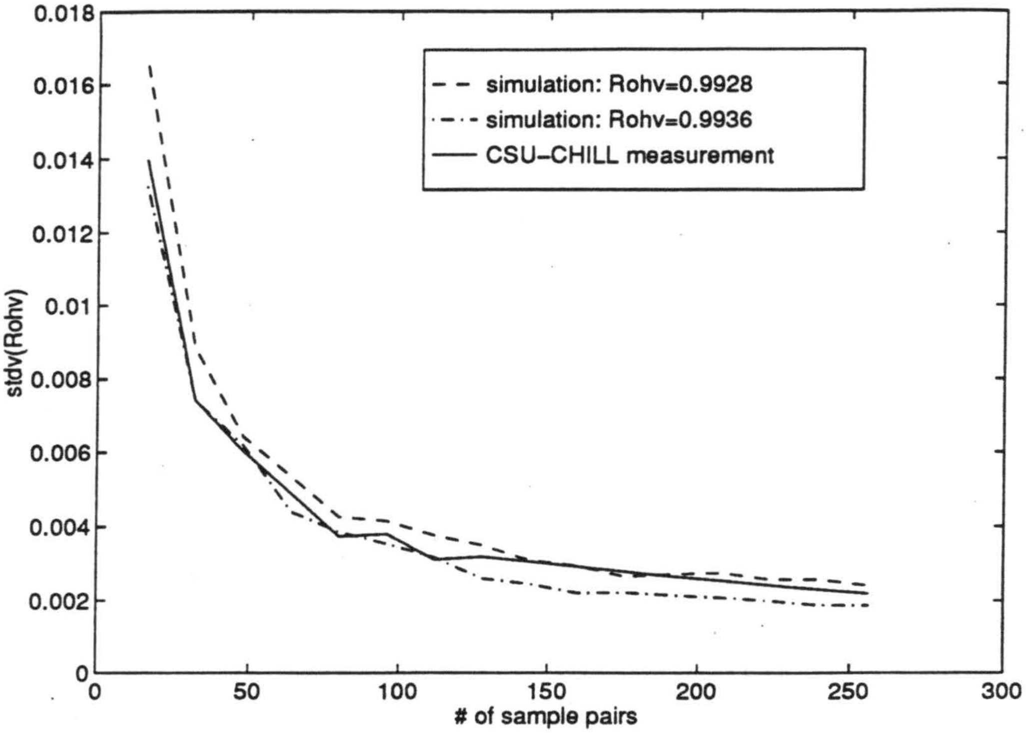

Fig. 3a Standard deviation of ρ_{hv} versus number of (H,V) sample pairs. Solid line shows the CSU-CHILL data from light rain below the bright-band. The mean ρ_{hv} (Rohv) and Doppler spectral width σ_v are obtained from long-time averaging of the data, and are used as input to the simulations. Two simulations are shown with mean ρ_{hv}=0.9928 and 0.9936, respectively, and $sigma_v$=1.385, Guassian shape spectrum.

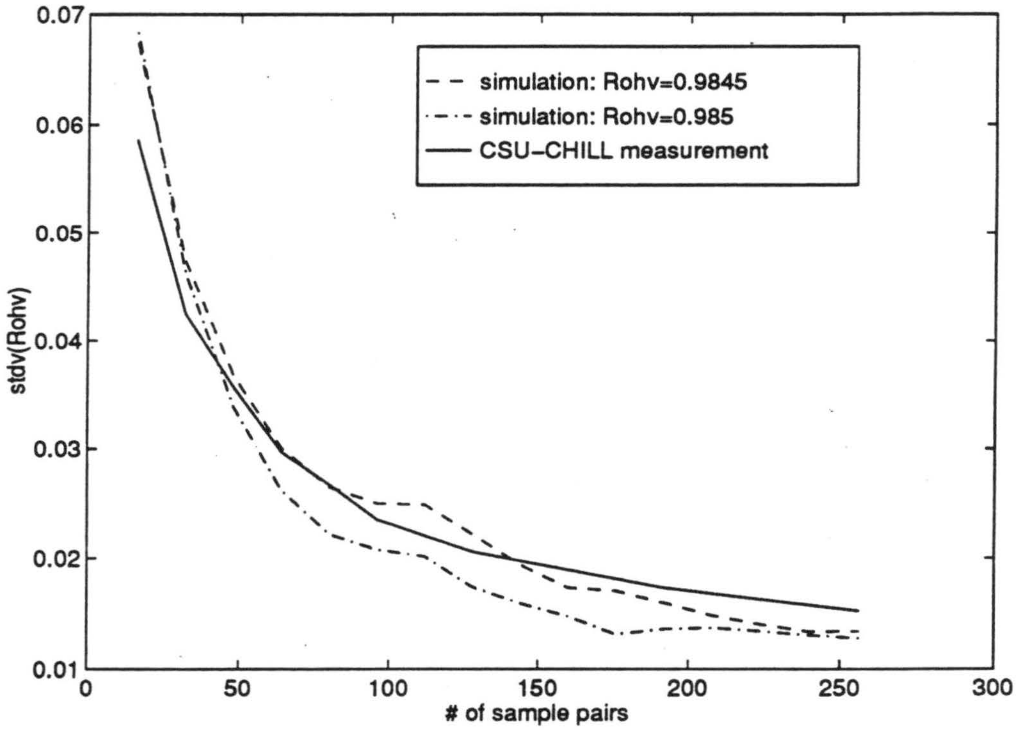

Fig. 3b As in Fig. 3a except data collected in the bright-band. The mean ρ_{hv} are 0.95 and 0.945, respectively, and σ_v=1.08 ms^{-1}.

(x = -47, y = -43.7 km). The precipitation sequence reported by observers near point B followed that suggested by Fig. 4c: As the storm moved northeastward over the area, rain became mixed with hail, followed by a brief episode of concentrated, damaging (golfball sized) hail.

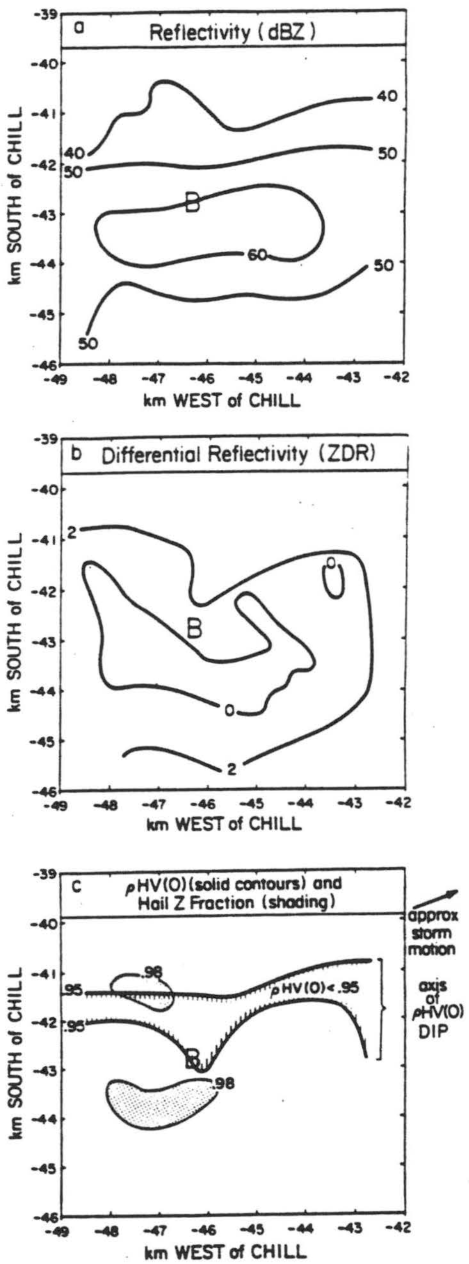

Figure 4: Data at 1826 MDT, 6/3/94. Beam height is ~600 m AGL. Hail damage occurred in the area of point "B". a) Reflectivity (dBZ). b) Differential reflectivity (Zdr, dB). c) Regions of relatively low copolar correlation and relatively high hail fraction (shaded). See text for details.

Software Engineering
(Dave Brunkow, Software Engineer)

LDR Calculation

One of the primary benefits of the new CSU-CHILL antenna is improved cross-polar isolation. Linear Depolarization Ratio (LDR=10log(Svh/Shh)) is the simplest of the crosspolar parameters. A new LDR data collection mode was added to the signal processor program. A four pulse polarization sequence (VHXH) is utilized, where V and H are copolarized Vertical and Horizontal samples, and the X is a transmit H, receive V sample. All of the previously available fields (Z, Z_{dr}, Velocity, $ø$dp, and $\rho_{hv}(0)$) are calculated during the HVH sequence, while the cross-polar power calculation is performed during the X sequence slot. The lowest observable LDR was limited by the polarization switch to about -20 db. Still, this did allow a first look at LDR fields during the Spring/Summer of 1994. After the dual transmitter/receiver installation is complete, this lower limit should be reduced to approximately -35 db. The second receiver will also eliminate the need for the X polarization slot, and LDR can be calculated using the normal VH alternating polarization sequence.

An example of the initial LDR data obtained during the last year is shown in the height profiles presented in Fig 5. These data were taken when light, stratiform rain was falling at the radar. Melting of the precipitation particles begins as they fall through the 0^{o} C level near a height of ~2.3 km AGL. As the particles transition from ice to water, a reflectivity bright band results centered just below 2 km (Fig. 5a). The melting also results in a Z_{dr} enhancement as the particles become increasingly wet and dense, yet maintain oblate shapes (Herzegh and Jameson, Bull. Amer. Soc., 73, 1365-1374). In the lower portion of the melting layer, only the largest particles remain in a partially frozen, oblate state. Since the differential reflectivity is particularly sensitive to the shapes of the larger sized particles, positive Z_{dr} values extend down to ~1.5 km (Fig. 5a). Below ~ 1.5 km where the particles have fully melted, both the Z_h and Z_{dr} profiles stabilize atvalues typical of light rain. Within the melting layer the larger ice particles are still in a water-soaked transition state, while some smaller particles have completely melted into drops. The coexistence of these particle shapes leads to a

ρ hv(0) reduction to ~.87 at the 1.8 km height level (Fig. 5b). Also, the presence of relatively large, wet melting particles in this mixed layer raises the LDR return to -14 dB (Fig. 5b). Thus, with the current CSU-CHILL configuration, plausible LDR observations have been made under conditions in which the cross-polar return is sufficiently strong. When the upgrade to the dual channel configuration is completed, cross-polar measurements, such as LDR, will be possible in a much wider variety of meteorological echoes.

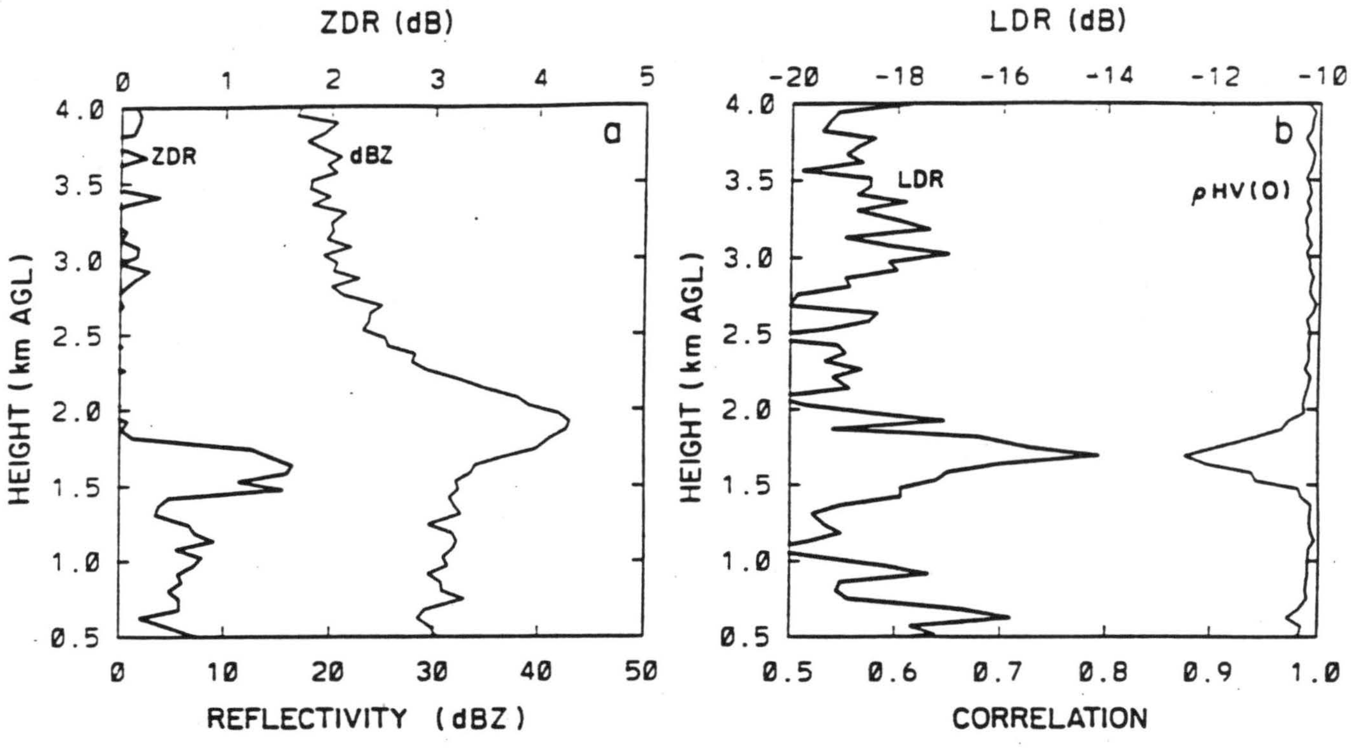

Figure 5: Bright band data recorded at 1554 MDT on 5/13/94. The RHI azimuth is 168°. Data from a range of 11.8 km were used to construct the vertical profiles. (a) Reflectivity (dBZ, thin line), and differential reflectivity (Z_{dr}, thick line). (b) Copolar correlation coefficient (ρ hv(0), thin line), and linear depolarization ratio (LDR, thick line).

Recent CSU-CHILL Publications (Reprints available on request)

Aydin, K., V. N. Bringi, and L. Liu, 1994: Rainrate estimation in the presence of hail using S-band specific differential phase and other radar parameters. Accepted for publication in *J. Appl. Meteor.*

Bringi, V. N., L. Liu, P. C. Kennedy, V. Chandrasekar and S. A. Rutledge, 1994: Dual multiparameter radar observations of intense convective storms: The 24 June 1992 case study. *J. Meteor. Atmos. Physics*, in press.

Carey, L. D., and S. A. Rutledge, 1994: Multiparameter and dual-Doppler radar study of the kinematic and microphysical evolution of lightning producing storms in northeastern Colorado. *Preprint, 1994 Global Circuit-Lightning Symposium*, AMS Annual Meeting, Nashville, TN, January, 1994.

Carey, L. D., and S. A. Rutledge, 1994: A multiparameter radar case study of the microphysical and kinematic evolution of a lightning producing storm. *J. Meteor. Atmos. Phys.*, in press.

Kennedy, P. C., and S. A. Rutledge, 1994: Dual-Doppler and Multiparameter Radar Observations of a Bow Echo Hailstorm. *Mon. Wea. Rev.*, in press.

Kennedy, P. C., N. E. Westcott, and R. W. Scott, 1994: Reply to the comments of C. A. Doswell III on "Single-Doppler radar Observations of a Mini-Supercell Tornadic Thunderstorm", *Mon. Wea.. Rev.* in press.

Liu, L., V. N. Bringi, V. Chandrasekar, E. A. Mueller, and A. Mudukotore, 1994: Analysis of the copolar correlation coefficient between horizontal and vertical polarizations. *J. Ocean. Atmos. Tech.*, in press.

McAnelly, R. L., J. E. Nachamkin, and W. R. Cotton, 1994: The development of an MCS in a quasi-tropical environment in northeastern Colorado. AMS Sixth Conference on Mesoscale Processes, 17-22 July 1994, Portland, OR.

Mudukotore, A., V. Chandrasekar, and E. A. Mueller, 1994: The differential phase pattern for the CSU-CHILL radar antenna. Submitted to *J. Atmos. and Oceanic Tech.*

Nachamkin, J. E., W. R. Cotton, and R. L. McAnelly, 1994: Analysis of the early growth stages of a High Plains MCS. Submitted to the AMS Sixth Conference on Mesoscale Processes, 17-22 July 1994, Portland, OR.

Rauber, R. M., M. K. Ramamurthy, and A. Tokay, 1994: Synoptic and Mesoscale Structure of a Severe Freezing Rain Event: The St. Valentine's Day Ice Storm. *Wea. and Forecasting*, **9**, 183-208.