

NASA CONFERENCE PUBLICATION

NASA CP-2161

FIRST SCIENTIFIC WORKING GROUP MEETING OF  
AIRBORNE DOPPLER LIDAR WIND VELOCITY  
MEASUREMENT PROGRAM

August 25-26, 1980  
NASA Marshall Space Flight Center

Edited by John W. Kaufman  
Space Sciences Laboratory

October 1980

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1. REPORT NO. NASA CP-2161		2. GOVERNMENT ACCESSION NO.		3. RECIPIENT'S CATALOG NO.	
4. TITLE AND SUBTITLE First Scientific Working Group Meeting of Airborne Doppler Lidar Wind Velocity Measurement Program				5. REPORT DATE October 1980	
				6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) Edited by John W. Kaufman				8. PERFORMING ORGANIZATION REPORT NO.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS  George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812				10. WORK UNIT NO.	
				11. CONTRACT OR GRANT NO.	
				13. TYPE OF REPORT & PERIOD COVERED  Conference Publication	
12. SPONSORING AGENCY NAME AND ADDRESS  National Aeronautics and Space Administration Washington, D.C. 20546				14. SPONSORING AGENCY CODE	
15. SUPPLEMENTARY NOTES  Prepared by Space Sciences Laboratory, Science and Engineering Directorate					
16. ABSTRACT  This document summarizes the results of the first scientific working group meeting of the MSFC Airborne Doppler Lidar Wind Velocity Measurement Program held at the Marshall Space Flight Center on August 25-26, 1980.					
17. KEY WORDS Remotely measured winds. Laser technology Airborne research in meteorology Doppler principles				18. DISTRIBUTION STATEMENT  <i>John W. Kaufman</i> Unclassified—Unlimited	
19. SECURITY CLASSIF. (of this report)  Unclassified		20. SECURITY CLASSIF. (of this page)  Unclassified		21. NO. OF PAGES  134	22. PRICE  NTIS

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## INTRODUCTION

The first scientific working group meeting of the MSFC Airborne Doppler Lidar Wind Velocity Measurement Program was held August 25-26, 1980, at the Marshall Space Flight Center. The working group meeting followed naturally from an exploratory meeting on the MSFC Airborne Doppler Lidar system held at MSFC in April 1980. This effort is part of the objective of the Severe Storms and Local Weather Research Program of the NASA Office of Space and Terrestrial Applications (OSTA).

The purpose of the first scientific working group meeting was fourfold: (1) to identify flight test options for engineering verification of the MSFC Doppler Lidar; (2) to identify flight test options for gathering data for scientific/technology applications; (3) to identify additional support equipment needed on the CV-990 aircraft for the flight tests; and (4) to identify postflight data processing and data sets requirements. The working group identified approximately ten flight options for gathering data on atmospheric dynamics processes, including turbulence, valley breezes, and thunderstorm cloud anvil and cold air outflow dynamics. These test options will be used as a basis for planning the fiscal year 1981 tests of the Doppler Lidar system.

In addition to the minutes of the first scientific working group meeting, this report contains summaries of the material presented at the meeting, reports by the working group technical teams, and a meeting attendance list.

MINUTES OF THE FIRST SCIENTIFIC WORKING GROUP MEETING OF  
THE AIRBORNE DOPPLER LIDAR WIND VELOCITY MEASUREMENT PROGRAM

The first scientific working group meeting of the MSFC Airborne Doppler Lidar Wind Velocity Measurement Program was held on August 25-26, 1980, at the NASA Marshall Space Flight Center.

The morning of the first day was devoted to providing the working group members with information about the lidar system, its status and schedule, data processing, wind retrieval from Doppler lidar observations, an overview of the Cooperative Convection Precipitation Experiment (CCOPE), and CV-990 flight operations. During the afternoon of the first day and the early morning of the second day the working group divided into teams to: (1) identify and develop flight test options, (2) identify postflight data processing and data set requirements, (3) review real-time data display requirements, and (4) identify additional support equipment needed on the CV-990 aircraft for the FY81 flight tests. The results of these team activities were reported in the plenary session of the working group during the late morning of the second day.

The convective phenomena team was chaired by Dr. James Telford of the University of Nevada; the secondary flows, boundary layer, turbulence, and wave team was chaired by Dr. Daniel Fitzjarrald of the Florida State University Geophysical Fluid Dynamics Laboratory. A list of the team members is provided as part of Appendix A. A float team consisting of representatives of the Doppler lidar hardware, data processing, and flight operations aspects of the program supported the activities of the science teams.

The agenda of the meeting is included with the vugraph material presented by Dr. George H. Fichtl (see Appendix A). This material also includes a summary of the key results of the April 1, 1980, exploratory meeting on the scientific and technological applications of the MSFC Doppler Lidar System, the scientific opportunities to apply the lidar system, an updated science working group schedule, experiments, requirements, and a list of the working teams and their activities. Also included is a chart on the Doppler lidar characteristics which depicts how wind velocity data are acquired by the Doppler lidar.

Mr. James Bilbro gave a status review of the Doppler lidar system and schedule. The basic points of the presentation were: (1) the status of the Doppler lidar hardware and modifications, (2) placement of the lidar and associated hardware on board the CV-990 aircraft, (3) various procedures for pulsing the laser beam, (4) data reduction options and error analyses in regard to pointing the laser beam, (5) range capability (i.e., out to approximately 10 km), etc.

Dr. Harold Jeffreys and Mr. Carl Buck provided information on the real-time data processing and display of data. Also, the postflight data

processing issue was discussed (see Appendix B). The data display topics included the on-board aircraft data acquisition system (ADDAS) as well as the inertial navigation system (INS) and ancillary data (e.g., temperature/dew point) to be obtained. The working group members expressed concern that the current concept for displaying the maximum intensity of the Doppler lidar backscatter signal might be difficult to interpret during flight operations. It was suggested that a separate CRT display should be used to display such information in view of the fact that new data are important relative to assessing Doppler lidar performance and for making scientific and operational decisions in real time. James Bilbro pointed out that a certain amount of modification of the currently planned on-board processing and data display is possible, so that a separate display of Doppler lidar backscatter intensity may be possible. The only constraints for implementing the separate display of Doppler lidar backscatter intensity are computer memory size and cost.

Questions arose about the amount of time required to hardcopy the Doppler lidar data aboard the CV-990 aircraft after it is displayed on the output CRT (which also serves as the storage device of processed Doppler lidar data for the on-board data processing). It was pointed out that it takes 10 seconds to obtain a hardcopy of data, so that very little data would be lost during the copy routine.

The postflight processing of wind components into wind vectors was discussed. It was pointed out that the forward and rearward looking Doppler lidar beams are separated in time, with the time differential increasing with range. It was further noted that combination of the forward and rearward looking beams into wind vectors is a matter of scientific interpretation. Therefore, the working group suggested that data sets of forward and rearward looking Doppler lidar winds should be provided, in addition to a data set in which the forward and rearward looking beams are combined in a rational manner to yield total wind vectors.

In the context of defining cloud boundaries, questions arose (Dr. Richard Doviak and Dr. William Vaughan) concerning the distance the laser beam could penetrate into a cloud. James Bilbro said that in most convective cloud cases the Doppler lidar beam will have negligible penetration; however, if clouds are significantly thin (e.g., cirrus), significant penetration can occur. The answer will depend on the drop or crystal size distribution and liquid water or ice content within the cloud. It was also noted by James Bilbro that, for a typical convective cloud, a very pronounced change in backscatter signal intensity will occur and that this return could be used to define cloud backscatter and cloud boundary in the postflight data processing activity.

Dr. Robert W. Lee provided a presentation on wind retrieval from Doppler lidar observations. His vugraphs are provided in Appendix C. This presentation clearly pointed out the need for precise specification of postflight data set requirements relative to accuracies, confidence bands, combination of forward and rearward looking wind components to obtain total vector winds, and calculation of kinematic quantities, such

as vorticity, divergence, etc. Appendix D is a report by Robert Lee on wind field retrieval from Doppler lidar observations which includes much of the material presented by Dr. Lee at the meeting.

Dr. Lavon J. Miller provided an overview of the CCOPE. Appendix E is the material used in his presentation. Extensive discussion took place after this presentation relative to (1) flight operations and (2) the kinds of data that could be acquired with the Doppler lidar at the CCOPE. It is clear from the discussions that close coordination and extensive planning with the CCOPE on the part of the Doppler lidar team members will be required if the Doppler lidar is used at the CCOPE. In this regard Lavon Miller requested that representatives from the Doppler lidar team participate in the October CCOPE aircraft operations planning meeting to be held at NCAR, Boulder, Colorado. Current plans include the attendance of George Fichtl and John Kaufman at this meeting. Furthermore, during the CCOPE, close coordination of the CV-990 flight operations with the CCOPE operations center in Miles City, Montana, will be required. This could prove to be problematic because the CV-990 will most likely be stationed at Rapid City, South Dakota. However, it is not a problem that cannot be solved.

The CCOPE offers the opportunity to acquire ground truth wind velocity measurements with the Doppler radars in the CCOPE radar network for verification of the Doppler lidar system. In addition, scientific opportunities relative to performing fundamental studies with the Doppler lidar may be possible at the CCOPE in regard to gust front dynamics, anvil dynamics and precipitation efficiency, dry air entrainment associated with cumulus turrets, and feeder flow under small cumulus clouds, as well as boundary layer studies in prestorm conditions. This is discussed in more detail in the report by the convective phenomena team (Appendix G).

George Alger commented on how CV-990 operations will take place. He pointed out that the CV-990 has approximately a 7-hour flight endurance. Typically for a flight test a 1-hour period will be required for flight planning, and the flight would take place approximately 2 hours after the planning phase. Thus, weather forecasts will play a key role in our flight activities. George Alger pointed out that, once the CV-990 is in the air, changes in the flight plan are possible. However, such changes in flight plans must be coordinated with James Bilbro and George Alger to coordinate the changes with the pilots. Mr. Alger stated that the first two to three flights will most likely be used for getting "bugs" out of the instruments and familiarizing the flight crew with the operation of the Doppler lidar.

After these discussions, George Fichtl gave a presentation in preparation for the team meetings that took place in the afternoon and the next morning (August 26). His presentation charts are given in Appendix F.

The reports of the team meetings are provided in Appendices H through J. Reports by Dr. Richard Doviak (NSSL) and Dr. Randall Koenig (NSF) provide details on recommended flight test options, recommended flight paths, on-board data displays, postflight data processing, scientific and technical rationale, and purposes (Appendices I and J).



The meeting proved to be successful in accomplishing the goals set forth earlier in these minutes. The identified flight options and other inputs will be used to prepare a flight option document. This document will summarize the experiments and will be used: (1) for determination of Doppler lidar operational settings, e.g., pulse length, number of pulses to be used in calculating averages, etc., and (2) for CV-990 flight planning.

Questions regarding these minutes may be directed to George H. Fichtl (205 453-0875) or John W. Kaufman (205 453-3104).

  
John W. Kaufman

**APPENDIX A**

**PART I OF PRESENTATION BY  
DR. GEORGE H. FICHTL, MSFC**

ES82

MEETING AGENDA

NAME

6. 10. 10. 10. 10.

DATE

AUGUST 1980

AUGUST 25, 1980

8:30	INTRODUCTION AND MEETING PLANS	G. H. FICHTL/MSFC
9:00	STATUS OF DOPPLER LIDAR SYSTEM AND SCHEDULE	J. W. BILBRO/MSFC
9:30	REAL TIME DATA DISPLAYS	C. BUCK, H. JEFFREYS/M&S COMPUTING
10:00	POST FLIGHT DATA PROCESSING	C. BUCK, H. JEFFREYS/M&S COMPUTING
10:30	WIND FIELD RETRIEVAL FROM DOPPLER LIDAR OBSERVATIONS	R. W. LEE/LASSEN RESEARCH
10:45	OVERVIEW OF THE COOPERATIVE CONVECTIVE PRECIPITATION EXPERIMENT (CCOPE)	L. MILLER/NCAR
11:15	CV-990 FLIGHT OPERATIONS	G. ALGERS/ARC
11:45	PREPARATION FOR TEAM MEETINGS	G. H. FICHTL/MSFC
12:00	LUNCH	
1:00	TEAM MEETINGS	

AUGUST 26, 1980

8:00	TEAM MEETINGS
10:00	CONVENE MEETING
10:10	TEAM REPORTS
12:10	LUNCH
1:30	DISCUSSIONS
4:00	ADJOURN

ES82

RESULTS OF APRIL 1980  
EXPLORATORY MEETING

G.H. FICHTL

AUGUST 1980

- OPPORTUNITY TO MAKE DETAILED FLOW MEASUREMENTS OF MESOSCALE AND MICROSCALE PROCESSES
- SYSTEM VERIFICATION FLIGHTS SHOULD BE PERFORMED IN COOPERATION WITH OTHER FIELD EXPERIMENTS TO OBTAIN "GROUND TRUTH" DATA.
- PARTICIPATION IN PLANNED FIELD EXPERIMENTS WILL SIGNIFICANTLY INCREASE SCIENTIFIC RETURN FROM DOPPLER LIDAR PROGRAM.
- PARTICIPATION IN COOPERATIVE CONVECTIVE PRECIPITATION EXPERIMENT (CCOPE) IS STRONGLY RECOMMENDED.
- UTILIZATION OF DOPPLER LIDAR IN OTHER THAN HORIZONTAL MODE CAN YIELD IMPORTANT AND NEEDED DATA; E.G., VERTICAL LINE OF SIGHT CAN PRODUCE DATA ON ENTRAINMENT PROCESSES OCCURRING AT TOP OF CONVECTIVE CLOUDS.

ORGANIZATION:  <b>ES02</b>	<b>MARSHALL SPACE FLIGHT CENTER</b>  <b>SCIENCE OPPORTUNITIES</b>	NAME: <b>G.M. FICHTL</b>  DATE: <b>AUGUST 1980</b>
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**CONVECTIVE PROCESSES**

- SUBCLOUD DYNAMICS
- ENTRAINMENT
- CLOUD TURRET DYNAMICS
- COLD AIR OUTFLOW
- WARM AIR INFLOW
- ANVIL CLOUD STRUCTURE
- CLOUD ENVIRONMENT DYNAMICS

**LOCAL CIRCULATIONS**

- SEA AND LAND BREEZES
- MOUNTAIN/VALLEY FLOWS
- HEAT ISLAND EFFECTS
- FLOW AROUND TERRAIN FEATURES
- MODEL VERIFICATION "GROUND TRUTH"

**WAVES AND TURBULENCE**

- GRAVITY WAVE STRUCTURE
- CLEAR TURBULENCE
- BREAKING WAVES
- GENERATION AND DISSIPATION
- MOUNTAIN WAVES

**ATMOSPHERIC BOUNDARY LAYER**

- MEAN FLOWS
- TURBULENCE CHARACTERISTICS
- INVERSION DYNAMICS
- ENTRAINMENT PROCESSES
- ORGANIZED LARGE EDDY STRUCTURE

**AEROSOL DYNAMICS**

- TRANSPORT PROCESSES
- ENTRAINMENT AND DETRAINMENT PROCESSES
- FLUX OF AEROSOL THROUGH TROPOPAUSE AND FRONTS
- AEROSOL CLOUD STRUCTURE

**ENGINEERING AND AERONAUTICAL APPLICATIONS**

- WIND ENERGY
- WIND FIELDS FOR AIRCRAFT TAKEOFF AND LANDING
- INDUSTRIAL AERODYNAMICS
- POLLUTION MONITORING
- AGRICULTURE AVIATION SPRAY TECHNOLOGY

ORGANIZATION:

MARSHALL SPACE FLIGHT CENTER

NAME:

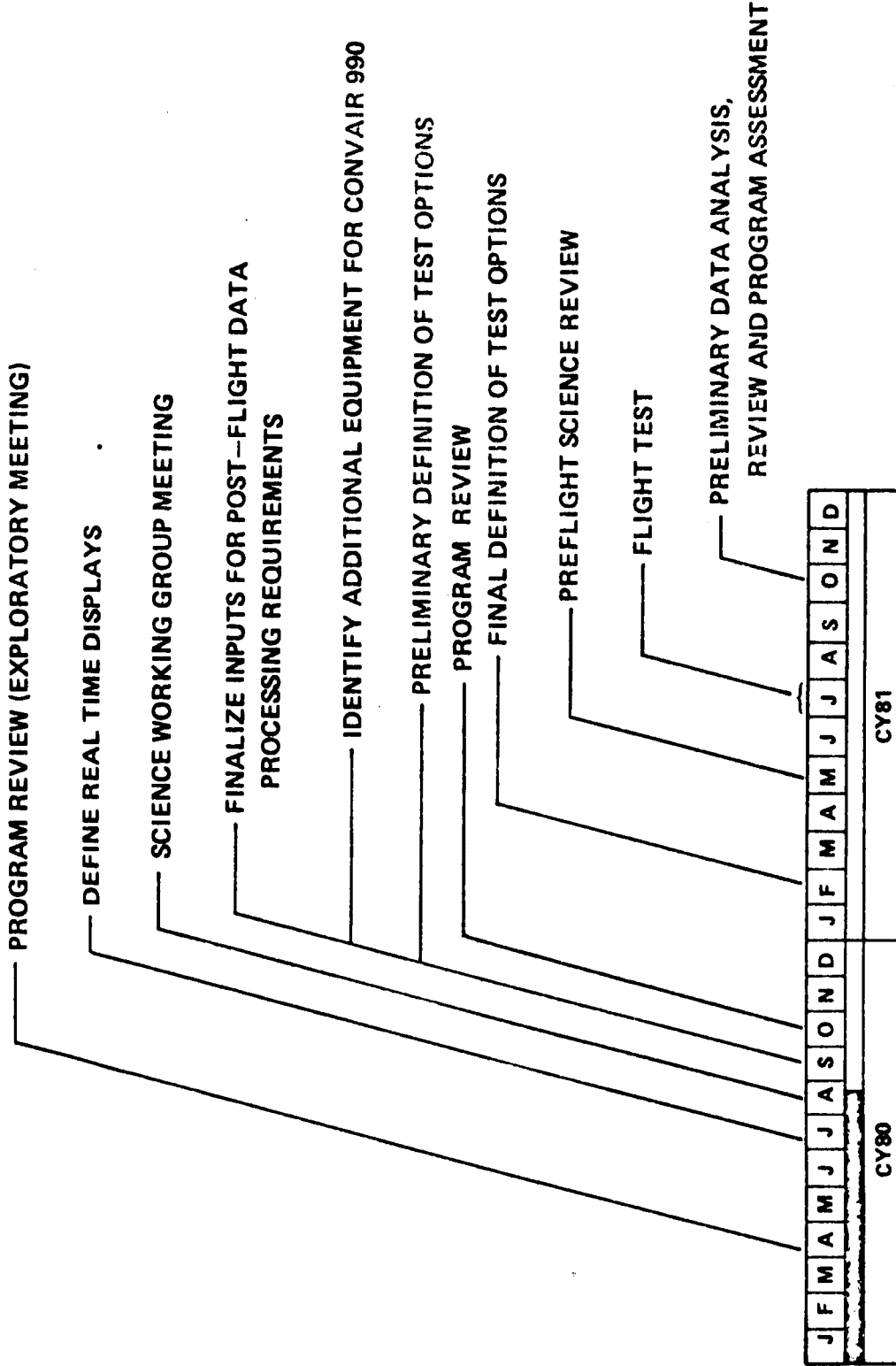
G. H. FICHTL

ES82

# SCIENCE WORKING GROUP SCHEDULE

DATE:

AUGUST 1980



ORGANIZATION  ES82	MARSHALL SPACE FLIGHT CENTER  MEETING OBJECTIVES	NAME: G. H. FICHTL  DATE: AUGUST 1980
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- IDENTIFY FLIGHT TEST OPTIONS
  - SCIENTIFIC/TECHNOLOGY APPLICATIONS
  - ENGINEERING APPLICATIONS
- IDENTIFY ADDITIONAL SUPPORT EQUIPMENT NEEDED ON THE CV-990 AIRCRAFT FOR FLIGHT TESTS
- IDENTIFY POST FLIGHT DATA PROCESSING AND DATA SETS REQUIREMENTS

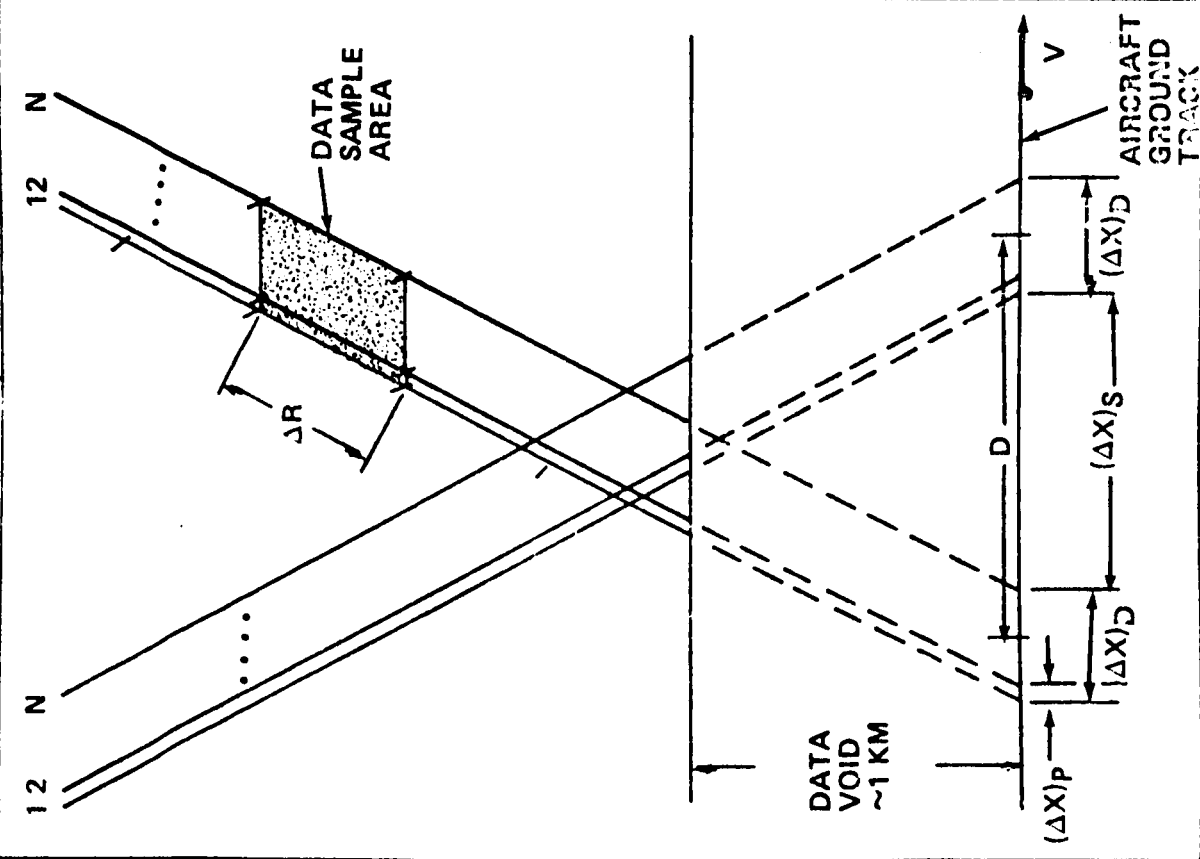
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FORM 205-80C

ORGANIZATION: MARSHALL SPACE FLIGHT CENTER  
 NAME: G.H. FICHTL  
 DATE: AUGUST 1980

DOPPLER LIDAR CHARACTERISTICS

ES82



V = GROUND SPEED OF AIRCRAFT  
 $\tau$  = PULSE WIDTH  
 PRF = PULSE REPETITION FREQUENCY  
 $\Delta R$  = RANGE RESOLUTION =  $C\tau/2$   
 $\Delta t$  = TIME INTERVAL BETWEEN PULSES =  $1/PRF$   
 $(\Delta X)_P$  = DISTANCE BETWEEN PULSES ALONG GROUND PATH =  $V\Delta t$   
 N = NUMBER OF PULSES IN DATA SAMPLE AREA  
 $(\Delta X)_D$  = GROUND TRACK RESOLUTION =  $\frac{(N-1)V}{PRF}$   
 $(\Delta X)_S$  = DISTANCE ALONG GROUND PATH BETWEEN FORWARD AND REARWARD DIRECTED BEAMS  
 T = MINIMUM TIME REQUIRED TO REVERSE LASER PROPAGATION DIRECTION,  $T \leq (\Delta X)_S/V$

PARAMETER	MAGNITUDE	EXAMPLE
V	150-250m sec <sup>-1</sup>	SPECIFY: $\Delta R, (\Delta X)_D, D$  CALCULATE: $\tau = 2 \frac{\Delta R}{C}$ $N = (\Delta X)_D \frac{PRF}{V} + 1$ $(\Delta X)_S = D - (\Delta X)_D$ $T = \frac{(\Delta X)_S}{V}$
$\tau$	2,4,8 $\mu$ sec	
PRF	140 PULSES sec <sup>-1</sup>	
$\Delta R$	300,600,1200m	
$\Delta t$	0.00714 sec	
$(\Delta X)_P$	1.07-1.79M	
N	20-200	
$(\Delta X)_D$	21.4-358.0M	
$(\Delta X)_S$	113m MINIMUM	
T	0.75 sec	



ORGANIZATION

ES82

MARSHALL SPACE FLIGHT CENTER

WORKING TEAMS

NAME

G. H. FICHTL

DATE

AUGUST 1980

CONVECTIVE PHENOMENA TEAM

- H. ORVILLE
- J. TELFORD
- J. MILLER
- G. WILSON
- R. KOENIG
- D. BOWDLE
- B. JONES\*
- R. W. LEE ^

FLOAT TEAM

- G. H. FICHTL/J. KAUFMAN
- J. BILBRO\*/C. DIMARZIO\*
- E. WEAVER\*
- G. ALGER ▽

- \*HARDWARE
- ^ DATA PROCESSING
- ▽ FLIGHT OPERATIONS

SECONDARY FLOWS, BOUNDARY LAYERS,  
TURBULENCE, WAVE TEAM

- J. SCOGGINS
- W. FROST
- D. FITZJARRALD
- R. DOVIK
- W. CLIFF
- J. CAHIR
- R. MURTY
- C. BUCK ^
- H. JEFFREYS ^ \*
- S. JOHNSON\*

APPENDIX B

MATERIAL PRESENTED BY  
DR. HAROLD B. JEFFREYS, M&S COMPUTING

SEVERE STORMS MEASUREMENT SYSTEM  
REAL TIME DATA PROCESSING  
AND DISPLAYS

## REAL-TIME DATA PROCESSING AND DISPLAYS

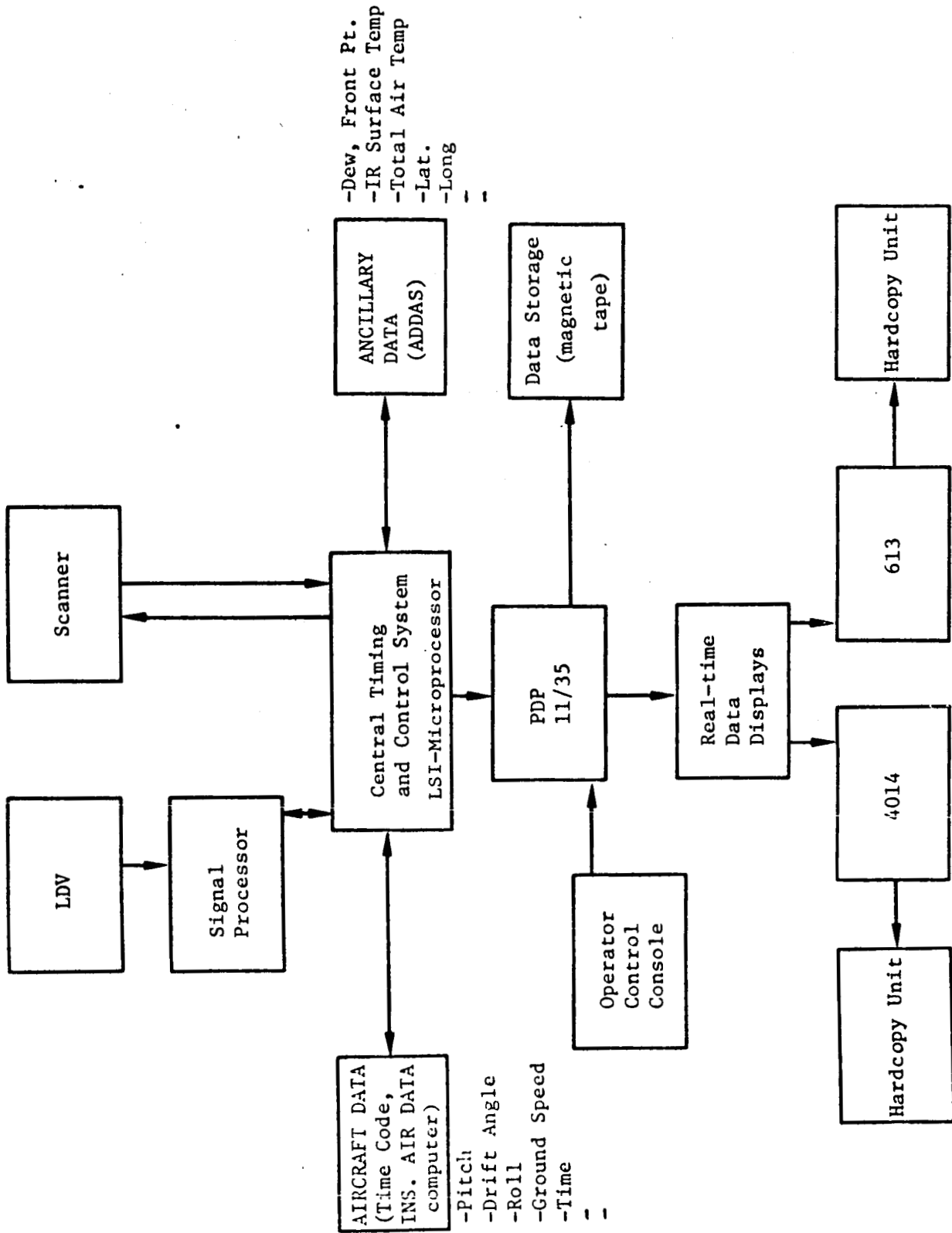
### Objectives:

- Provide the system operator with real-time system performance check.
- Provide data recording of all SSMS data.
- Provide meteorologist with real-time indications of meteorological data measurements.
  - Aid for directing flight profiles in real-time.
  - Aid for directing SSMS operation.
- Provide day to day feed-back to meteorologist, system operators, flight crew for flight planning on subsequent flight test days.

### Limitations:

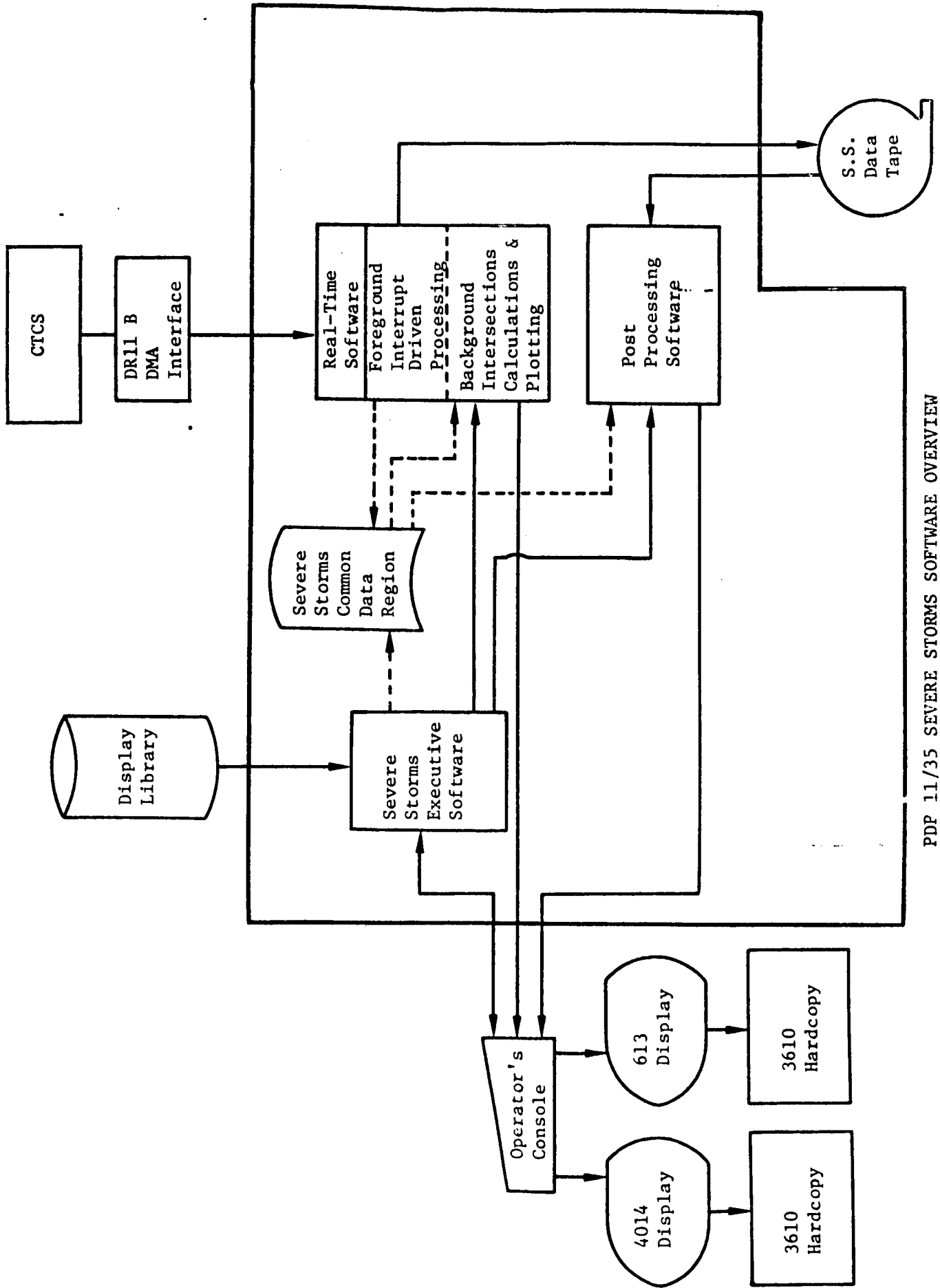
- Defined real-time data processing algorithms and displays employ 95% of current systems capability.
  - Core
  - Speed
  - Display Capacity

REAL-TIME DATA FLOW



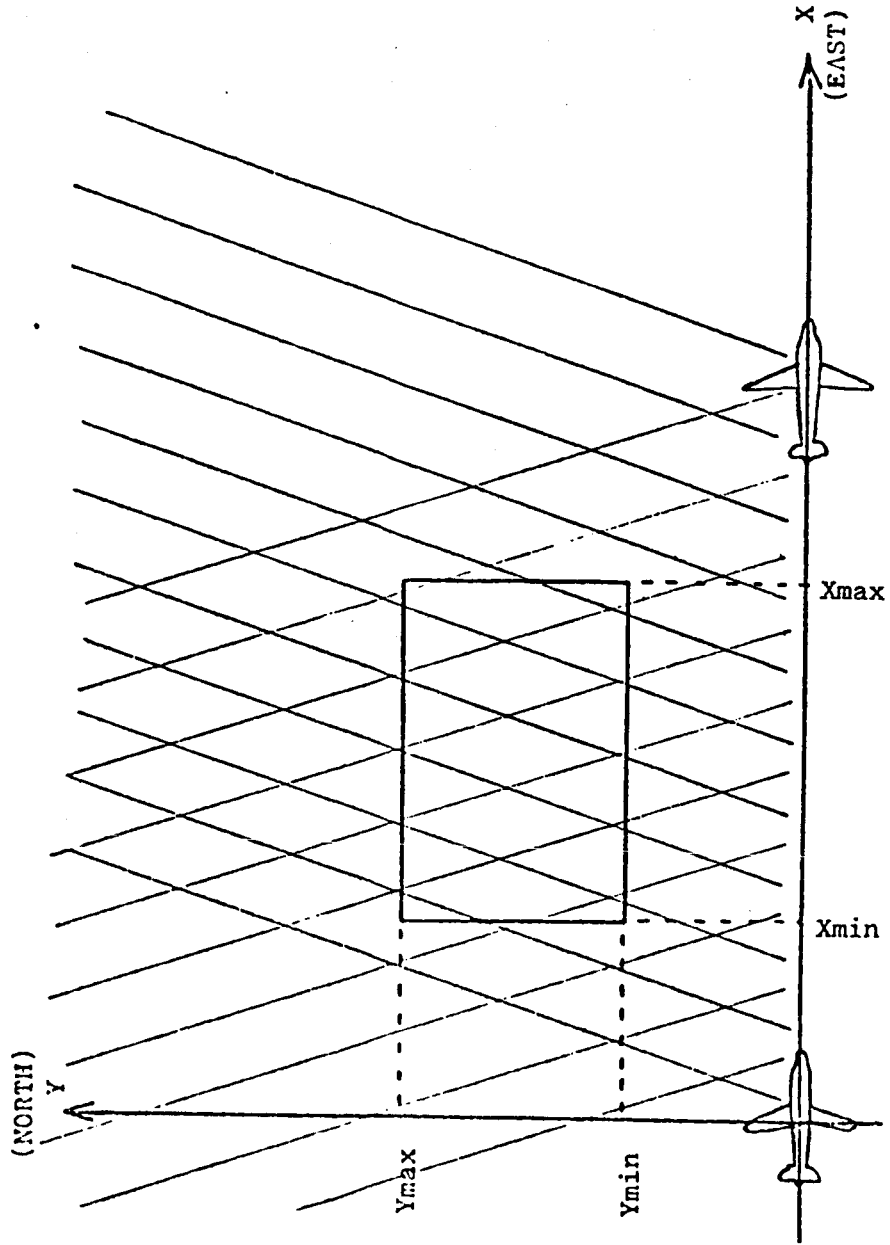
- Pitch
- Drift Angle
- Roll
- Ground Speed
- Time
- 
- 

- Dew, Front Pt.
- IR Surface Temp
- Total Air Temp
- Lat.
- Long
- 
-

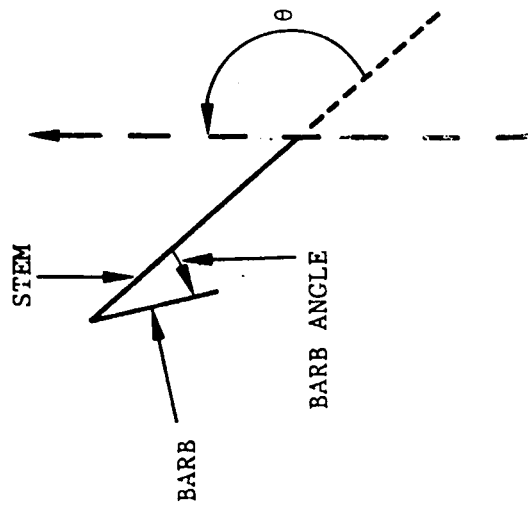


PDP 11/35 SEVERE STORMS SOFTWARE OVERVIEW

SEVERE STORMS MEASUREMENT SYSTEM SCANNING GEOMETRY



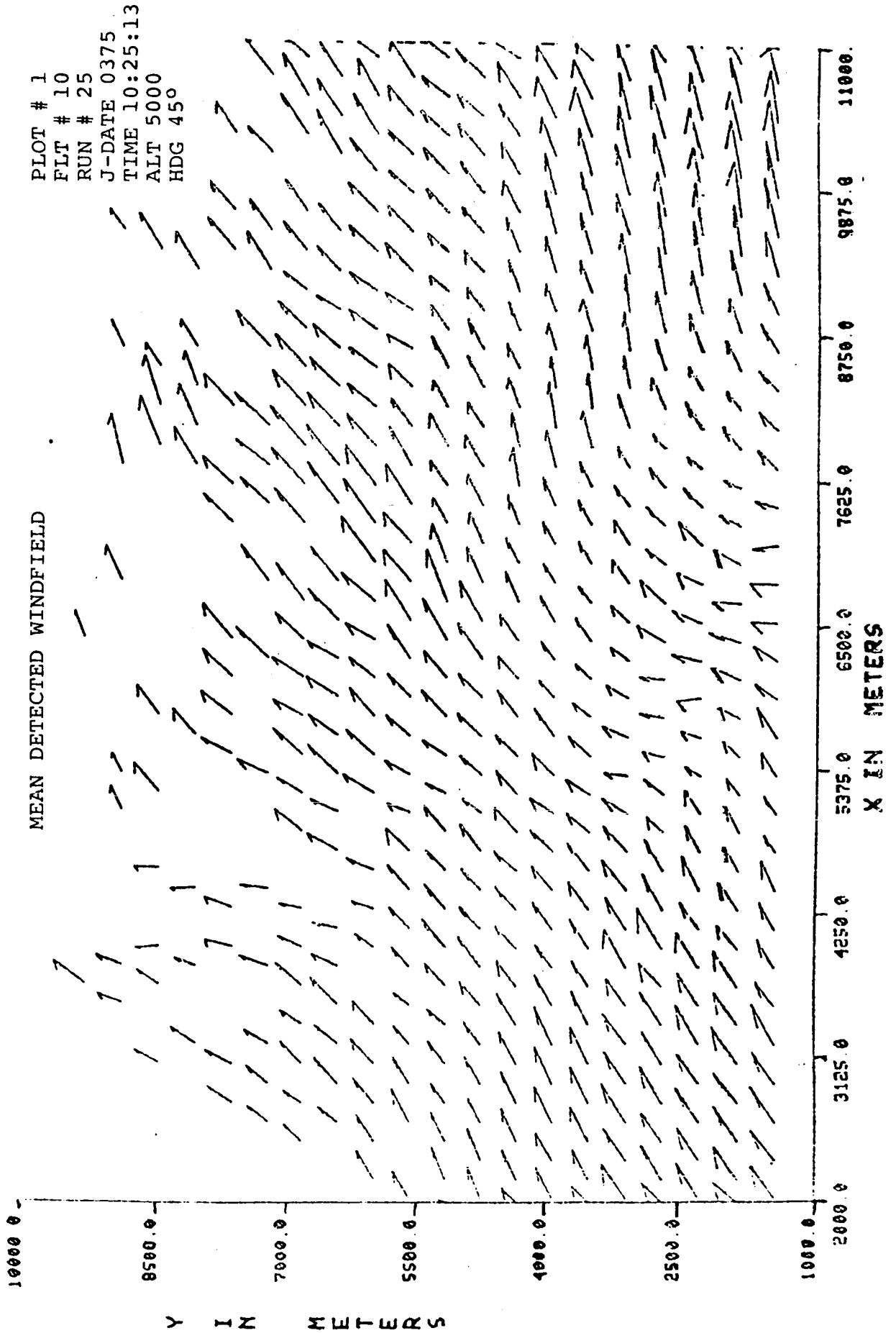
REAL-TIME DISPLAY PLOTTING MODEL



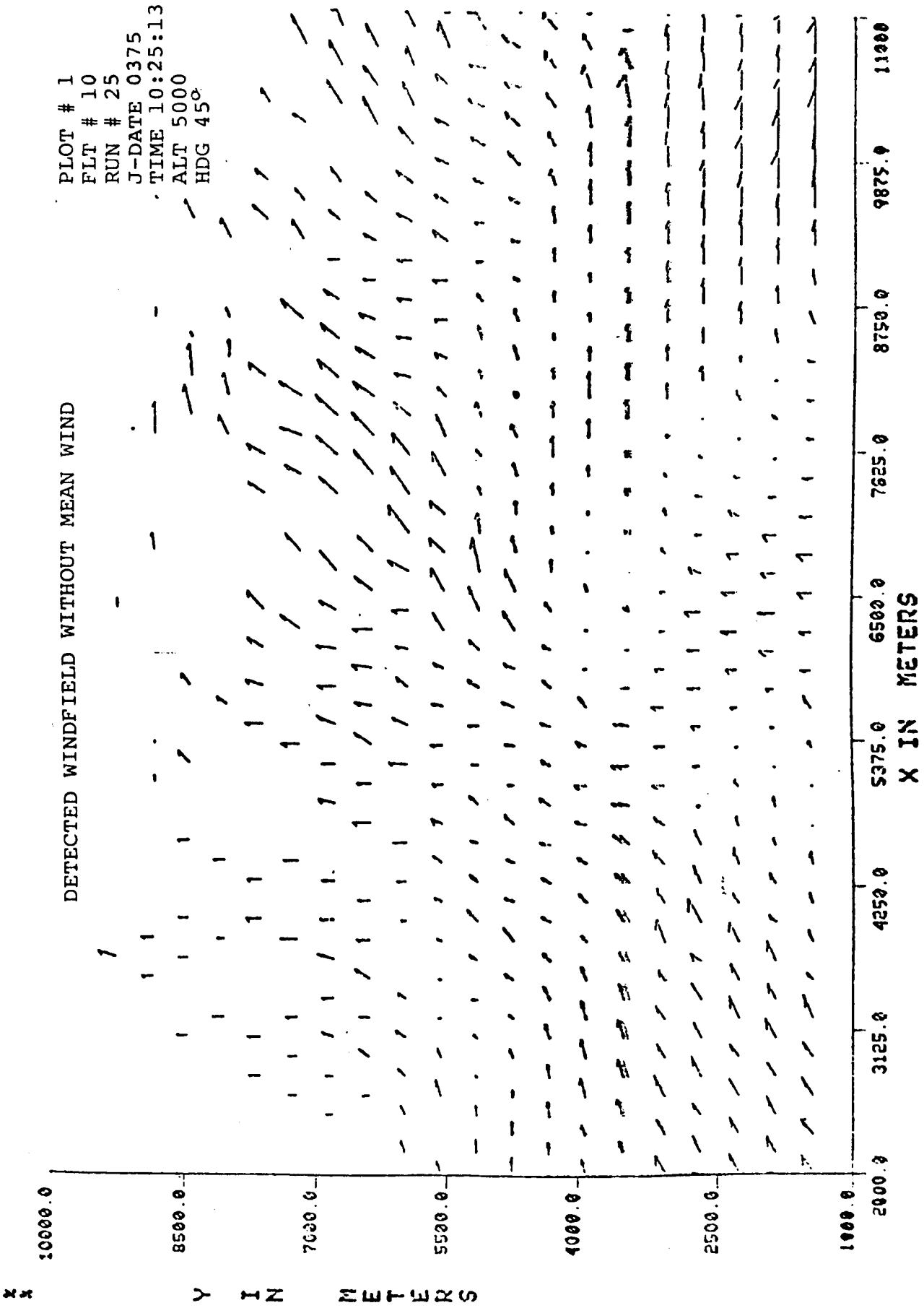
- Stem - wind direction and magnitude velocity
- Barb angle - length proportional to the velocity variance
- $\theta$  - orientation of the velocity vector with respect to North
- Barb - length proportional to signal intensity



REAL-TIME WIND FIELD DATA DISPLAY



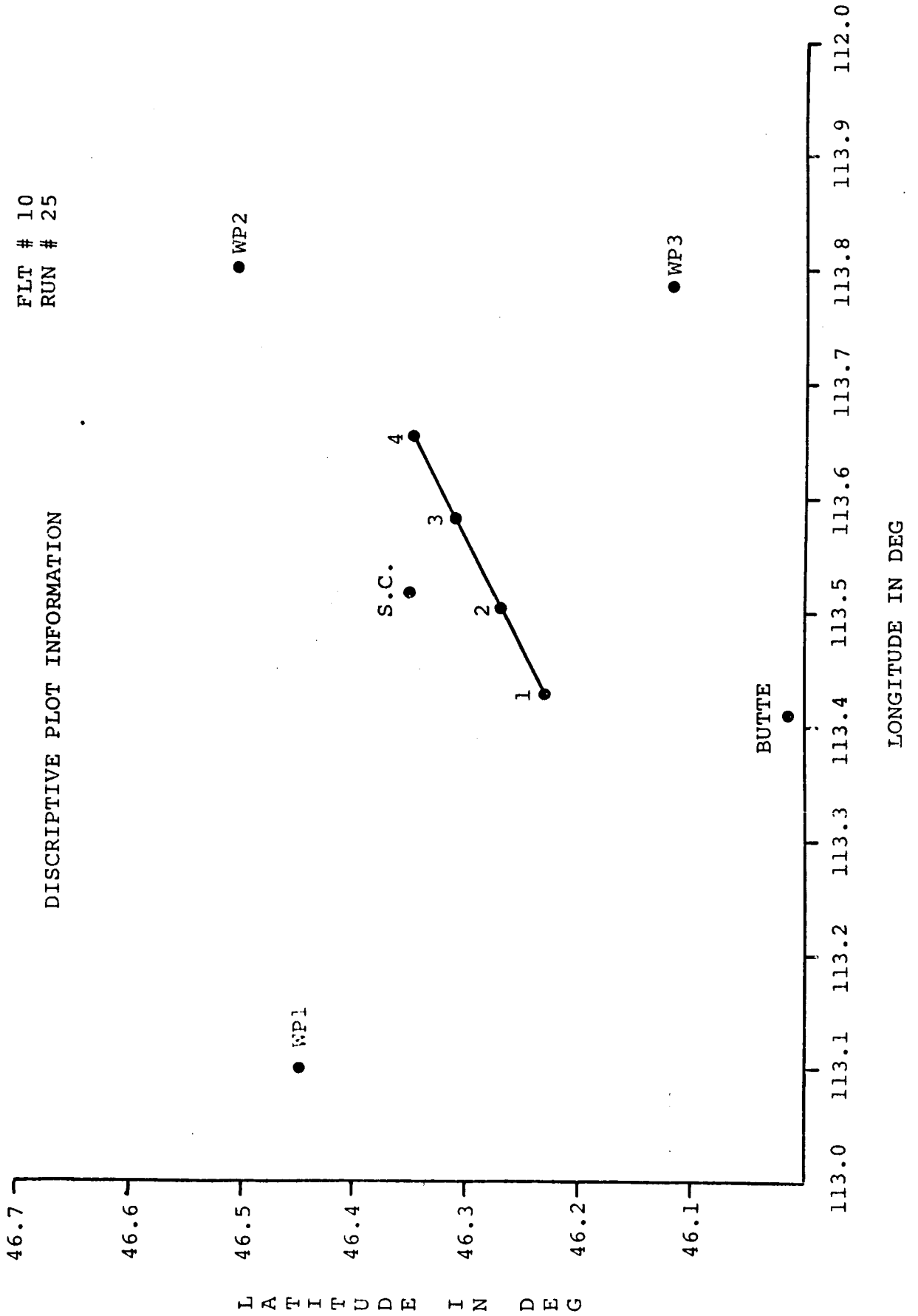
POTENTIAL REAL-TIME DATA DISPLAY



REAL-TIME AREA AIR TRACK MAP DATA DISPLAY

FLT # 10  
RUN # 25

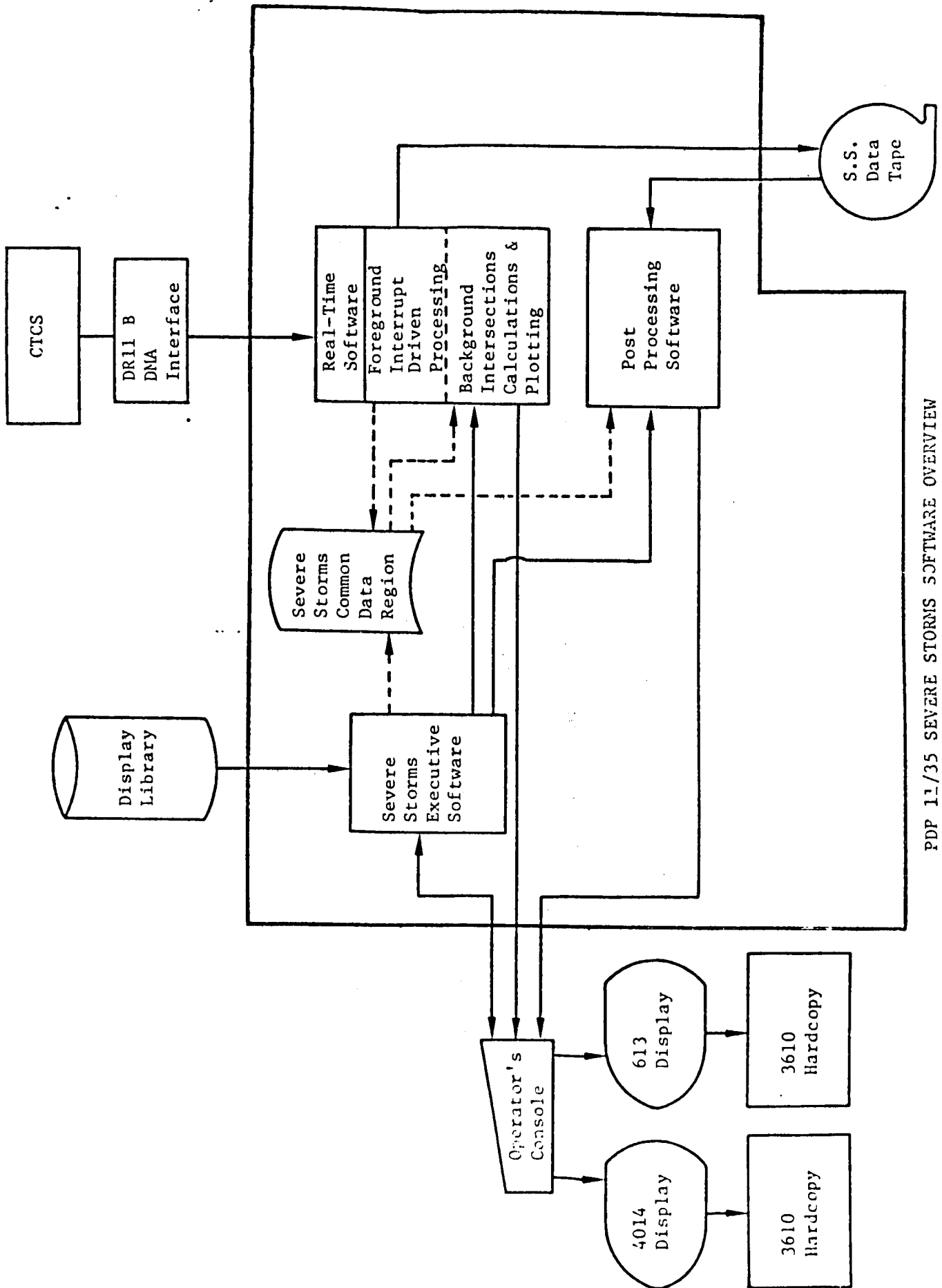
DISCRIPTIVE PLOT INFORMATION



SEVERE STORMS MEASUREMENT SYSTEM  
POST FLIGHT DATA, PROCESSING, AND DISPLAYS

## SEVERE STORMS REAL-TIME DATA STORAGE

- All data which is collected during an execution of the severe storms software is stored on magnetic tape.
- One file on a magnetic tape will contain all of the data for a single run.
- One volume of magnetic tape may contain multiple data files.
- A data file consist of a single header record describing the flight number, run number, date, etc., followed by a variable number of data records.
- Data records on tape will be composed of alternating Forward and Aft scan records.



PDP 11/35 SEVERE STORMS SOFTWARE OVERVIEW

SEVERE STORMS MAGNETIC TAPE DATA RECORD FORMAT

WORD NO.	NAME	SYMBOL	MINEMONIC	FORMAT * LSB	RANGE	COMMENTS
FOLLOWING IS CALLED PRIMARY DATA						
1	East Distance	X	X	integer 10m	+327,680m	
2	North Distance	Y	Y	integer 10m	+327,680m	ref. to starting point
3	LOS Direction		LOAD	integer 0.1°	-0°-360°	
4	Status (formerly summary fault			coded		
5	Pulse width	I	PW	coded		
6	Processor Status		PS	coded		
7	Spare		SP1			
8	Spare		SP2			
9	Spare		SP3			
10	Spare		SP4			
11	Spare		SP5			
12	LIDAR amplitude	M <sub>0</sub>	MZERO	integer 0.09dB	0-92 dB	first range gate
13	LIDAR velocity	V <sub>eos</sub>	VLOS	integer 0.08m/s	+328m/s	first range gate
14	LIDAR width	M <sub>2</sub>	MTWO	integer TBD		first range gate
297	LIDAR Amplitude	M <sub>0</sub>	MZERO	integer 0.009dB	0-92 dB	last range gate
298	LIDAR Velocity	V <sub>eos</sub>	VLOS	integer 0.08m/s	+328 m/s	last range gate
299	LIDAR Width	M <sub>2</sub>	MTWO	integer TBD		last range gate
FOLLOWING IS ANCILLARY AND DIAGNOSTIC DATA						
300	Flight No.		NFL	BCD one		Julian date
301	Day No.		IDAY	BCD one		7999 Max.
302	Run No.		NRUN	BCD one		
303	Time, Seconds		TSEC	BCD (1/10)sec		
304	Time, Hr:Min		KHM	BCD min		
305	Pressure Altitude,	A <sub>p</sub>	PALT	integer 135Kft.x2	-13	
306	Pressure Altitude,	A <sub>p</sub>	PALT	integer 5Kft.x2	-13	
307	Radar Altitude	A <sub>r</sub>	RALT	integer TBD		
308	Dea/Frost Point	D <sub>r</sub>	DFP	BCD 0.1°C	+100°C	
309	Static Air Temp.	T	SATM	BCD 0.1°C	+100°C	
310	IR Surface Temp	T <sub>g</sub>	IR-SUR	BCD 0.1°C	+100°C	
311	Total Air Temp	TAT	TAT	BCD 0.1°C	+100°C	
312	Latitude, Minutes		LAT	BCD 0.1min	59.9 to +59.9	
313	Degrees		LAT	BCD 1 deg	-90 to +90	
314	Longitude, minutes		LON	BCD 0.1min	-59.9 to +59.9	
315	Degrees		LON	BCD 1 deg	-180 to +180	
316	True heading	TH	TH	integer .04deg		
317	True Airspeed	TAS	TAS	integer 450x2-12kts.	0 to 360	
318	Ground Speed	GS	GS	integer 1000x2-13kts.	0-1000 Kts	
319	Drift Angle	DA	DA	integer 90x2-11deg.	+39.9	
320	Wind Speed	WS	WS	BCD 0.1kt	0-500 Kts	
321	Wind Direction	WD	WD	BCD 0.1deg	0-360	
322	Pitch	P	PITCH	integer 180x2-12	+90	
323	Roll	R	ROLL	integer 180x2-12	+180	
324	Wedge Angle(inner)	e <sub>1</sub>	THETA1	BCD 0.1deg	0 to 360	
325	(outer)	e <sub>2</sub>	THETA2	BCD 0.1deg	0 to 360	
326	Time to position			integer 10	327860 msec	
327	Sensor Motor Temp			integer TBD		
328	LOS Elevation	LOSE	LOSE	integer 0.1°	+90	
329	Pulses per inte-		MINT	integer 5	20-95	
330	Number of Lags			integer 1	0-8	
331	Spare					
332	Check sum		CKSM	integer TBD		

## POST FLIGHT DATA PROCESSING

### Objectives:

- Provide the meteorological community with sufficient data which is formatted suitable for severe storm/wind flow field research.
- Provide the system engineers with data sufficient for evaluating system performance
- Perform high fidelity data processing of SSMS data unconstrained by the time limitations of computer computations and display hardware.

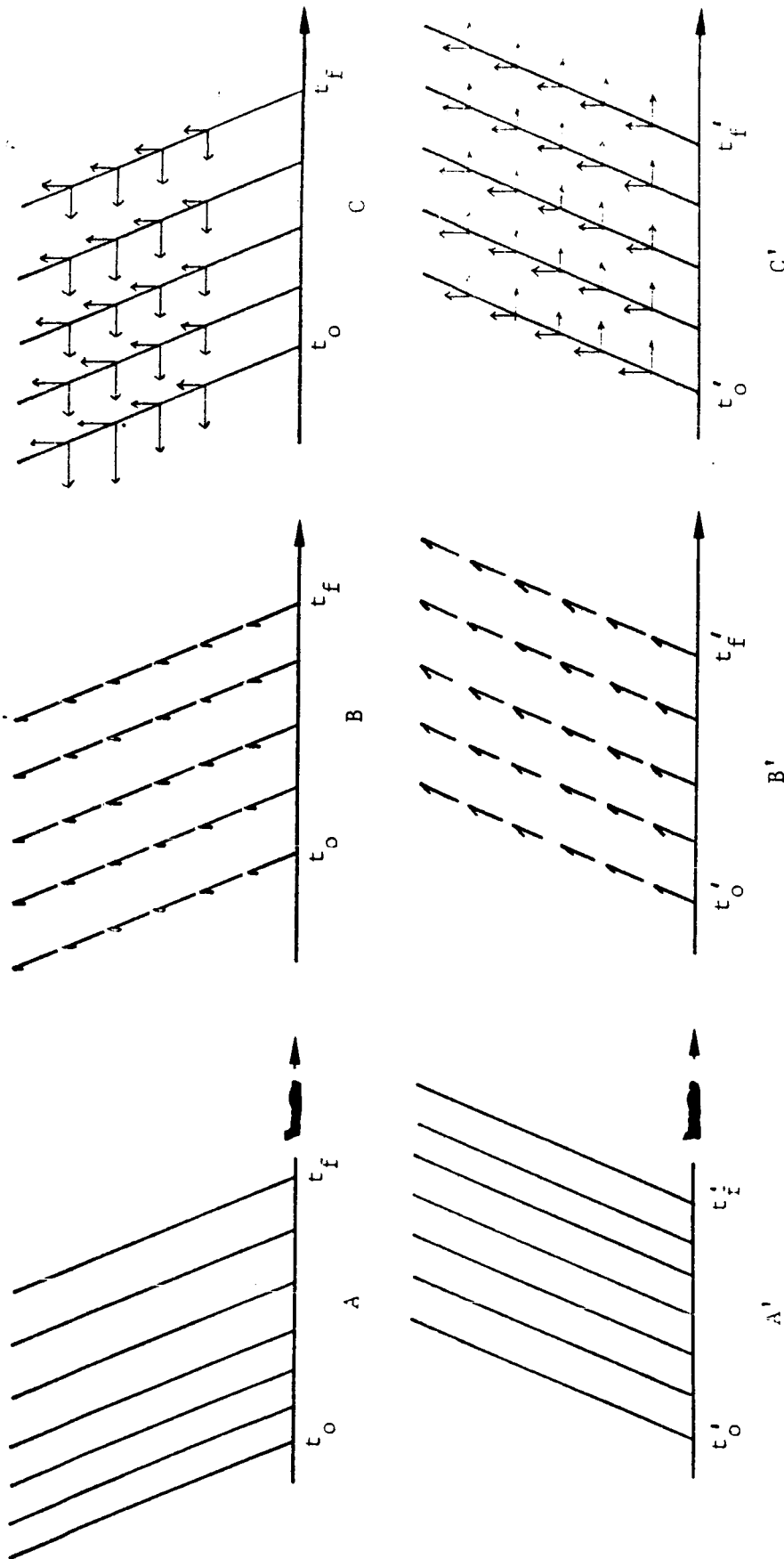
P. 14

### Requirements:

- TBD (via meteorological community)



EXAMPLE OF RECOMMENDED POST FLIGHT DATA PROCESSING



- C and C' permit calculation of time and mean wind corrected velocity flow fields.
- Mean wind velocity may be subtracted out resulting in eddy flow mapping of velocity.

APPENDIX C

PART I OF PRESENTATION BY  
DR. ROBERT W. LEE, LASSEN RESEARCH

## THE PROBLEM

- \* Operate on 2 scalar fields to produce vector field
- \* Produce user products from vector field
- \* Establish reliability of results

## DATA PROBLEMS

- \* Sparse measurements
- \* Irregular distribution
- \* Varying quality
- \* Imperfect orthogonality
- \* Aliasing due to sampling volume
- \* Measurements not simultaneous

## DESIRED ALGORITHM CHARACTERISTICS

- \* Tolerant of gross errors
- \* Wind field continuity
- \* Nearly complete fields
- \* Known data reliability
- \* Optimal use of measurements

## SOLUTION ELEMENTS

- \* Adaptive smoothing and interpolation
- \* Parametric fit to model
- \* Least-squares techniques
- \* Obtain error variance

## CHARACTERISTICS OF MODEL

- \* Must be able to represent actual field
- \* Parameters easily determined from data
- \* Model response controllable to match data
- \* Tune model using evaluation criteria

## SIMULATION ELEMENTS

1. Goals (user products, errors)
2. Wind fields (known properties)
3. Realistic velocity errors
4. Geometric errors
5. Solution algorithm
6. User products
7. Evaluation



## ALGORITHM STEPS

1. Obtain measurements & ancillary data
2. Establish data reliability
3. Edit data (assign weights)
4. Smoothing (adaptive fit to model)
5. Advection
6. Produce vector field
7. Produce user products plus errors
8. Evaluate results

## REQUIRED USER INPUTS

- \* Desired user products
- \* Evaluation criteria for these products
- \* Tradeoff considerations

**APPENDIX D**

**PART II OF PRESENTATION BY  
DR. ROBERT W. LEE, LASSEN RESEARCH**

**WINDFIELD RETRIEVAL FROM DOPPLER LIDAR OBSERVATIONS**

**Interim Technical Report No. 1**

**Contract NAS8-33389**

**Prepared for the George C. Marshall Space  
Flight Center, National Aeronautics and  
Space Administration, Huntsville, Alabama**

**June 1980**

**R. W. Lee**

**LASSEN  RESEARCH**

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**MANTON CALIFORNIA 96059**

## Abstract

An approach to the retrieval of a vector wind field from Doppler lidar observations is developed in general terms. The field of radial velocity measurements from each look angle is modeled by a smooth surface, the parameters of the model being determined from the data by least-squares techniques. The vector wind field and higher-order fields are obtained from the two modeled surfaces. Estimated measurement errors are taken into account, and error estimates are available for all output data sets.

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## I. Introduction

This report is concerned with the problem of retrieving vector wind measurements in a plane from radial wind measurements made in that plane using two different look angles. There are several possible approaches to this problem, but certain characteristics of the data require a certain amount of care in the selection of the approach.

The measurements are made by an airborne Doppler lidar system. The sensitivity of this system is limited, and the windfield tracer - naturally occurring aerosols - is not always present in sufficient quantities for a satisfactory return. For this reason the radial velocity measurements will vary greatly in accuracy, causing errors in the inferred vector field which will be magnified by the less than perfect orthogonality of the two look angles. Finally, the utility of the higher-order attributes to be derived from the vector windfield - vorticity and divergence, for example - will be limited by noise and error in the inversion process.

These considerations clearly suggest an inversion algorithm which is tolerant of gross measurement errors and which minimizes the effects of random errors in the data. Achieving these goals without greatly reducing the resolution of the measurements requires care.

Section II below consists of a more precise definition of the inversion problem. Elements of this definition are presented in detail in section III. The primary inversion steps of editing and smoothing are considered in section IV. Two related topics are discussed briefly in section V, while the steps required for implementation and evaluation of the suggested algorithm are outlined in section VI. This final step - the evaluation of the solution algorithm - is just as important as the selection of the algorithm itself. Only when the error characteristics of the solution are known can one interpret the measurements with confidence.



## II. Problem definition

Simply stated, the goal is to derive a two-dimensional vector field from two scalar fields. In practice, most of the data manipulation will take place on the separate scalar fields (see section V.B, however, for an alternate strategy), and conversion to a vector field becomes a final, trivial operation.

Since a solution to the problem posed depends upon the definition of that problem, some care must be exercised in characterizing the problem itself. Of particular importance here are certain problems inherent in the measurements, and the need for a considered definition of the properties desired in the solution.

### II.A. Problems with the data

The measurements of the two radial velocity fields may be sparse (missing data points), and they certainly will vary greatly in quality. These two attributes will be pre-eminent in the selection of a solution algorithm. In addition, the measurements are made on irregular grids, with no agreement between the measurement points in the two scalar fields. Finally, the two scalar observations are not orthogonal, making the conditioning of the scalar-vector transformation less than ideal.

### II.B. Desired results

It is not easy to quantify the characteristics required in the solution data set, but it is important to attempt to do so. The solution algorithm will be optimized according to these criteria, so obviously the criteria must be appropriate.

The general requirement is for smooth flow fields of known accuracy. These fields must be useful in a visual sense, and the errors in the statistical properties of these fields must be known and acceptably small.

### II.C. The solution in general terms

Clearly the path to the solution is one of data smoothing and interpolation. These steps must be accomplished in a way that is optimal given the data characteristics and the desired goals of the solution field. In addition, the solution must be efficient in that it makes use of all a priori information about the measurements.

#### II.D. Steps required for solution implementation

In addition to careful statement of the problem and the desired solution goals, selection of an algorithm requires a procedure for evaluation of the algorithm according to those goals. Such an evaluation will require operation on real and simulated data sets, with visual and statistical interpretation of the end products. Under these conditions the algorithm can be "tuned" and optimized for the actual characteristics expected of the raw data.

### III. Expanded problem definition

#### III.A. Specific nature of data relevant to optimal field retrieval

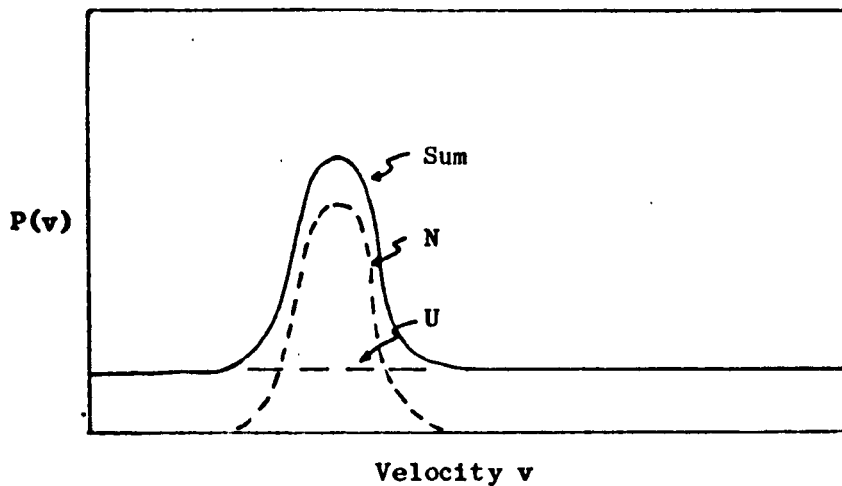
As mentioned above, the data is sparse. This may be due to range attenuation, lack of aerosols, or both. While missing data points will be a particular problem at long range, they can occur at any range.

The quality of the measurements will vary greatly. The Doppler estimator used for measurement of radial velocity has certain (known) error characteristics depending upon the signal-to-noise ratio of the signal return and the spectral width of the signal. The probability distribution of this error is sketched in figure 1. It consists of two parts: a normally-distributed term  $N$  and a uniformly-distributed term  $U$ . At very low signal-to-noise ratios the uniformly-distributed term gives rise to "wild" estimates of radial velocity, which account for most of the error variance.

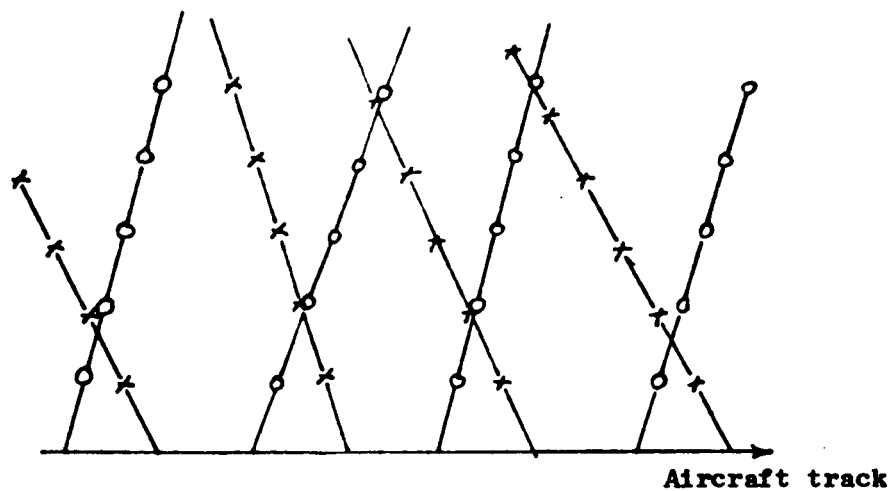
In addition to estimation errors produced by the Doppler processor there is an inherent sampling error present regardless of the signal-to-noise ratio. Since the Doppler return has finite bandwidth any finite realization of that return will be subject to an error variance due to sampling. At high signal-to-noise ratios this is the dominant error term.

The locations at which radial velocities are observed do not form a regular grid. The angles at which the observations are taken will vary slightly due to aircraft dynamics, as shown in exaggerated form in figure 2. The gridpoints of one scalar field will bear little or no relationship to those of the other field. The observation angles will not differ by the desired 90 degrees, but by approximately 40 degrees. This lack of orthogonality will magnify data errors in the vector component parallel to the aircraft track.

The spatial sampling of the laser beam presents further problems. The beam resolution cell is long (~300 m) and narrow (~30 cm radius); each measurement will consist of the average of a number of such cells displaced horizontally by approximately 1 meter. Such a resolution volume will average effectively in one spatial dimension (range), but not in the other two. The resulting under-sampling of the spatial windfield (particularly in the vertical dimension) will lead to an increased error variance in the data from aliased energy in the spatial windfield. This is further complicated by the fact that the measurements are not necessarily made in the desired plane, but at a horizontal angle subject to random excursions about zero. Indeed, the effect



**Figure 1:** Probability distribution of Doppler estimation errors for a certain signal-to-noise ratio.  $N$  and  $U$  are normally- and uniformly-distributed variance components.



**Figure 2:** Exaggerated observation grid.  $X$  and  $O$  represent backward and forward look angle data points.

will be reduced by intentionally jittering the vertical axis of the system to achieve some averaging in that dimension.

If the turbulent parameters of the windfield can be estimated - and this should be possible from the data itself - then the variance due to under-sampling can be estimated.

Finally, there is a data problem due to the fact that the two scalar fields do not result from simultaneous observations. The time lag between the observations varies with range, being on the order of 30 seconds at maximum range. This is sufficient time for the windfield to translate by one or more resolution cells, and it may be necessary to advect the measurements according to the local mean wind vector for an appropriate time interval (which may vary with range) in order to achieve the required time registration of the measurements.

### III.B. Inversion goals

The first use of the vector flow field will be visual, in the understanding of flow fields in the clear-air vicinity of severe storms. Thus the inferred vector field must be sufficiently smooth to allow the eye to trace parcel flow. Stated another way, the continuity between neighboring vector estimates must be reasonably high.

Aside from visual aesthetics the vector field must possess certain statistical properties. Useful vorticity and divergence fields must be obtainable from it. This in turn requires that the errors in the estimated divergence and vorticity be below some threshold (perhaps a certain percentage error) for a substantial percentage of the observations, and in addition that the errors themselves can be estimated. Obviously a vorticity estimate of 0.01/sec is not useful if the standard error is 0.1/sec, or if the error is unknown. The allowable errors in vector wind and higher-order functions, expressed as percentages at some confidence level, are very important inputs to the algorithm optimization and evaluation process.

Finally, the inverted data must be as complete as possible. Gaps in the derived fields must be filled where possible by interpolation, even though this may reduce resolution in the vicinity of the missing data points. Care must be exercised in such interpolation to ensure that good data points are not contaminated by bad.

### III.C. Generalized solution

In general smoothing and interpolation are achieved through the reduction in the degrees of freedom of the solution field below those of the input data, and through careful selection of those degrees of freedom retained in the solution. Only by sacrificing degrees of freedom - and here resolution - in the solution field can data reliability be enhanced and error variance estimated. Stated in spatial terms, resolution is reduced to obtain greater data stability. In spectral terms, knowledge of field components of high spatial frequency is sacrificed so that knowledge of lower spatial-frequency components will be enhanced. Clearly a balance must be struck somewhere in between the extremes: perfect knowledge of the mean wind on a 10x10 km square is of little value in the severe-storm program, as is no knowledge on a 100x100 m grid.

The general process of smoothing and interpolation is one of modeling. One selects a mathematical framework by which to model the output field, and determines the parameters of that model from the measurements.

The success of the smoothing process depends to a large extent upon the suitability of the model selected. The model must be appropriate in several respects. First it must be able to represent the natural features of the windfield adequately. It must be possible to control the spatial-frequency response of the model readily, to allow control over the smoothness of the solution. Finally, it must be mathematically tractable: a model is not useful if it takes an hour of computer time to invert a minute's worth of data.

Once a model is selected the parameters of that model may be determined from the data. Such a parameter fit may be achieved in a straightforward manner using least-squares techniques, but note that this requires use of objective error criteria. The solution is optimal in terms of these criteria, but one must make sure that the criteria are appropriate. In general these criteria will involve some compromise between spatial resolution and data stability, between smoothness or continuity and error variance.

Given that a model has been selected and the solution obtained for a certain set of error criteria, it remains to evaluate the probable errors in the various end products - wind vectors, vorticity, etc.

### III.D. Solution implementation

The generalized solution outlined above can be implemented in the following sequence:

1) Obtain data. In addition to recording the raw data, this step includes obtaining all ancillary data which will be useful in data interpretation - time and location, look angles, other meteorological data, etc.

2) Establish data reliability. From the signal-to-noise ratio estimate and other parameters, estimate the probable error of the velocity estimate. This error may consist of two parts with different probability distributions.

3) Editing. The data must be put into a form that the smoothing algorithm can use. In addition to assigning a weight to the data point reflecting its probable error, and assigning to that point coordinates, spectral width, etc., an additional operation is desirable. The measurement may be compared with neighboring points (in two dimensions) as a test of measurement continuity. If the measurement is discrepant its weight may be reduced. This process will remove to a great extent the effects of "wild" estimates produced by the uniform portion of the Doppler estimator error. This operation is explored in more detail in section IV.A.

4) Smoothing. This step includes solving for the model parameters in terms of the weighted data, interpolating where required, and reducing the resolution of the measurements where data quality is low. Estimates of error variances should be carried through this process. Finally, the solution field can be sampled on any desired grid. This operation is described in detail in section IV.B.

5) Produce vector field. The two scalar fields may be combined to form the vector flow field, again carrying through the estimated errors.

6) Produce end products. Higher-order fields may be obtained through operations upon the vector flow fields, in each case carrying error estimates through the process.

7) Evaluation. The last step is to evaluate the utility of the resulting end products. If there are serious problems with them, it must be determined from error propagation which aspect of the raw data most seriously compromises the result. If that data aspect cannot be corrected, it should be determined whether or not alterations in the model can reduce the effects.

#### IV. Detailed implementation

##### IV.A. Data editing

The goal of the data editing process is to produce data of known error characteristics for the smoothing algorithm. All information available must be brought to bear in evaluating a given data point. The following list includes the most important factors.

1) Signal-to-noise ratio. From the signal amplitude estimate at the range gate of interest, in comparison with the amplitude estimates at very large ranges (where no signal is expected), an estimate of the signal-to-noise ratio can be obtained. This estimate can be used in conjunction with the (known) error characteristics of the Doppler estimator to produce a probable velocity error estimate consisting of two parts as suggested above: a normally-distributed component and a uniformly-distributed component.

2) Spectral width. The Doppler estimator produces as a matter of course an estimate of the signal spectral width. Spectral width enters into the Doppler processor error equations. Note however that useful estimates of spectral width are not produced at very low signal-to-noise ratios.

3) Continuity. Continuity may be used in two dimensions as a check upon data consistency. Continuity tests may be applied to amplitude and width estimates as well. In a typical case the weighted median value of the eight neighboring points might be compared with the point in question. Note that the median or most probable value is more useful here than the mean value, since the mean can be severely disturbed by a single bad data point.

4) Constraints. The expected characteristics of the windfield can be used as a further check upon data integrity. For example, a constraint upon velocity gradients (shear) can be used as an input for continuity tests. Limits may be set upon maximum values of velocity as a test for reasonableness. As with all constraints, care must be exercised to ensure that actual features of the wind field which were not expected are not obscured. Use of adaptive or interactive constraints can achieve this goal.

Should a given data point fail one or more tests for reliability, the weight of that point may be reduced, or in severe cases a missing data point may be declared.

Note that the editing process can be combined with the smoothing or filtering process. A first fit of the data points gives a trial solution and



a deviation for each data point. These deviations are a measure of continuity and can be used to alter the weighting given the data. A second iteration of the solution gives a revised output field.

#### IV.B. Data smoothing

##### IV.B.1 General

Data points can be considered in isolation, but since smoothing implies that each data point has an influence upon its neighborhood it is useful to consider the two-dimensional measurements as forming the height of a two-dimensional surface. The process of data smoothing then becomes one of fitting a surface of a certain character as nearly as possible to the measurements, in (for example) a least-squares sense.

Each form of data manipulation can be interpreted in terms of a surface of a certain type. For example, point data may be considered to form a surface composed of blocks centered at the measurement points, the height of each block indicating the value of the measurement at that point. That is, the data point is the altitude of the surface for that grid square. A continuous surface can be created by placing the data points at the vertices of the surface, with straight lines joining the vertices defining the surface (that is, linear interpolation between the data points, with grid rectangles broken into two triangles by a single diagonal). Surfaces formed with continuous first- or higher-order derivatives require the overlapping influence of several measurement points at each point on the surface.

##### IV.B.2 Continuous surfaces

Continuous surfaces may be modeled by many analytic or elementary functions. The most commonly used functions are polynomials (including splines, Hermite and other orthogonal polynomials), Fourier series, Bessel functions and spheroidal functions. The choice of a basis function depends upon:

- 1) Suitability for the problem. Some functions lend themselves to a particular coordinate system or situation. For example, Bessel functions are often appropriate for cylindrical coordinates, and Fourier series for band-limited functions.

- 2) Mathematical ease of use. Polynomials, for example, offer few difficulties in integration or differentiation, no convergence problems, etc.

3) Parameter flexibility. The degrees of freedom of some functions can be easily "tuned" to control the parameters of the surface. For example, the small-scale wiggles of a surface modeled by a Fourier series are easily controlled by limiting the order of the series.

#### IV.B.3. Surface adaptability

Since the quality of the data varies from point to point on the surface, it may be reasonable to allow the nature of the surface to vary as well. That is, in regions of high data quality the smoothness constraint on the surface may be relaxed to allow the model to represent smaller-scale features. Conversely, in regions of poor or missing data surface smoothness must be constrained even further to preserve surface continuity. This trade-off between surface smoothness and resolution may be made in an adaptive manner, with the algorithm itself sensing the need for constrained smoothness.

#### IV.B.4. Suitable models for flow fields

Due to its easily-controlled spatial-frequency response, a Fourier surface is attractive. However, the difficulty of incorporating data of varying quality, on a non-uniform grid, is substantial. The model of choice is a locally-defined polynomial with a basis function of limited extent. Such a model offers ease of solution using least-squares techniques, no grid problems, controllable basis size and smoothness, and continuity to any desired derivative. Suitable basis functions would include linear, quadratic or higher functions over limited (sliding) basis regions, or spline functions.

As an example, consider the lowest-order surface fit. A region of influence is defined around a point for which surface height is to be estimated. Data points in this region of influence are summed in a weighted average, the weights being derived from the error variances assigned to those points, with (for example) an additional weighting function formed by a two-dimensional Gaussian centered at the estimation point. This weighted averaging is equivalent to fitting a local plane to the data in the vicinity of the estimation point. To achieve the accuracy desired, the size of the region of influence (defined by the two-dimensional Gaussian weighting function) can expand or contract as required to enclose a suitable number of measurement points. Such an approach is easily implemented, and sliding the Gaussian region of influence around the

plane gives a continuous estimation surface. However, with this simple approach shear in the windfield cannot be fitted by the model at each point; the result is a poor fit requiring increased smoothing.

Use of the next higher order surface solves the shear problem: at each estimation point one fits the height and slope of a plane surface. Shear is no longer a problem - the fitting errors are limited to curvature and higher-order derivatives.

At some point increasing the order of the model (that is, increasing the degrees of freedom in the solution) increases noise in the surface beyond a tolerable level. The optimum surface order remains to be determined; there will be a compromise between higher order and reduced region of influence which must be determined by simulation.

Splines are a particularly attractive form of polynomial basis function since the approximating functions are easily constrained to be continuous on the boundaries between grid points.

#### IV.B.5 Model fitting

Once a model has been selected and the controllable parameters defined, it remains to determine those parameters. The most suitable solution technique is the linear least-squares approach. The variable weights of the data points are easily taken into account, along with additionally-imposed geometrical weighting. One particular advantage of this approach is the availability with the solution of an estimate of the solution error variance.

Once the parameters of the surface have been determined, that surface may be sampled at any desired grid pattern.

## V. Short topics

### V.A. Spectral width and signal amplitude

Although they have received little attention thus far, the signal amplitude and spectral width are also measured by the Doppler processor. These two quantities may also be considered to form solution surfaces, and the same techniques described above may be applied to the estimation of the parameters of these surfaces: editing, smoothing and interpolation.

Additional redundancy is present in these measurements, since information from the two look angles may be combined.

Note that a portion of the apparent spectral width may be contributed by horizontal velocity shear within the target volume. Since the velocity field is being determined independently, it is possible to correct for this contribution under the assumption that the shear variance and the spectral width add incoherently.

### V.B. An alternate solution strategy

While this report has treated the data from the two look angles as being independent until their combination in the vector field, another approach is possible.

The wind field model may assume a single surface as a potential field. The measurements become directional derivative estimates of this surface, and techniques for surface reconstruction from derivative information can be used.

Note however that this process is strictly valid only when the divergence of the actual wind field is zero. Thus the potential field so derived will naturally produce a zero-divergence field. Divergence may then be recovered from the measurements by a second-stage solution, solving for a divergence field from the difference between the measurements and the inferred zero-divergence field. There may be a problem here since the divergence and circulation may be locally correlated.

## VI. Algorithm implementation and evaluation

### VI.A. Implementation of the surface-fitting model

This section is an outline of the steps required to take this solution technique from the generalized concept described in this report to the functional stage. The primary questions to be resolved at this point are:

- 1) Definition of the most appropriate surface model
- 2) Definition of the appropriate solution technique for that model

These two questions are inextricably joined. Their solution will arise through an iterative process of evaluation and optimization.

Once a model and a solution technique are chosen, they must be "tuned up" with reference to the practical problems of the data at hand. This must be done with the data end use firmly in mind, employing a well-defined evaluation technique and a set of evaluation criteria. Such tuning will determine the appropriate editing and weighting schemes, grid sizes and spatial resolution.

The suitability of the resulting algorithms is critically dependent upon the accuracy and realism of the evaluation technique, discussed in the next section.

### VI.B. Algorithm evaluation

Since the solution technique will be optimized through interaction with a process of evaluation, the technique will ultimately be optimal only in terms of that evaluation procedure. Only if the evaluation procedure reflects the realities of the data and the wind field can one expect the solution algorithm to be optimal for the data.

In addition to providing a test bed for optimizing the solution algorithm, evaluation provides two important byproducts:

- 1) Confidence in the results. If the user can take a real or synthetic wind field, probe it with a simulated lidar system, contaminate the data with reasonable errors, and still retrieve a useful approximation of the original wind field, then he can have some confidence in using the algorithm upon data for which there is no confirming data.

- 2) Error propagation. By use of simulation the errors in user products can be estimated in terms of the errors in the raw data. User products without error variance estimates are of marginal utility; this is especially true of higher-order products such as convergence.

The following items may be taken as defining the components of an evaluation program:

1) Goals. A set of target goals should be established, in probabilistic terms. For example, one might desire that the vector wind components be measured to 2 m/s 90% of the time, or that vorticity be accurate to  $10^{-3} \text{ s}^{-1}$  on a 1-km scale.

2) Input data sets. Both simulated and actual wind fields (taken from multiple-Doppler observations) are of value - the former for their controlled nature and the latter for their realism. Obviously the statistical properties of these fields must be accurately known.

3) Signal-to-noise ratio. For simulation purposes, realistic signal-to-noise ratios must be assigned to the data points on a random basis. This would include range variation, dropouts, Rayleigh statistics, etc. This signal-to-noise ratio will be used to assign probabilistic errors to the radial velocity simulations, so it is important that they be realistic.

4) Wild measurements. In the transition from signal-to-noise ratio to velocity error, an appropriate number of totally-random estimates must be included to reflect the component of Doppler estimator error which is uniformly distributed.

5) Geometry. The grid points and look angles should be varied in a random way with reasonable values of variance.

6) Solution. Given the velocity field as probed by the synthetic lidar system - noise and all - an estimate of the original velocity field may be obtained by using the solution algorithm under test.

7) User products. The output wind field estimate may be transformed into the desired end products: visual fields, statistics, higher order fields.

8) Evaluation. The errors and utility of the user products must be assessed through comparison with the initial data set, using the evaluation goals as criteria for success.

The results of this evaluation may suggest alterations in the model or solution technique, or may suggest that certain user products cannot be reliably obtained from data of the quality simulated. By varying the characteristics of the input data set, the sensitivity of the inversion process to data problems of a given type may be determined. These sensitivity factors may suggest certain constraints upon the experimental operation, in order to improve recovery of a given user product.

## VII. Conclusion

This report has suggested an approach to the retrieval of a wind field estimate from lidar measurements. This approach seems likely to draw the maximum amount of useful information from that data. Note however that some degradation of system resolution is required.

The emphasis of this approach is upon error analysis at all stages of the solution. It is felt that user products (wind fields, divergence fields, etc.) without explicit error estimates and confidence levels are of marginal value. This is particularly true of smoothed fields. A smoothed random field cannot be distinguished from the smoothed fields reported by dual Doppler observers, and one should have no confidence in such highly mathematical products unless shown an error propagation example.

With such error analysis techniques, including a carefully planned evaluation technique, one can be confident that one will know when the derived wind field has significance. This apparently modest claim is highly important when an experiment is likely to have marginal results: it is far more preferable to have a few good wind fields of known reliability - even if they represent only a small portion of the measured fields - than to have results of doubtful validity for all the data sets.

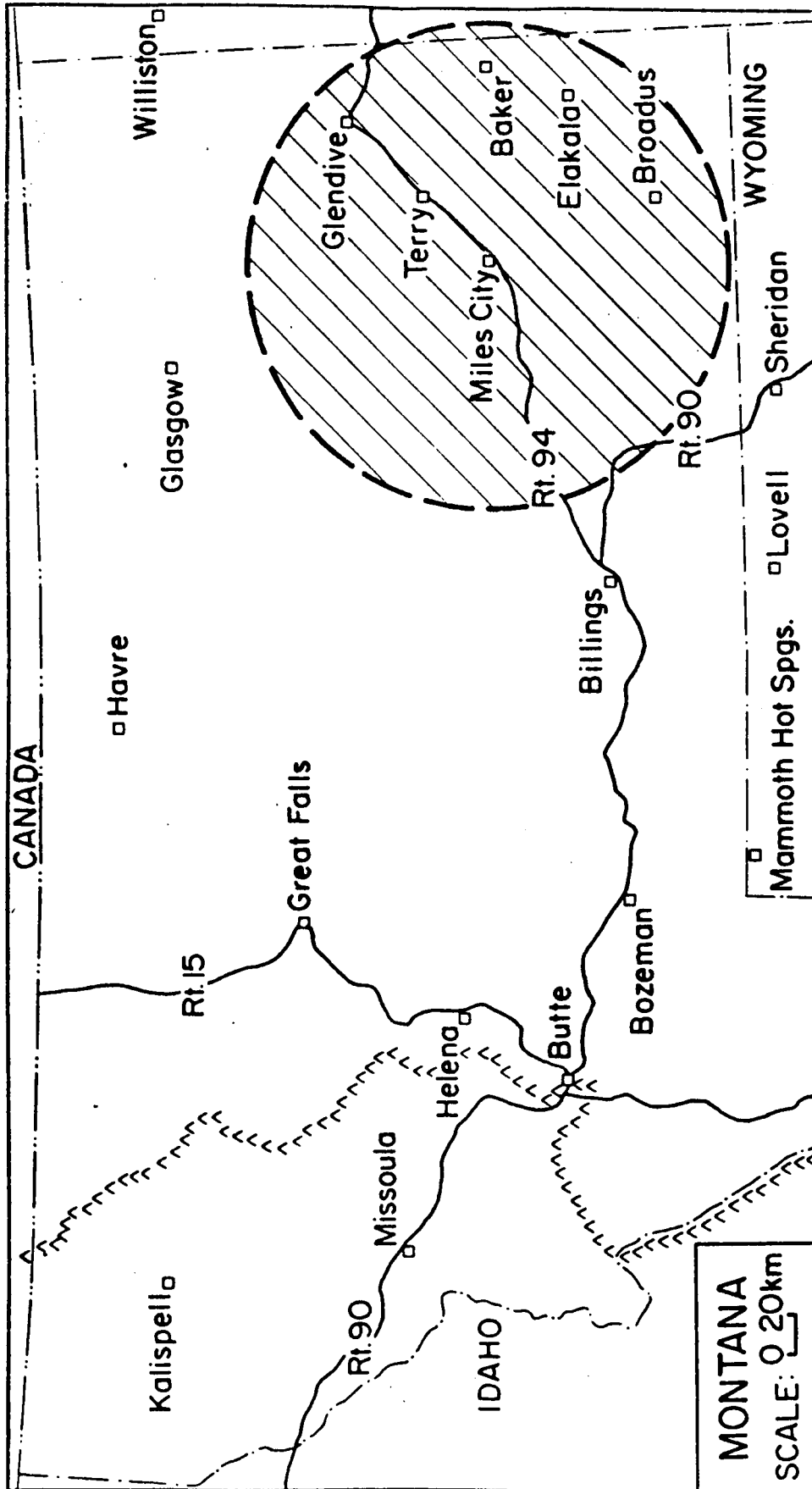
APPENDIX E

MATERIAL PRESENTED BY  
DR. LAVON J. MILLER, NCAR, BOULDER, COLORADO



COOPERATIVE CONVECTIVE PRECIPITATION EXPERIMENT

- COLOCATED WITH DEPT. OF INTERIOR, WATER AND POWER RESOURCE SERVICE, HIPLEX
- SE MONTANA AT MILES CITY
- IMPROVE UNDERSTANDING OF THE PHYSICS OF CONVECTIVE PRECIPITATION
- MAJOR EMPHASIS IS PLACED ON OBTAINING A GOOD DESCRIPTION OF WHOLE CONVECTIVE PRECIPITATION SYSTEM
- FRAMEWORK WITHIN WHICH SINGLE, SIGNIFICANT, TRACTABLE PROBLEMS ARE INVESTIGATED



SCIENTIFIC OBJECTIVES:

- HYDROMETEOR EVOLUTION
- PRECIPITATION EFFICIENCY
- ORIGINS OF ICE
- ENTRAINMENT OR MIXING
- STORM STRUCTURE AND ENVIRONMENT
- STORM INITIATION
- ATMOSPHERIC CHEMISTRY
- STORM ELECTRIFICATION

## HYDROMETEOR EVOLUTION:

- GROWTH THROUGH ICE PROCESS
- TRAJECTORIES, GROWTH ENVIRONMENTS AND SIZE DISTRIBUTIONS OF GRAUPEL, RAIN AND HAIL
- GRAUPEL AS EMBRYO OF HAIL AND RAIN
- ICE PROCESS IS TOO SLOW TO FORM PRECIPITATION WITHIN MODERATE ( $\approx 10 \text{ MS}^{-1}$ ) UPDRAFTS IN STRAIGHTFORWARD WAY
- PRECIPITATION-SIZED ICE PARTICLES ARE OBSERVED IN MODERATE TO STRONG UPDRAFTS

PRECIPITATION EFFICIENCY:

•PART OF MORE GENERAL WATER BUDGET SPECIFICATION

•AMOUNT OF WATER VAPOR INPUT VERSUS AMOUNT OF  
PRECIPITATION OUTPUT

•MAJOR FACTORS IN MOISTURE BUDGET OF CLOUDS

UPWARD FLUX OF VAPOR IN UPDRAFT

DOWNWARD FLUX OF PRECIPITATION IN DOWNDRAFT

EVAPORATION WITHIN PRECIPITATION SHAFT

CONVERSION OF CLOUD DROPLETS TO PRECIPITATION

ENTRAINMENT OR MIXING OF CLEAR AIR INTO CLOUDY AIR

ORIGINS OF ICE:

- DOMINANT MECHANISM OF PRECIPITATION FORMATION IS DIFFUSIONAL GROWTH OF ICE CRYSTALS FOLLOWED BY ACCRETION (RIMING) OF CLOUD DROPLETS BY ICE PARTICLES
- ENVIRONMENT WITHIN WHICH EARLY FORMATION OF ICE OCCURS
- WHICH ICE PARTICLES BECOME PRECIPITATION EMBRYOS
- RELATIONSHIP BETWEEN IN-CLOUD ICE PARTICLE CONCENTRATIONS AND ICE NUCLEUS CONCENTRATIONS FOUND IN THE INFLOWING AIR

ENTRAINMENT OR MIXING:

- DRIER ENVIRONMENTAL AIR MIXES WITH CLOUDY AIR
- PROCESS OCCURS BOTH LATERALLY AND VERTICALLY
- FULLY THREE-DIMENSIONAL AND TIME-VARYING
- SCALE SIZES AND PARTITIONING OF RELATIVE IMPORTANCE

STORM STRUCTURE AND THE ENVIRONMENT:

- GENERAL DESCRIPTION OF PHYSICAL CHARACTERISTICS OF STORMS AND THE ENVIRONMENT WITHIN WHICH THEY DEVELOP, INTENSIFY AND DECAY
- ENCOMPASS (REALISTICALLY) SCALES FROM SMALL CONVECTIVE ELEMENTS OR CELLS ( $\sim 2-5$  KM) TO STORMWIDE ( $\sim 10-50$  KM)
- DYNAMICS OF CELL GENESIS - GROWTH AND INTERACTION AS WELL AS INTERNAL MECHANISMS
- PROCESSES ACTING TO DETERMINE CELLULAR STRUCTURE



STORM INITIATION:

- GENERAL PROBLEM OF INITIATION OF CONVECTION
- INTENSIFICATION AND ORGANIZATION OF BROAD SCALE CONVECTION INTO SPECIFIC STORMS
- ROLES OF ELEMENTS SUCH AS TOPOGRAPHY, ATMOSPHERIC WAVES, EXISTING STORMS, SYNOPTIC FRONTS AND TURBULENCE

ATMOSPHERIC CHEMISTRY:

- EFFECT OF CLOUDS ON CHEMISTRY OF THE ATMOSPHERE
- CLOUD AND PRECIPITATION CHEMISTRY IN GREAT PLAINS  
 COMPARED TO EASTERN UNITED STATES

STORM ELECTRIFICATION:

- CLIMATOLOGY RELATING LIGHTNING TO STAGES OF CLOUD  
 DEVELOPMENT
- SPECIFICATION OF ELECTRIC FIELD DEVELOPMENT ABOVE  
 CLOUD TOP
- STUDY MAJOR THUNDERSTORM ELECTRIFICATION MECHANISMS

## FACILITIES:

- RADAR - SURVEILLANCE AND 7 DOPPLER RADARS (2 ARE DUAL-WAVELENGTH)
  
- SURFACE - WPRS ~100 MESOMETEOROLOGICAL STATIONS, 50 AT 40 AND 20 KM SPACING, NCAR (PAM) ~28 STATIONS PLUS REMAINING WPRS STATIONS AT ~8 KM SPACING
  
- UPPER AIR - WPRS (2) AND NCAR (2) SONDES WITH NASA (10) AT ~50-60 KM SPACING
  
- SATELLITE - COLORADO STATE UNIVERSITY COLLECTS AND ANALYZES VISIBLE AND INFRARED FROM GOES-EAST VISSR
  
- AIRCRAFT - 12 TO 13 POWERED AND 1 GLIDER

RADARS:

•NCAR/FIELD OBSERVING FACILITY

CP-2 (S-BAND DOPPLER, X-BAND INCOHERENT)

CP-3 (C-BAND DOPPLER)

CP-4 (C-BAND DOPPLER)

•UNIV. CHICAGO - ILLINOIS STATE WATER SURVEY

CHILL (S-BAND DOPPLER, X-BAND INCOHERENT)

•NOAA/WAVE PROPAGATION LABORATORY

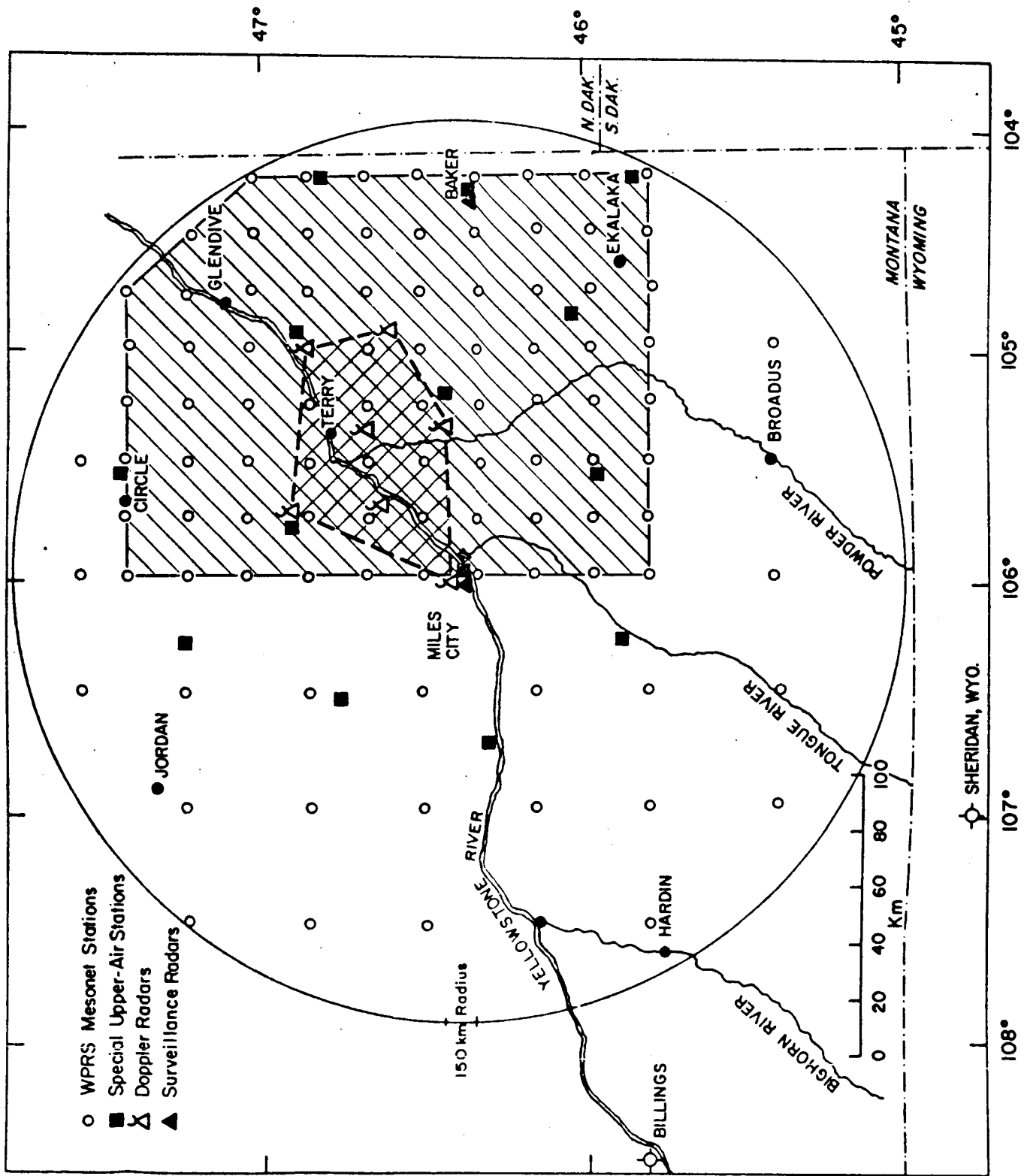
WPL-C (X-BAND DOPPLER)

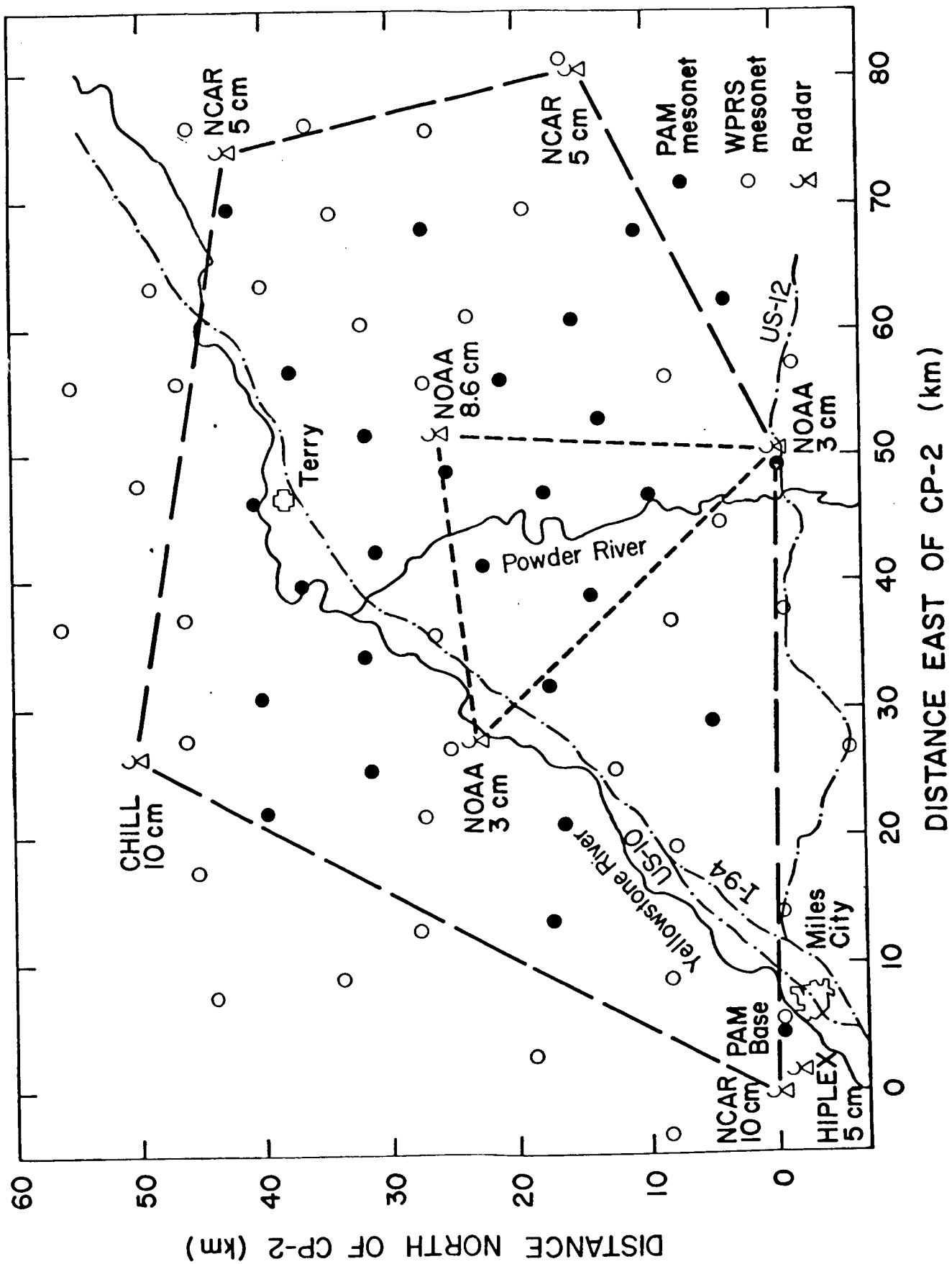
WPL-D (X-BAND DOPPLER)

WPL-E (K-BAND DOPPLER, DUAL POLARIZATION)

•HIPLEX

SWR-75 (C-BAND INCOHERENT)





AIRCRAFT:

- NATIONAL CENTER FOR ATMOSPHERIC RESEARCH (NCAR)  
BEECHCRAFT QUEEN AIR, N304D  
BEECHCRAFT QUEEN AIR, N306D  
NORTH AMERICAN ROCKWELL SABRELINER, N307D
  
- NCAR/NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA)  
SCHWEIZER 2-32 SAILPLANE, N9929J  
CESSNA 180, N52032
  
- UNIVERISTY OF WYOMING  
BEECHCRAFT SUPER KING AIR 200, N2UW  
BEECHCRAFT QUEEN AIR, N10UW
  
- SOUTH DAKOTA SCHOOL OF MINES AND TECHNOLOGY (SDSM&T)  
NORTH AMERICAN T-28, N510MH
  
- NATIONAL RESEARCH COUNCIL OF CANADA (NRC)  
DE HAVILLAND TWIN OTTER, CF-POK-X
  
- COLORADO INTERNATIONAL CORPORATION (CIC)  
LEARJET 23, N88TC
  
- NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA/GODDARD  
SPACE FLIGHT CENTER  
WB-57F
  
- UNIVERSITY OF NORTH DAKOTA (UND)  
CESSNA CITATION II
  
- COMMERCIAL OPERATOR  
PHOTOGRAPHIC/CHAFF AIRCRAFT

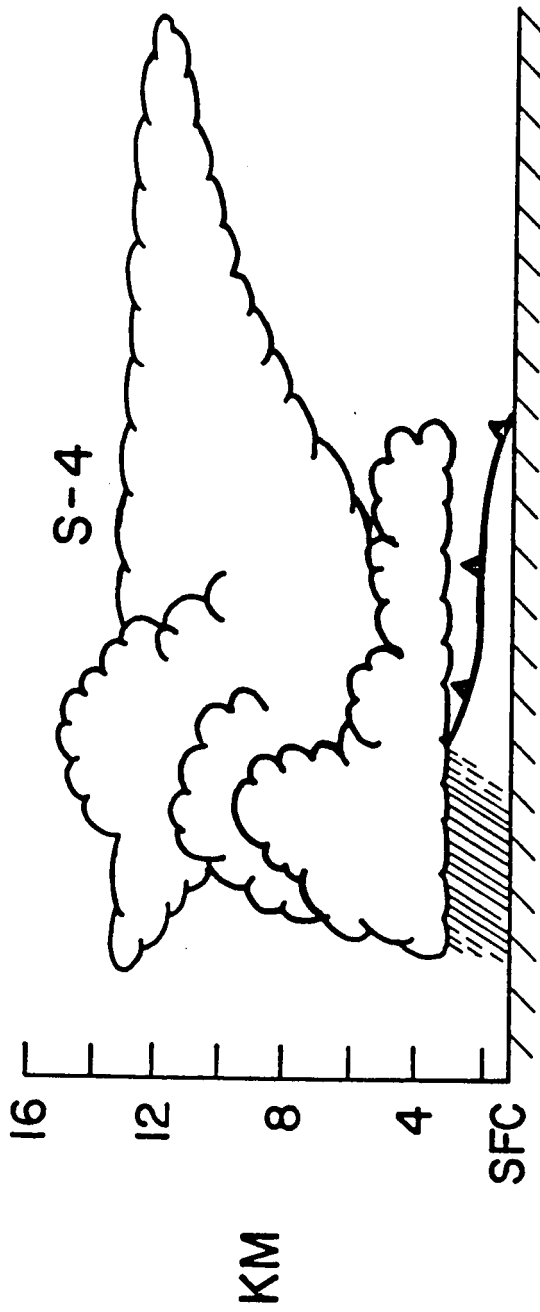
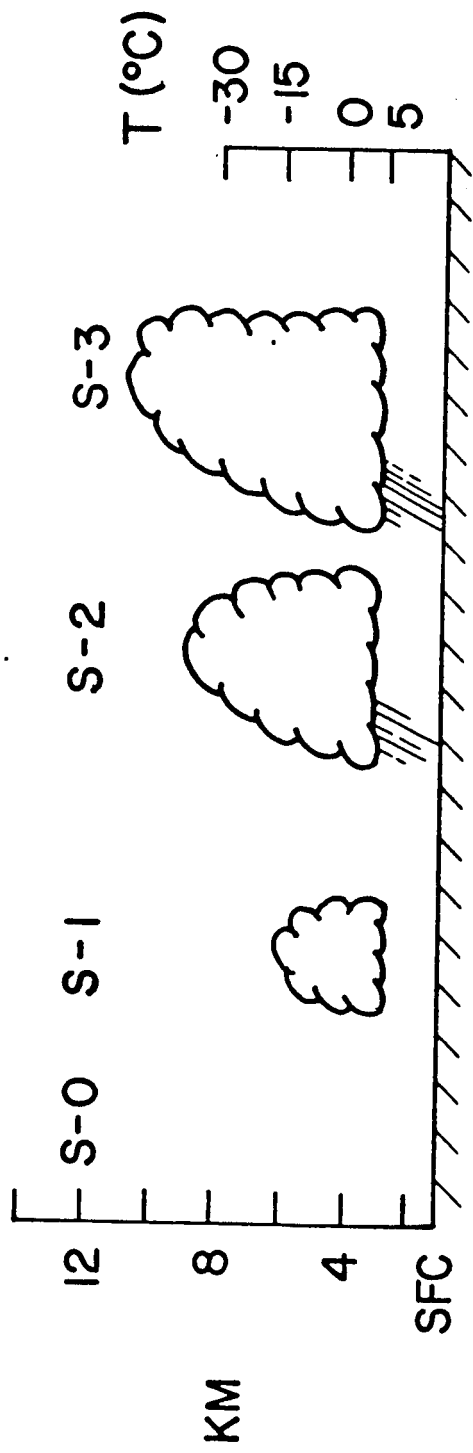
## AIRCRAFT MEASUREMENTS:

- POSITION - MULTIPLE AIRCRAFT POSITIONING SYSTEM  
(~10 TRACKABLE)
- PRESSURE, TEMPERATURE AND DEW POINT
- WINDS - HORIZONTAL, VERTICAL AND TURBULENT
- CLOUD AND PRECIPITATION PARTICLES
  - LIQUID WATER CONTENT
  - PARTICLE SIZE DISTRIBUTIONS (PARTICLE MEASURING SYSTEM PROBES, CAMERA, FOIL IMPACTOR, HAIL SPECTROMETER, ICE PARTICLE COUNTER, PARTICLE REPLICATOR)
- NUCLEI POPULATIONS
  - MEMBRANE FILTERS, IMPACTOR SLIDES, AND EXPANSION CHAMBER
- CLOUD PHOTOGRAPHS
- SURFACE INFRARED TEMPERATURE
- ELECTRIC FIELD AND ELECTRICAL CONDUCTIVITY
- CLOUD TOP TEMPERATURE AND ALTITUDE
- INTEGRATED CLOUD LIQUID WATER CONTENT AND PRECIPITATION PHASE



EXPERIMENTAL APPROACH:

- STUDY ENTIRE LIFETIMES OF CONVECTIVE CLOUDS
  
- FIELD OPERATIONS ORGANIZED INTO THREE (ARBITRARY)  
STAGES
  - PRESTORM
  - EARLY STORM
  - MATURE STORM



PRESTORM:

- BOUNDARY LAYER HEATING AND MOISTURE CONVERGENCE THAT START CONVECTION
  
- MECHANISMS OF CONTINUANCE OR REGENERATION OF STORMS
  
- CONTINUOUS SURVEILLANCE FOR WEATHER NOW - AND FORECASTING, DESCRIBING BACKGROUND KINEMATIC AND THERMODYNAMIC STRUCTURE OF THE ATMOSPHERE AND DESCRIBING AREAS IN WHICH DEEP, MOIST CONVECTION IS INITIATED
  
- INTENSE SURVEILLANCE FOR INSPECTION OF ATMOSPHERIC CHARACTERISTICS WITHIN AREAS OF OCCURRENCE OF DEEP, MOIST CONVECTION
  
- MEASUREMENTS CONCERNED MOSTLY WITH BROAD SCALE PHENOMENA WITH EMBEDDED SMALLER SCALE PROCESSES

EARLY STORM:

• CONCERNED WITH SMALL CLOUDS AND EARLY PHASES OF MATURE STORMS

• OBJECTIVES

SPECIFICATION OF ENTRAINMENT OR MIXING PROCESSES

DETERMINATION OF PRIMARY ICE FORMATION REGIONS

DEFINITION OF PRECIPITATION GROWTH TRAJECTORIES

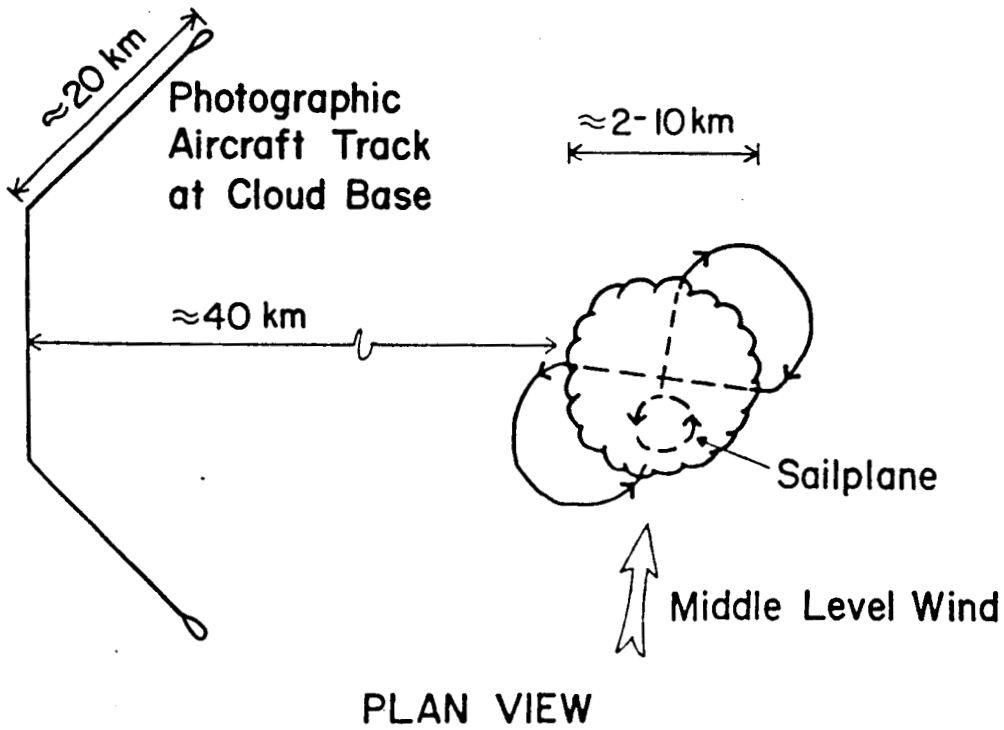
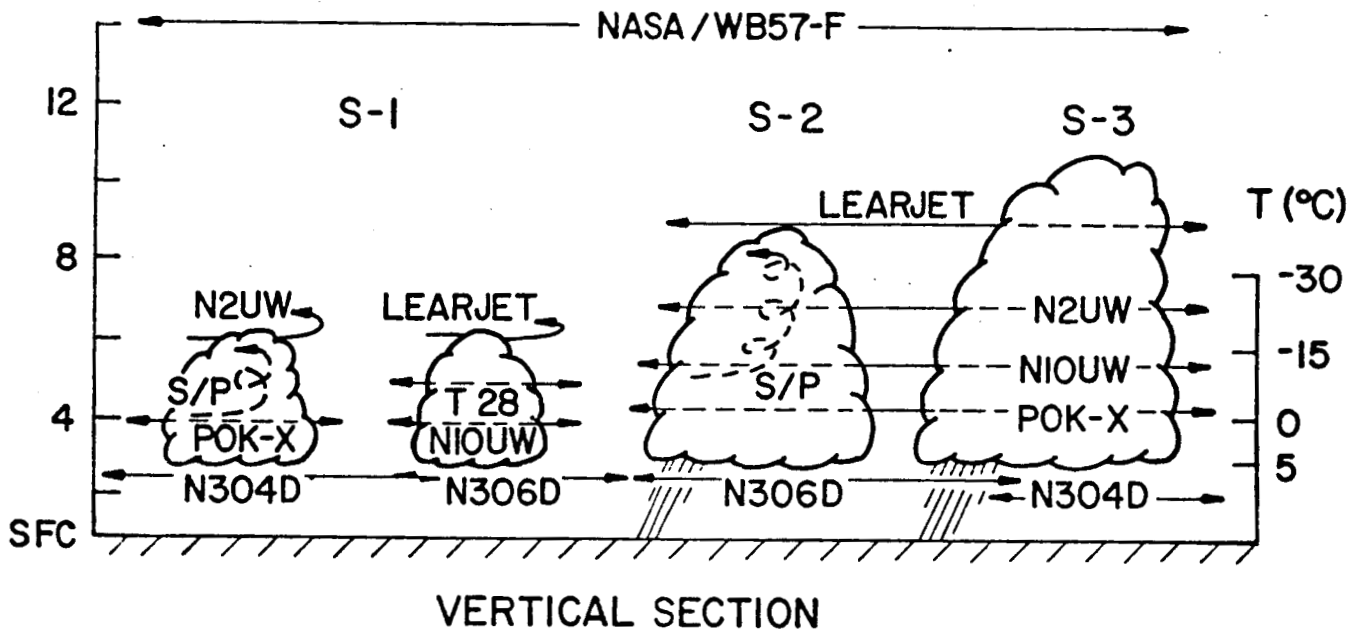
ELUCIDATION OF CLOUD EFFECTS ON AEROSOL AND CLOUD CONDENSATION NUCLEI POPULATIONS.

• SMALLER SPATIAL SCALES (~100'S OF METERS)

• SHORTER TIME SCALES (~1-2 MINUTES)

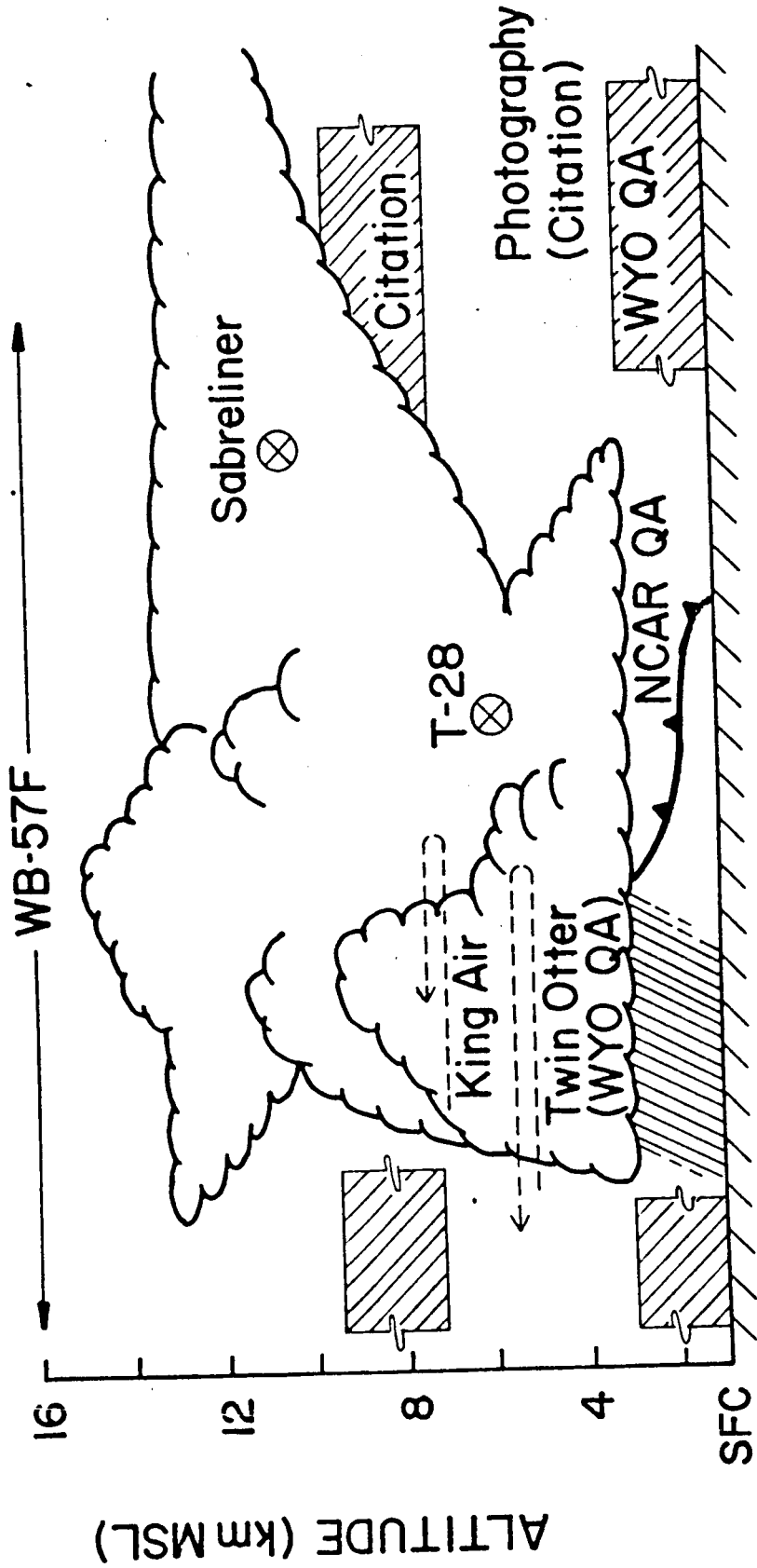
• MULTIPLE AIRCRAFT PENETRATIONS AND GLIDER ASCENT

• RADAR DETECTION OF SMALL PARTICLES AND CHAFF FOR WIND DETERMINATION



MATURE STORM:

- CHARACTERIZED BY TOPS IN EXCESS OF  $\sim 9$  KM MSL OR REFLECTIVITIES GREATER THAN  $\sim 45$  DBZ
  
- OBJECTIVES
  - SPECIFICATION OF HYDROMETEOR EVOLUTION
  - DESCRIPTION OF STORM STRUCTURE AND EVOLUTION
  - DETERMINATION OF WATER BUDGET COMPONENTS AND FACTORS AFFECTING PRECIPITATION EFFICIENCY
  - INVESTIGATION OF ENTRAINMENT OR MIXING PROCESSES
  
- SPATIAL SCALES FROM CELLS TO STORM ( $\sim 2-50$  KM)
  
- TEMPORAL SCALES OF  $\sim 2$  MIN TO STORM LIFETIMES
  
- AIRCRAFT MEASUREMENTS IN NEAR ENVIRONMENT AND T-28 PENETRATIONS
  
- RADAR MAPPING OF PRECIPITATION AND KINEMATIC STRUCTURE



DATA MANAGEMENT AND ANALYSIS:

- FIELD QUALITY CONTROL
  
- LEVEL 1 DATA (FROM DEVELOPED INSTRUMENTATION)  
REDUCED AND ARCHIVED TO SPECIFIED DEGREE  
• AVAILABLE TO ALL PARTICIPANTS AS SOON AS POSSIBLE
  
- LEVEL 2 DATA (FROM EXPERIMENTAL INSTRUMENTATION)  
SPECIAL REDUCTION AND LIMITED ARCHIVING  
AVAILABILITY NEGOTIABLE WITH PRINCIPAL INVESTIGATOR
  
- CASE STUDY APPROACH TO DESCRIBE STORM
  
- SPECIFIC ANALYSES FOR HYPOTHESES TESTING



OPERATIONS AND SCHEDULES:

• EXPERIMENTAL PERIOD FROM EARLY MAY THROUGH EARLY  
AUGUST, 1981

• OVERALL COORDINATION FROM OPERATIONS CENTER AT  
MILES CITY

OPERATIONS DIRECTOR  
CP-2 SCAN CONTROLLER  
DOPPLER RADAR COORDINATOR  
AIRCRAFT COORDINATORS  
T-28  
ABOVE CLOUD BASE  
BELOW CLOUD BASE

• TIME TABLE

CCOPE OPERATIONS PLAN: NOV. 1980-FEB. 1981  
PARTICIPANTS MEETING: FEB. 1981  
DISTRIBUTION OF OPERATIONS PLAN: MAR. 1981  
INSTALLATION AND CALIBRATION OF OBSERVING  
SYSTEMS: MAR.-APR. 1981  
REHEARSAL: MAY, 1981  
FIELD PROGRAM: MAY-AUG. 1981  
REMOVAL OF FACILITIES AND INSTRUMENTS: AUG.-OCT.  
1981

APPENDIX F

PART II OF PRESENTATION BY  
DR. GEORGE H. FICHTL, MSFC

ORGANIZATION:

MARSHALL SPACE FLIGHT CENTER

NAME:

G. H. FICHTL

TEAM ACTIVITIES

DATE:

AUGUST 1980

ES82

- FORM INTO TEAMS, 1:00 P.M., AUGUST 25, 1980
- SELECT A TEAM CHAIRMAN
- IDENTIFY AND DEVELOP FLIGHT TEST OPTIONS
- IDENTIFY AND DEVELOP POST FLIGHT DATA PROCESSING AND DATA SETS REQUIREMENTS
- REVIEW REAL TIME DATA DISPLAY PROCEDURES
- IDENTIFY ADDITIONAL SUPPORT EQUIPMENT NEEDED ON THE CV-990 AIRCRAFT FOR FLIGHT TESTS
- REPORT RESULTS TO SCIENCE WORKING GROUP - 10:00 A.M., AUGUST 26, 1980

ORGANIZATION

MARSHALL SPACE FLIGHT CENTER

TITLE

G. H. P.

ES82

# EXPERIMENTS REQUIREMENTS

DATE

AUGUST 1980

- DEFINE ATMOSPHERIC PHENOMENA TO BE PROBED
- DEFINE AIRCRAFT TRAJECTORY REQUIREMENTS
  - RELATIVE TO ATTRIBUTES OF PHENOMENA TO BE PROBED, E.G.
    - RELATIVE TO RIDGE LINE FOR MOUNTAIN WAVES
    - RELATIVE TO MEAN WIND VECTOR FOR BOUNDARY LAYER ROLL STUDIES
    - RELATIVE TO THUNDERSTORM COLD AIR OUTFLOW
- DEFINE HORIZONTAL TRAJECTORY OF AIRCRAFT
- DEFINE ALTITUDE ALONG TRAJECTORY
  - ETC.
- DEFINE DATA ACQUISITION REQUIREMENTS
  - RANGE RESOLUTION,  $\Delta R$
  - GROUND TRACK RESOLUTION,  $(\Delta X)_D$
  - DISTANCE BETWEEN DATA POINTS ALONG GROUND PATH,  $2D$
- DEFINE POST FLIGHT DATA PROCESSING AND DATA SETS REQUIREMENTS

MARSHALL SPACE FLIGHT CENTER

ES82

WORKING TEAMS

G. H. FICHTL

AUGUST 1980

CONVECTIVE PHENOMENA TEAM

H. ORVILLE  
 J. TELFORD  
 J. MILLER  
 G. WILSON  
 R. KOENIG  
 D. BOWDLE  
 B. JONES\*  
 R. W. LEE ▲

SECONDARY FLOWS, BOUNDARY LAYERS,  
 TURBULENCE, WAVE TEAM

J. SCOGGINS  
 W. FROST  
 D. FITZJARRALD  
 R. DOVIK  
 W. CLIFF  
 J. CAHIR  
 R. MURTY  
 C. BUCK ▲  
 H. JEFFREYS ▲\*  
 S. JOHNSON\*

FLOAT TEAM

G. H. FICHTL/J. KAUFMAN  
 J. BILBRO\*/C. DIMARZIO\*  
 E. WEAVER\*  
 G. ALGER 7

\*HARDWARE

▲ DATA PROCESSING

▽ FLIGHT OPERATIONS

APPENDIX G  
REPORT OF CONVECTIVE PHENOMENA TEAM

The First Scientific Working Group Meeting

MSFC Airborne Doppler Lidar Wind Velocity Program

NASA/MSFC, 25-26 August 1980

Report of Convective Phenomena Team.

H. Orville, R. Koenig, J. Miller, J. Telford.

B. Jones, G. Alger, R. Lee, D. Bowdle.

1. Introduction and Flight Plans

A Group meeting was assembled to focus on the planning of specific experiments, to establish some priorities, identify interested scientists who would like to participate, establish any special requirements, make recommendations on data processing, and to prepare flight plan outlines.

The types of experiment of interest to the group were discussed first, without regard to priorities or importance. After the ideas had been explored, it became clear that since the number of convective storms in the CCOPE (Cooperative Convective Precipitation Experiment) field experiment area would be limited to only a few days during the operational time period the flight plans had to be designed with a hierarchy of abort experiments so that the easily identified and lowest probability events should take priority until their quota is filled. It was estimated from the basis of 60 flying hours total, from which testing and ferry time must be deducted, that optimistically 45 hours flying would be available in the CCOPE experimental area. With five hours per flight this would be 9 flights, from which 3 would likely to be aerosol experiments which could not combine with the Convective requirements. This leaves 6 flights of 5 hours each for planning

purposes of the Convective team.

The CV990 aircraft would probably be based at Ellsworth A.F.B. near Rapid City (210 miles to Miles City) or Minot A.F.B. (260 miles to Miles City) near Minot. And since it is desirable to cruise at 25000 ft. the pilots should have a good view of the cloud top situations from 10 minutes or more before reaching the measurement area. Thus a flight plan to explore the outflow around Cumulo-nimbus anvils can be chosen at this time when such cloud conditions are present. If Cumulo-nimbus anvils are not visible at this stage, but we see clearly defined, growing, and decaying, cumulus turrets, below, say, 30,000 ft. then the entrainment study can be selected.

Since it takes a 2 hour period to prepare for a flight, and probably an hour from the decision to take-off to reaching the vicinity of the experimental area, there may be occasions when the cloud field we encounter on the site will be unsuitable for either of these measurement programs. In these cases a decision will have to be made as to whether to implement some study in the boundary layer, or to sacrifice the ferry time to site and abort the mission by returning to base. Another alternative is to seek targets of opportunity beyond the CCOPE support area, and anyhow it is possible that interesting measurements can be obtained during the ferry run to the target area. For example it is of interest to look at particle reflectivities in cirrus cloud.

Flight patterns below cloud cannot be discussed in detail at this present time since tight cooperation with CCOPE operations will be essential for work in this area below cloud but we request such support. The study of storms gust front dynamics, another high priority mission we also wish to recommend, will be particularly sensitive to careful coordination.



The other experiment below cloud, to study the feeder flow for small, non-precipitating cumulus, may be best carried out away from the storm of prime interest to CCOPE. In this case the aircraft will be below cloud so that the selection of suitable individual clouds will not be possible and long straight runs are probably the preferred observation mode.

A very interesting data set could be gathered by flying encircling squares around a moderate sized growing cumulus at levels from above cloud tops to below cloud base. However since this lidar device requires clear air for its successful use there is some doubt as to whether there will be adequate useful opportunities, since the requirement is that a cloud is sufficiently isolated, from a base say at 10,000 ft., to, say, 16,000 ft., so as to leave about 10 miles cloud-free air around it in all directions. If this occurs it should be taken as a target of opportunity.

Other targets of opportunity should be accepted during instruments check out flights. If marine stratus is encountered near Moffat, or the clear air boundary layer, or cirrus, these would also be possible targets at this stage.

## 2. Detailed Instrumentation Considerations and Target Area Flights

### Plans

#### (a) Rectangles around clouds.

The measurements will be taken in non-turning level flights except for the cloud-top entertainment studies. This requirement is set by the need to intersect every air parcel twice with a horizontal beam, if the two horizontal components of velocity are to be derived. It should also be noted that the air velocity is being measured relative to the

velocity of the instrument within the aircraft. Thus any relative movement between the optics of the lidar and the velocity reference given by the initial platform, will appear in the final result as an error, unless this displacement, and relative velocities and angular rates, are included in the processing operations to derive the true velocity. Rapid vibration is virtually impossible to account for in this way, and hence must be eliminated mechanically. Flexure of the airframe and mounts needs to be examined to be sure they are negligible at the hoped for accuracy, which we understand can be a fraction of a meter per second. The separation between the lidar and the platform will produce a velocity difference when the attitude of the aircraft is changing, heading is probably the largest component, and this must be corrected for. Thus inertial velocity (3 axis) and attitude (3 axis) must be recorded fast enough to allow smooth differencing to give rates covering the maximum response frequency of the aircraft, say, 2 cycles per second. The vibration modes of the platform should be checked to ensure that no appreciable motion occurs beyond the recording frequency, since then aliasing would inject false motion into the data.

A problem exists in obtaining precise verification of the instrumental performance since detailed matching of the air velocity of parcels in turbulent motion with, say, a radar chaff echo, is likely to be impossible, so that only smoothed averages can be checked. Thus if the atmospheric scientists using the data are going to have confidence in the measurements every precaution will need to be taken to demonstrate that we have accounted for all errors. No new discovery can be made with measurements which cannot be trusted.

Each encircling flight to measure air motion around a cloud anvil will need to have flight legs parallel and perpendicular to the shear.

Since the lidar device points out from the left hand side of the aircraft only the velocities on the left hand side can be measured. Because turning-flight prevents the normal sampling density fore and aft it was the opinion of the convective team that all turns during sampling rectangles should be right hand turns of 270 degrees of arc, so that the straight and level flight would extend to the extremes of the area under study, which would often encompass a storm cloud and hence contain inaccessible areas because of cloud obscuration. With an estimated reliable range of 10 km (10 miles max.) it was felt that the opposite legs of the rectangle should be about 20 km apart, provided the cloud fitted comfortably within this dimension. In enclosing a cirrus anvil the legs heading down shear would usually need to be extended, perhaps to 100 km on occasions, to examine a large part of the ice crystal region.

There is a real question as to whether the scattering aerosol will be dense enough at the higher levels to give lidar returns. If the returns are too uncertain these data gathering ideas will have to be revised.

For the rectangles below the level of the anvil it is important to examine the air in the direction down shear, but below the anvil, where the air is free of ice crystals. This air will probably show signs in the moisture and velocity fields of having been part of the cloud a little earlier. Thus these rectangles should cross beneath the anvil as close to the cloud as the pilots feel can be accomplished without risks of encountering hail. Modifications of these plans may have to be made on site to avoid precipitation, or flying too much in surrounding cloud, which will obscure the lidar.

It is a requirement for the software to clearly distinguish the

cloud edge in a lidar return and ensure that the cloud edge is clearly delineated on all plan plots, such as that of velocity. It was felt that the proposed velocity vector field was too complex to be assimilated where the tag on the wind vector needed to be interpreted for both length and angle. It was suggested that a better display would be to have a simple arrow for wind magnitude and direction with a blob as an arrowhead, where the area of these elements represented range corrected echo intensity (and to display velocity variance separately). The aim would be to have the density of an area proportional to its reflectivity.

It was generally felt that an experimenter needed to receive a raw data tape with all the data merged to a single tape which he could readily read into a Fortran (or other) language program.

(b) Cloud top Study

The second level experiment to be chosen in flight is based on the need to study motion of the cloud surface at the top and sides of cloud turrets where it is thought the entrainment of dry air into the cloud begins. Since, ideally, we need the vertical component of the motion of the cloud edge, because the buoyant energy release transfers initially to vertical motion, a single doppler lidar beam looking downwards would be the first choice. However since there are theoretical reasons for expecting that the component of velocity responsible for the entrainment is the component perpendicular to the cloud surface, and since the normal small wandering of the aircraft heading will prevent locating the beam on any particular spot of cloud, there seems no reason why a beam pointed down at 45 degrees of arc below the horizon while the aircraft circles above cloud top should not give extremely valuable information.

To begin with, until the operation and cloud behaviour are better understood, this is probably the preferred choice, anyhow.

Thus the flight plan calls for the aircraft to circle above the cloud turret. Since the lidar beam can be deflected downwards by 20 degrees by the optics, then 30 degree banks on the aircraft would be a suitable flight parameter for determining the height and turning radius. Some sort of crude optical sighting device in the cockpit could be used to assure the pilot that he was maintaining radar contact with the chosen cloud turret top.

In this operation we are seeking to obtain a detailed knowledge of how the surface of the cloud responds to the in-cloud turbulence, and how this results in exterior dry air entering the cloud through this surface boundary. Thus we would request that the capacity of the data system be devoted to recording as much information as possible about the regions of penetration just into the cloud surface, and from the air just outside. The fore and aft scanning procedure would need to be stopped, and by using the computer to range gate over say 10 to 20 bins at the cloud edge, and using individual 1 micro-second pulse gates without any averaging, the full data capacity could be devoted to this narrow range of interest. This range selection would need to be a continuous software monitored function. It is also desirable to use software amplitude control to avoid saturation of the cloud edge, so that diluted cloud regions, where evaporation has reduced the liquid water content, can be faithfully recorded for intensity of echo as well as for their velocity profile.

It would be nice to scan across the cloud surface so that successive radar hits were contiguous, but this is too much to expect, except by relying on chance scans like this every now and again in the

records. It is essential to have a video camera coaxial with the lidar beam to record the cloud surface visually in real time as these flights proceed. Visible time on each frame is needed. In this way the wander velocity of the cloud image should be visibly evident. With care it may be possible for the pilot to maintain the cloud image rotating smoothly in the beam, so we measure an advancing track around the cloud turret.

It is not clear what duration of this circling flight can be maintained with accuracy and without incapacitating passengers. We would suggest one hour for planning purposes. A total period of four or five hours in the season is a reasonable target.

The subcloud, non-precipitating cumulus, feeder flow study similarly needs special operational considerations. The problem here is that when the aircraft is a few hundred feet below cloud base in an extended area of cloud it is not possible to see the cloud tops or sides. Thus the desired flight profile of a rectangle located so as to scan the area below a small vigorously growing cumulus is probably impractical since we cannot select the position of such clouds when we are beneath them. Thus the practical approach is to fly long legs beneath the cloud region, up and down the shear direction as based on the subcloud and mid cloud wind difference, and record on the video tape all the information that can be seen of the cloud bases. In this way cases can be selected where a good correlation between the wind field and its location below cloud base will let us establish the flow structure relative to the cloud. This needs to be done at several levels below cloud base on each occasion, say 500 ft., 1,000 ft. and 1,500 ft. below bases. The runs would then be perhaps 30 to 60 km in length with turns at the end to bring the return back 10 km. to the left so that the same area is scanned again on return. The altitude for these runs will

probably be 10,000 to 16,000 ft. and will require careful coordination with aircraft control.

The gust front study may be possible as an airborne alternative choice, but probably will need separate selection as a mission because of the tight coordination needed for the aircraft. The plan would be to descend beneath the storm or squall line and locate the front with guidance from the radars or other aircraft. It is then desired to fly parallel to the front a few kilometers ahead of it, with a return track on roughly the same line as the previous track so as to complete the circuit and begin the next leg. The legs would typically be about 30 km for a single storm, and 100 - 500 km for a squall line, in length, with the procedure turns beyond this. Depending on terrain it would be desirable to repeat the pattern at altitudes of 100 m, 300 m, 1,000 m, and 2,000 m, or as time permits. In rough terrain these heights would need to be modified.

If all weather failed, then the ultimate backup experiment would be to study the aerosol contents and velocity distributions in the convective planetary boundary layer. This would simply involve a race track box pattern at various levels from just above the inversion so near the surface. A similar procedure at higher altitude would enable cirrus particle densities and motion to be studied with altitudes from just above cirrus tops to just below the cirrus base. These studies could also be conducted on long horizontal stretches during ferry runs.

The marine or continental stratus observations would be similar to the boundary layer and cirrus layers mentioned in the last paragraph except that the cloud top banked circle (anticlockwise) entrainment observations should be added, and occupy a substantial time period, since these are the most important observations in this case, and

flights at levels within cloud are not likely to be useful. Subcloud turning observations (clockwise) below cloud base to measure vertical motion of the base of marine stratus would be extremely valuable when adequate airspace is available.



APPENDIX H  
REPORT OF SECONDARY FLOWS, BOUNDARY LAYERS,  
TURBULENCE AND WAVE TEAM

Report 1 of 2

THE FIRST SCIENTIFIC WORKING GROUP MEETING  
MSFC AIRBORNE DOPPLER LIDAR WIND VELOCITY PROGRAM  
NASA/MSFC, August 25-26, 1980

Report of Secondary Flows, Boundary Layers, Turbulence,  
and Wave Team

Team Members: J. Scoggins, D. Fitzjarrald, R. Doviak,  
W. Cliff, (W. Frost absent)

1. Introduction

The following is a brief summary of the report to the entire group by the boundary layer team. The primary objects of discussion were possible test plans and their relative merits and operational difficulties. Four likely candidates for the flight tests were discussed in some detail and are given later. General criteria for a flight test option are that: (1) there be a good opportunity for comparison with other measurement techniques, (2) the flow to be measured is of considerable scientific or practical interest, and (3) the airborne laser Doppler system is well suited to measure the required quantities. The requirement for comparison, i.e., ground "truth", is particularly important because this will be the first year of operation for the system. It will be necessary to demonstrate that the system does actually measure the winds and compare the results with other methods to provide a check on the system error analysis. The uniqueness of the laser-Doppler system precludes any direct comparison, but point measurements from tower-mounted wind sensors and two-dimensional fields obtained from radars with substantially different sampling volumes will be quite useful.

The flight test options presented below can be economically grouped to minimize ferry time. The first two (California Central Valley and San Geronio Pass) are in California, so that the aircraft can be based at NASA Ames. They should be done early in the program, as soon as the engineering tests are completed. The next test would logically be at NSSL in Oklahoma, where the schedule is flexible and opportunities for tower and radar comparison are good. By this time considerable operation experience should have been gained, so that moving up to Montana to the CCOPE experiment would be the next step. The CCOPE is by far the most complex operationally, requiring integration into a very big and busy experiment. Success would be maximized by having as much experience as possible with the operation of the system and some confidence that the system does measure what it is supposed to measure. On the way east to NSSL and back west from CCOPE, the Boulder NOAA/NCAR tower instruments can be compared in a fly-by.

In addition to the flight test options, the real-time data display was discussed in some detail. The recommendations are presented later. A summary of the flight test options is given first, followed by the discussion of the data display and, finally, by details of the flight test options.

## 2. Summary of Flight Test Options

### A. California Central Valley

Purpose: Investigate the spatial and temporal variation of the boundary layer wind flow patterns in the Central Valley, examine the detailed flow patterns in the vicinity of ag-burning smoke plumes, and the local flow near the Geysers geothermal field.

Data Comparison: 1500 ft tower at Walnut Grove, possibility of tracer release by DOE Livermore, surface wind field at the Geysers.

Flight Requirements: Racetrack pattern around Central Valley near top of mixed layer (approximately 3000 ft), continue from noon through evening. Smoke plumes as targets of opportunity, box patterns at various levels at the Geysers.

Interest: Important problem in applied meteorology, of great interest to air pollution researchers. Interesting and complicated local flow, very little data available. Collaboration from California Air Resources Board, EPA, DOE Livermore, and UC Davis.

Suitability: Well suited for measurement by Doppler system, with space scales and resolution within system possibilities. Good place to try out the different resolutions, etc., of the system.

### B. Wind Resource Assessment of San Geronio Pass, California

Purpose: Investigate spatial and temporal variations of flow through mountain pass in Southern California.

Data Comparison: 100 m tower, 50 m tower, twelve 10 m towers, and several years of averaged data.

Flight Requirements: Back and forth pattern at several levels at the end of the pass. Continue for sufficient time (approximately 3 or 4 hours) to see the evolution of the flow.

Interest: Prime candidate for wind energy farm. Spatial details of the flow needed to compare with surface and small tower data. Climate type wind data available for 3 years, but nothing to give the extent in space of the wind resource. Collaboration with Southern California Edison, DOE Wind Energy Program, California State Wind Energy Commission, Battelle Pacific Northwest Laboratories.

Suitability: Space and time scales well within system capabilities. Interest is in the fine-scale details of the motion (approximately 0.5 km).

### C. Radar/Tower Comparison at NSSL

Purpose: Fly-by 1500 ft tower in Oklahoma City and cover the same area as NSSL dual-Doppler radars. Compare the measurements by two different instruments and determine the two-dimensional spectra of the wind at different levels in the boundary layer.

Flight Requirements: Fly-by tall tower. Racetrack pattern at different heights within the boundary layer. Pattern coinciding with area covered by NSSL radars.

Interest: Excellent opportunity for comparison with another instrument that measures a two-dimensional wind field in clear air. Wind patterns and spectra can be compared. Scientific interest in horizontal spectra. Collaboration with NSSL.

Suitability: Space and time scales within system possibilities. Interested in all the scales within the flight box that can be resolved by the system; therefore, the finest possible resolution would be desired.

### D. CCOPE, Large Field Experiment in Eastern Montana

Purpose: Compare boundary layer wind measurements with those measured with radars (clear air and chaff release), aircraft, and surface measurements at the CCOPE test site. Measure the before-cloud and under-cloud convergence in the boundary layer.

Flight Requirements: To be coordinated with CCOPE to avoid conflicts with multitude of other aircraft operating in area. Will schedule some flights on "off days" or early in the day to be able to compare with radars without getting in the way of other aircraft.

Interest: Opportunity for contribution to large experiment. Many collaborators. Should be confident of the system and experienced in operation because this is not the best place to experiment with it due to large number of other aircraft.

Suitability: Same as for boundary-layer measurements at NSSL.

### 3. Real-Time Data Display

As a result of discussion within the group and with the M&S personnel who designed the display software, it was concluded that the intensity (S/N) information was not adequate. It was not possible to look at the vector display and see the intensity information easily. It was believed that this would be a most important quantity to look at during the flight. There was considerable discussion regarding the form of the display, but no clear consensus was reached. Any display of the scalar field of intensity would be easier to read than the arrowhead lengths on the wind vector display.

### 4. Details of Flight Test Options

Some details of the proposed flight tests are given below. In two cases they represent a summary of the group discussions. For the San Geronio

Pass test the description is supplied by W. C. Cliff. Detailed flight plans were discussed by the group, but in view of the many uncertainties it appears better to proceed in a more general manner at this point. Certainly, it will be desired to try all the different resolutions and operation modes in the first tests. Operation at different turbidity levels will also be necessary to see what range can actually be attained. The first tests should provide all these opportunities, together with ground truth for comparison. Assuming that all is in order, the last test should be to contribute to the CCOPE experiment.

#### California Central Valley Flight Test Option

Justification: The air flow and circulation patterns within the Central Valley are of great interest because of their importance in air pollution assessment and control. Pollution within the valley at present is primarily due to agricultural burning, but the increasing pressures of urbanization and the proposed siting of a large fossil-fuel power plant indicate that other sources will dominate in the near future. The wind data available at present are not adequate to assist the regulators who are controlling agricultural burning (California Air Resources Board, various county air quality groups) or the planners interested in long-term problems (EPA, ARB, electric utility, DOE). A high-quality measurement of the temporal and spatial variations of the flow would be a significant contribution.

In addition to the general flow patterns, there are two additional flow measurements that would be of considerable use. By studying the details of flow near the large ag-burning smoke plumes, it may be possible to minimize the pollution. Some work on this has been done by researchers at UC Davis, but additional data would be helpful. A large interagency effort has been conducted to determine the details and climatology of the local air flow in the vicinity of the Geysers geothermal field in northern California. A short-term measurement of the wind flow patterns would be useful to the mesoscale modellers (UC Davis, DOE Livermore).

This area provides a number of advantages for the testing of the airborne laser-Doppler system. It is close to NASA Ames, has some possibilities for comparison of data (1500 ft tower at Walnut Grove, instrumentation at the Geysers, tracer release by DOE Livermore), has at least one place (Sacramento Delta) where the flow is quite regular and known in direction, and is normally quite high in optical scatterers.

#### San Geronio Pass Test Option

Principal Investigator: Dr. William C. Cliff, Battelle PNL

Objective: To characterize the vertical and horizontal extent of the accelerated flow region through and on the east side of San Geronio Pass.

Location: San Gorgonio Pass, California. San Gorgonio Pass is located approximately 120 miles due east of Los Angeles, California.

Description of Area: San Gorgonio Pass is approximately 40 km (25 miles) long with a westerly elevation of approximately 760 m (2500 ft) gradually dropping to an elevation of approximately 200 m (700 ft). The width of the pass is generally approximately 8 km (5 miles) [at a contour approximately 300 m (1000 ft) above the pass floor]. On the east end the pass quickly broadens and becomes an open desert floor. The mountain rises to approximately 3350 m (11,000 ft) within 16 to 24 km (10 - 15 miles) on each side of the valley floor.

Regions for Wind Assessment: The easterly 8 km (5 miles) of the pass and the adjoining 16 km (10 miles) of desert valley floor. The valley floor area to be assessed is roughly 16 km (10 miles) in the east-west direction by 24 km (15 miles) in the north-south direction. The pass area to be assessed is roughly 8 km in the east-west direction and 8 km in the north-south direction.

Elevations of Horizontal Wind Field Mapping: Anticipated flight paths should be at approximately 100 m (~330 ft), 300 m (~1000 ft), 500 m (~1600 ft), and 1500 m (~5000 ft) above grade level over the valley and with the potential addition of a 1000 m (~3000 ft) elevation taken in the pass (refer to Fig. 1).

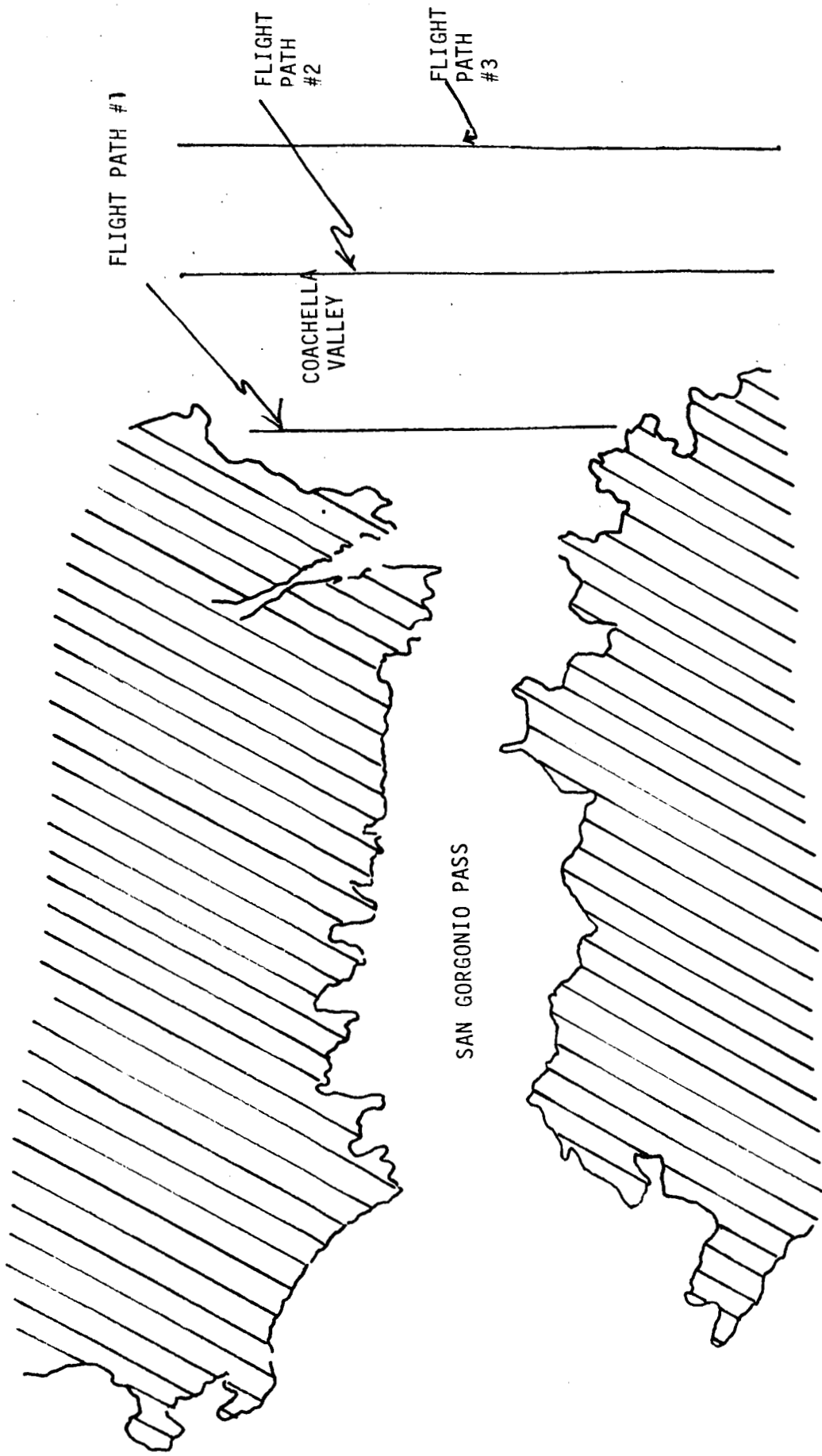
Desired Horizontal Spatial Resolution of Velocity Field: For elevations below 300 m (approximately 1000 ft) a resolution of  $\leq 300$  m is desired. Above 300 m a resolution of  $\leq 500$  m is desired.

Ground Truth Data Availability: At the expected test period the following meteorological data stations will be operating and the data will be available for the test program:

- a. One 100 m (330 ft) tower, 4 levels of instrumentation
- b. One 50 m (160 ft) tower, 3 levels of instrumentation
- c. Approximately twelve 10 m (33 ft) towers with instruments at 10 m level only

Previous Data Available:

- a. One 100 m (330 ft) tower; approximately 1 year of data
- b. One 50 m (150 ft) tower; approximately 3 years of data
- c. 20 stations at 10 m (33 ft); 1 year (August '78 - August '79)
- d. 12 stations at 10 m (33 ft); approximately 1.5 years



(basic figure taken from Aerovironment report number AV-R-9511, March 1979)

SAN GORGONIO PASS TEST OPTION FLIGHT PATHS FOR NASA AIRBORNE DOPPLER LIDAR

Flight paths for number 1 to be at heights above grade level of 100m, 300m, 500m, 1000m, 1500m  
 Flight paths for numbers 2 and 3 to be at all heights given for flight paths for number 1  
 except that the 1500m level is to be excluded

FIGURE 1

Agencies Expressing Interest in San Gorgonio Test Option:

- a. DOE Federal Wind Energy Program/Wind Characteristics Program Element
- b. Southern California Edison Co.
- c. State of California/California Wind Energy Commission
- d. Battelle, Pacific Northwest Laboratories

Justification: The San Gorgonio Pass region is a known high wind resource region and is currently identified as a DOE candidate wind turbine site for the potential placement of one or multiple large wind turbine(s). The area is of extreme interest to the State of California Energy Commission and the Southern California Edison utility company as a high wind resource region for the potential placement of a large wind turbine farm for electrical power production. Southern California Edison has already purchased two large wind turbines from private companies, the first of which has been field erected and is expected to become operational later this year (1980).

To establish the number of large wind turbines that this region's wind resource could support, the vertical and horizontal extent of the accelerated flow resource needs to be determined. The San Gorgonio Pass accelerates the flow from the west side of the mountains through the pass and spreads the accelerated flow onto the desert floor on the easterly side of the pass. The vertical extent of the accelerated flow is required to assess the potential mountain flow which may feed to the lower levels if wind turbines extract energy from the lower level winds. The vertical extent is needed to determine how much land comprises the rich wind resource area for wind turbine placement. There is extensive ground truth data assured during the testing, as described under "Ground Truth Data Availability," for system verification of the airborne NASA Doppler lidar system. This program provides a direct spin-off of advanced NASA technology to other government agencies, DOE, and the State Energy Office of California, a private utility, Southern California Edison, and to the general public who will benefit from the power developed by optimally placed wind turbines in the test option area.

NSSL, Oklahoma Flight Test Option

Justification: This flight test provides an excellent opportunity to test the airborne laser Doppler system against another type of system that can measure a two-dimensional field of wind in clear air. NSSL has already used their dual-Doppler radars to look at the convection in the afternoon boundary layer. The laser system will provide a finer scale result to be compared with the radar-measured winds. The laser resolution is approximately a factor of ten smaller. The horizontal spectra can be compared in the larger scales, and the laser data will provide spectra of smaller scale turbulence. A well-instrumented 1500 ft tower is also available to check one point on the laser-measured wind field. Data reduction from the radars can be done quickly, so that a nearly day-by-day check can be made that the two systems are in agreement.



A significant advantage of this test option is that there is no scheduling problem. The radars are installed at NSSL and can be operated whenever the 990 is ready to fly. The tower instruments are also in regular operation. NSSL has conducted aircraft operations in both areas before, so there should be no difficulty from an operations standpoint. The absence of a large field program is an asset in this because it will allow the 990 laser system to set the schedule. This should be ideal for the first-year test, in view of anticipated difficulties in operating a new system and gaining experience in coordinating the aircraft movements to obtain the best possible wind data.

#### Participation in CCOPE

The CCOPE project is a very large field experiment aimed at cumulus dynamics on the high plains (eastern Montana). A large number of aircraft, Doppler radars, ground-level winds, and radiosondes are involved. Planning is elaborate, and coordination will be difficult. The project offers a good opportunity to make a contribution with the airborne laser-Doppler system. In the boundary layer, convergence and wind patterns in the clear air before storms develop and underneath the developing storms will be of great interest. At upper levels, convergence of aerosols and cloud-edge motions will be of interest. Such a complicated experiment is not the place to try out a new system, however. The airborne laser Doppler should be used enough before starting this project to ensure that the system is actually measuring what we believe it to be measuring. The operating procedures (flight tracks, altitudes, spatial resolution, range of operation, etc.) that yield good wind fields should be well proved by the time of the CCOPE. This will ensure that the participation will have a high yield and that the cooperation from the CCOPE participants will be worth their effort.

There will exist opportunities for testing the laser system using the radars that will be in position in the same manner as at NSSL. Either in clear air (a few of the radar sets) or with chaff drops (most of the radars), two-dimensional wind fields can be measured by the radars and compared with the laser system. Such comparisons will have to be on "off days" of the big experiments or early on flight days. This would entail some problems for the CV-990 because of the time necessary to plan flights and the expense of waiting in readiness for an appropriate time to fly.

Because of the scheduling difficulties inherent in such a big experiment, it appears a better idea to accomplish most of the operational and comparison testing in prior tests (the ones in California and at NSSL offer good opportunities) and to go to the large experiment with a system that is proven.

APPENDIX I  
REPORT OF SECONDARY FLOWS, BOUNDARY LAYERS,  
TURBULENCE AND WAVE TEAM

Report 2 of 2

Report by Team Member  
Dr. Richard Doviak, NSSL, Norman, Oklahoma



**U.S. DEPARTMENT OF COMMERCE**  
**National Oceanic and Atmospheric Administration**  
ENVIRONMENTAL RESEARCH LABORATORIES

National Severe Storms Laboratory  
1313 Halley Circle  
Norman, OK 73069

September 9, 1980

Mr. George Fichtl, ES82  
George C. Marshall Space Flight Center  
Huntsville, AL 35812

Dear George:

Thank you for inviting me to the first scientific working group meeting of an airborne lidar wind measurement program. We at NSSL look forward to a Joint NASA-NSSL experiment utilizing NASA's airborne Doppler lidar and NSSL's Doppler radars. I take this opportunity to confirm that our Doppler radar should be available for the joint experiment late June or July 1981 and we are attracted by the prospect of having the opportunity to compare the kinematic structure of the atmosphere measured independently by these two systems.

Upon my return to Oklahoma, we thought of some other experiments which you might want to consider conducting during the time the CV 990 is in Central Oklahoma. Hopefully, the aircraft can be stationed at Tinker Air Force Base for a week to 10 days during which time we could complete the listed experiments. They are:

- I. Comparison of Horizontal Wind Fields
  - II. Comparing Two Dimensional Spectra of the Kinematic Structure of the Convectively Driven Planetary Boundary Layer
  - III. Comparison of Doppler Derived Heat Flux Profiles with Those In Situ Aircraft Measurements
  - IV. Comparison of Mesoscale Divergence and Deformation Measurements in the Pre-Storm Environment
  - V. Comparison of Thunderstorm Gust Front Winds
- I. Comparison of Horizontal Wind Fields

This is one of the experiments we discussed at the meeting and is one that should be relatively easy to execute. The aircraft could fly at a fixed altitude (e.g., 1 km) some 40 km SW of Norman, and the radar and lidar both should have sufficient tracers on any sunny afternoon to map the wind. In this experiment we will compare (1) the mean horizontal wind averaged along the strip (e.g., 10x30 km<sup>2</sup> of atmosphere probed by the lidar, and (2) the secondary wind field patterns. I'm hopeful that we will get at least good agreement for (1) and comparisons could be made shortly (1-2 days) after the experiment. If we get good agreement with (2), I'll be delighted. In this experiment the aircraft should fly crosswind and along wind and comparisons of mean and secondary fields made.



9/9/80

## II. Comparing Two Dimensional Spectra

This experiment would provide data for an analysis of the type described in the enclosed paper,\* "Turbulence and Waves in the Optically Clear Planetary Boundary Layer Resolved by Dual Doppler-Radars". Of particular interest here would be to extend these measurements to obtain vertical profiles of  $u$ ,  $v$ ,  $w$ ,  $\sigma_u^2$ ,  $\sigma_v^2$ ,  $\sigma_w^2$  with radar and lidar. This experiment could be conducted as part of Experiment W I, but it would be necessary for the aircraft to make passes at 5 different altitudes (e.g., 300, 600, 900, 1200, and 1500 m). Can the aircraft make direct measurement of  $w$  and  $\sigma_w^2$ ? This would be important because computation of  $w$  from lidar and radar data is much more difficult, and it would be imperative to have a direct in situ measurement of turbulence even if it is along a single line whereas the lidar and radar provide an area of data.

## III. Comparison of Heat Flux

I've enclosed a copy of a paper, "Measuring Heat Flux and Structure Functions of Temperature Fluctuations with an Acoustic Doppler Sodar".\*\* There it describes a technique that can be used to relate profiles of vertical wind variance to profiles of heat flux. Although we have not performed the radar measurement yet, I'm confident that with minor modifications to our radar, we should be able to obtain the requisite data. We have a shrouded vertically pointed antenna that makes sidelobe levels small and I believe we would be able to collect data as low as 300 m above the surface. In this experiment we hope that the aircraft would be able to make spiraling ascents around the vertically pointed Doppler-radar if measurements of  $w$  are not compromised significantly. What we need to compare first is the profiles of  $\sigma_w^2$ , and if the aircraft is suitably instrumented, the heat flux profiles. Can the aircraft measure directly heat flux (by correlation of fluctuations in  $w$  and  $\theta$ )? As an adjunct to this experiment, we may want to perform fly-by's over our meteorologically instrumented 444 m tower where we can make heat flux comparisons with tower measurements.

One of our researchers (Bob Rabin) has recently suggested (see attached memo for the record) that the refractive index structure constant  $C_n^2$  can be obtained from knowledge of sensible heat  $H$  and latent heat  $E$  fluxes. Can the aircraft provide data so we can check this hypothesis? Can one make water vapor variance and temperature covariance measurements with the aircraft's radiometer? What are the characteristics of the radiometer?

## IV. Comparison of Mesoscale Divergence and Deformation in the Pre-Storm Environment

This may be the most trying experiment because we would have to wait until a storm situation develops in Central Oklahoma. Nevertheless, if such conditions do occur while the aircraft is here, I suggest we conduct it. I enclose a summary of a paper entitled, "Statistical Considerations in the Estimation of Wind Fields from Single Doppler Radar and an Application to Pre-Storm Boundary

\* This paper is not included in this report because of copyright restrictions; please see Radio Science, 15, No. 2, March-April 1980, pp. 297-317.

\*\* This paper is not included in this report; please see Journal of Applied Meteorology, 19, February 1980, pp. 199-205.

Ltr to George Fictl, ES82, NASA

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Layer Observations", that suggests that a single Doppler radar can map the mesoscale ( $L > 10$  km) patterns of divergence and deformation which we believe are important in the triggering of thunderstorms. This work is new at NSSL and untested. We suggest that the aircraft fly triangular patterns at constant altitude over large areas (say  $30 \times 30$  km<sup>2</sup>) and divergence and deformation computed using the mean winds measured along the path.

V. Comparison of Thunderstorm Gust Front Winds

This experiment will be the most difficult to perform because it requires the presence of a not too frequent phenomena within our radar range ( $\approx 60$  km) and good coordination between aircraft and radar. The forecast of the gust front in the time (2 hrs.) it takes the aircraft to be airborne from a standby position makes difficult the success of this experiment. Nevertheless, wind shear measurements in the clear air outflow of thunderstorms is important in assessing the capabilities of Doppler radars to determine gust front hazards to landing aircraft. In this experiment we would direct the aircraft, using radar observations, to fly along the gust front so that wind in the gust front measured by radar and lidar can be compared.

George, I hope I haven't overwhelmed you with experiments, but if we can do any one of these, I would consider the mission a success. Experiments I, II, and III could be accomplished in one day, IV and V in another. I would appreciate any information you would send me that describes the aircraft instrumentation and the products available. Give my regards to Ed Weaver and Jim Bilbro and please thank John Kaufman for kindly transporting me to the meeting. I didn't realize my motel was out of the way of his normal commuter route.

Sincerely,



Dick Doviak  
Chief, Advanced Techniques

Encls.

cc NSSL Managers  
Lee  
Zrnic  
Rabin  
Rajan, OU



**U.S. DEPARTMENT OF COMMERCE**  
**National Oceanic and Atmospheric Administration**  
 ENVIRONMENTAL RESEARCH LABORATORIES  
 National Severe Storms Laboratory  
 1313 Halley Circle  
 Norman, Oklahoma 73069

August 27, 1980

Memo for the Record

FROM: Robert Rabin

SUBJECT: Using radar to determine heating rate and evaporation near the earth's surface for an unstable boundary layer

Purpose: We would like to ascertain as much information as we can about the prestorm environment using Doppler radar. Besides the obvious use of Doppler derived wind fields, radar reflectivity from refractive index fluctuations may provide information on the temperature and moisture structure of the boundary layer. Stephen Burk and Dusan Zrnic have already suggested how reflectivity could reveal a weakening of the moisture capping inversion (see Memo for the Record - Dusan Zrnic, 12 May 1980). The purpose of this note is to review what is known about reflectivity in clear air as related to the turbulent fluxes of momentum, heat and moisture in the planetary boundary layer.

In clear air, the radar reflectivity,  $\eta$  (length<sup>-1</sup>), can be derived from the refractive index structure constant,  $C_n^2$  (length<sup>-2/3</sup>) and radar wavelength,  $\lambda$  (equation #1); see Hardy et al., 1966, J. Geophys. Res., 71, pp 1537-1552.

$$\eta \sim 0.38 C_n^2 \lambda^{-1/3} \quad (1)$$

(Refractive index,  $n$ , is nondimensional)

Recall also from Gossard 1977, Radio Sci., Vol. 12, No. 1, pp 89-105, equation #2.

$$C_n^2 = a^2 C_\theta^2 + b^2 C_q^2 - 2ab C_{\theta q}^2 \quad (2)$$

where  $C_\theta^2$  (Deg<sup>2</sup>·length<sup>-2/3</sup>),  $C_q^2$  (Water vapor density<sup>2</sup>·length<sup>-2/3</sup>), and  $C_{\theta q}^2$  (Deg·water vapor density·length<sup>-2/3</sup>) are the structure constants for potential temperature variance, water vapor variance, and temperature - water vapor covariance, respectively.  $a$  and  $b$  depend on the mean air temperature, water vapor density, air pressure, and radar wavelength:

$a = \frac{-\partial n}{\partial \theta}$  (deg<sup>-1</sup>),  $b = \frac{\partial n}{\partial q}$  (m<sup>3</sup> gr<sup>-1</sup>). For 10 cm radars the following constants are typical:

$$\left. \begin{aligned} a^2 &= 2.24 \times 10^{-12} \\ b^2 &= 17.8 \times 10^{-12} \\ 2ab &= 12.6 \times 10^{-12} \end{aligned} \right\} \text{Tropical Maritime Air}$$



$$\left. \begin{aligned} a^2 &= 1.25 \times 10^{-12} \\ b^2 &= 16.2 \times 10^{-12} \\ 2ab &= 9.01 \times 10^{-12} \end{aligned} \right\} \text{Warm Continental Air}$$

The radar detects backscattering from refractive index fluctuations of 5 cm scale size. The associated temperature and moisture variations are in the inertial subrange. There, the structure constants are functions of molecular dissipation rates of turbulent kinetic energy  $\epsilon$ , temperature variance  $\epsilon_\theta$ , water vapor variance  $\epsilon_q$ , and temperature-water vapor covariance  $\epsilon_{\theta q}$  (Equation 3); see Wyngarrd, et al., 1978, JAS, pp 47-58.

$$C_{\theta}^2 = 4 A_{\theta} \epsilon^{-1/3} \epsilon_{\theta} \quad (3a)$$

$$C_{q}^2 = 4 A_{q} \epsilon^{-1/3} \epsilon_{q} \quad (3b)$$

$$C_{\theta q}^2 = 4 A_{\theta q} \epsilon^{-1/3} \epsilon_{\theta q} \quad (3c)$$

where these are nondimensional constants

$$\begin{aligned} A_{\theta} &= 0.4 \\ A_{q} &= 0.4 \\ A_{\theta q} &= 0.5 - 0.6 \end{aligned}$$

Combining equations 1, 2, 3, the radar reflectivity can be written in terms of the dissipation rates (equation 4).

$$\eta = 1.52\lambda^{-1/3} \epsilon^{-1/3} (a^2 A_{\theta} \epsilon_{\theta} + b^2 A_{q} \epsilon_{q} - 2 ab \epsilon_{\theta q}) \quad (4)$$

The dissipation rates appear in the budgets (balance equations) of turbulent kinetic energy, temperature variance, water vapor variance, and temperature-specific humidity covariance. Fortunately, these budgets are best understood for unstable conditions (which concern the prestorm environment). Observations of the individual terms in the budgets suggest that the dissipation rates are functions of the following surface layer\* parameters:

1) Momentum Flux:  
 $u_{*}^2 = -\overline{u'w'} = \tau/\rho_0 \text{ (length}^2/\text{time}^2)$

where  $\tau$  = shearing stress

$u_{*}$  = friction velocity

$u'$  = fluctuation in wind component parallel to mean wind

$w'$  = fluctuation in vertical wind component  
 overbar represents ensemble average

$\rho_0$  = surface air density (mass/volume)

2) Sensible heat flux:  
 $H = \rho_0 c_p \overline{w' \theta'}$  (Energy/unit area/time)

\*The surface layer refers to the lower 10's of meters of the planetary boundary layer where the fluxes are nearly constant with height.

where  $C_p$  = specific heat of air at constant pressure (Energy/mass/deg)  
 $\theta'$  = fluctuation in potential temperature (Deg)

3) Latent heat flux:

$$E = La \overline{q'w'} \text{ (Energy/area/time)}$$

where  $La$  = latent heat of vaporization (Energy/mass)

$q'$  = fluctuation in water vapor/density (mass/volume)

The equations 5 a-d are based on surface layer measurements with the limitations of horizontal homogeneity and stationarity. (See Champagne et al., JAS, 1977, pp 515-530.)

$$\epsilon = \frac{u_*^3}{KZ} \left( 1 + 0.5 \left| \frac{Z}{L} \right|^{2/3} \right)^{3/2} \quad (5a)$$

where  $K = 0.35$  (universal constant, nondimensional)

$Z$  = height above ground (m);  $Z > Z_0$

$Z_0$  = roughness length (0)  $\sim 10^{-2}$  m

$$L = \left[ -u_*^3 \overline{T_v} / Kg(H/\rho C_p + 1.72 \times 10^{-6} (\overline{T})^2 \frac{E}{La}) \right]$$

$\overline{T_v}$  = Mean Virtual Temperature ( $^{\circ}K$ )

$\overline{T}$  = Mean Temperature ( $^{\circ}K$ )

$g$  = Gravitational Constant ( $m \ s^{-2}$ )

$$\epsilon_{\theta} = \frac{2 \cdot H^2 \phi_{\theta}}{KZ(\rho C_p)^2 u_*} \quad (5b)$$

where  $\phi_{\theta}$  = nondimensional vertical gradient of potential temperature.

$$= (1/1.35) \cdot \left( 1 - 9 \frac{Z}{L} \right)^{-1/2}$$

$$\epsilon_q = \frac{2 \cdot E^2 \phi_q}{KZ(La)^2 u_*} \quad (5c)$$

where  $\phi_q$  = nondimensional vertical gradient of water vapor density

$$= (1/1.35) \cdot \left( 1 - 9 \frac{Z}{L} \right)^{1/2}$$

$$\epsilon_{\theta q} = \frac{2 \cdot H \cdot E \cdot \phi_q}{KZ(\rho C_p La) u_*} \quad (5d)$$

(See Wyngaard, 1978, JAS pp 47-58)



Owing to experimental difficulties in measuring humidity fluctuations accurately, equations (5c-d) are perhaps less reliable than desired. However, all the equations are semi-empirical and should be considered approximations which best fit experimental data.

The Doppler radars cannot usually measure reflectivity accurately so close to the ground to concern the surface layer. Hence, we must consider parameterization of the dissipation rates above the surface layer. Such parameterization is based primarily on AMTEX observations. Equations 6(a-d) follow from Lenschow and Wyngaard, JAS 1980, pp 1313-1326; Wyngaard et al., 1978, JAS, pp 47-58; and Lenschow, JAS, 1974, pp 465-474.

$$\epsilon = \left(\frac{g}{T_V}\right) \left(\frac{H}{\rho C_p}\right) \left[ B + SP + \frac{0.57}{(SP+3.75)} (\overline{SP}-SP) + 0.7(\overline{B}-B) \right] \quad (6a)$$

where  $B = 1 - 1.5 Z/Z_i$  is the normalized buoyant production of turbulent kinetic energy (nondimensional)

$$\overline{B} = \int_{Z=0}^{Z=Z_i} B dZ = 0.25$$

$Z_i$  = inversion height (m)

$SP = -\frac{L}{Z} \left[ 1 - 15\frac{Z}{L} \right]^{-1/4}$  is the normalized shear production of turbulent kinetic energy

$$\overline{SP} = 21 \ln \frac{(1+x)}{2} + \ln \frac{(1+x^2)}{2} - 2 \tan^{-1} x + \frac{\pi}{2} = \int_{Z=0}^{Z=Z_i} SP dZ$$

$$x = \left( 1 - 15Z_i/L \right)^{1/4}$$

$$\epsilon_\theta = \left(\frac{H}{\rho C_p}\right)^{5/3} \left(\frac{g}{T_V}\right)^{-1/3} Z_i^{-4/3} \left[ D \left( 3\frac{Z}{Z_i} - 2 \right) + 9.3 \left( 1 - \frac{Z}{Z_i} \right)^2 \right] \quad (6b)$$

where  $D = 3.05 \overline{\theta} \frac{(E/La)}{(H/C_p)}$  Following Wyngaard et al. 1978

$$\text{when } \frac{d\theta}{dZ} = 0.61 \frac{\overline{\theta}}{\rho} \left(\frac{E}{La}\right) \left(\frac{H}{\rho C_p}\right)^{-1/3} \left[\frac{g}{T_V}\right]^{-1/3} Z_i^{-4/3}$$

or  $D = 1.4$  following Lenschow et al. 1980

$$\text{when } \frac{\partial \theta}{\partial Z} = 1.4 \left(\frac{H}{\rho C_p}\right)^{2/3} \left[\frac{g}{T_V}\right]^{-1/3} Z_i^{-4/3}$$

$$\epsilon_q = \left(\frac{E}{La}\right)^2 \left(\frac{H}{\rho C_p}\right)^{-1/3} \left(\frac{g}{T_v}\right)^{-1/3} (Z_i)^{-4/3} [10^{-5} \frac{Z}{Z_i} + .353 \left(\frac{Z}{Z_i}\right)^{-4/3}] \quad (6c)$$

$$\epsilon_{\theta q} = \left(\frac{E}{La}\right) \left(\frac{H}{\rho C_p}\right)^{2/3} \left(\frac{g}{T_v}\right)^{-1/3} (Z_i)^{-4/3} [D(0.5 \frac{Z}{Z_i} - 1) + 5(1 - 1.5 \frac{Z}{Z_i}) + 5.6(1 - \frac{Z}{Z_i})] \quad (6d)$$

Equations 6 do not apply at the upper limit of the PBL ( $Z > .8 Z_i$ ) because of entrainment through the inversion layer which is not only related to surface layer parameters. Other factors such as localized wind shear and wave phenomena also strongly affect the budgets of temperature and humidity variance and turbulent kinetic energy in that region.

Results of higher order turbulence models give  $u_*$  as an implicit function of surface layer geostrophic wind (pressure gradient) and sensible heat flux; equation 7 from Arya-Monthly Weather Review - Feb. 1971, pp 215-225.

$$\frac{k^2 G^2}{u_*^2} = [\log \left(\frac{Z_0}{Z_i}\right) + \log \left(\frac{Z_i}{-L}\right) + \log \left(\frac{f Z_i}{u_*}\right) + 1.5]^2 + \quad (7)$$

$$\left[ \frac{K u_*}{f Z_i} + 1.8 f \frac{Z_i}{u_*} e^{0.2 Z_i/L} \right]^2$$

where  $f$  = coriolis parameter  $\sim 10^{-4} s^{-1}$

$G$  - geostrophic wind (m/s)

Equations 4, 6 and 7 can be used to obtain radar reflectivity as a function of the surface layer sensible ( $H$ ) and latent heat flux ( $E$ ). Preliminary results are shown in Figure 1 for 50 and 300 m above ground. Reflectivity is plotted as a function of Bowen ratio ( $H/E$ ) for curves of constant available energy ( $H+E$ ). The values of available energy are typical for a clear spring day and yield reasonable magnitudes of reflectivity from clear air returns. As Bowen ratio increases (increase in  $H$ , decrease in  $E$  associated with soil drying) there is a large drop in reflectivity. This trend continues until  $H$  becomes approximately twice  $E$ . Reflectivity then increases if Bowen ratio becomes any higher. The minimum in reflectivity is a result of the negative effect of temperature-water vapor variance in equation 2.

Conclusions: The reflectivity ( $\eta$ ) appears quite sensitive to:

- 1) change in Bowen ratio ( $H/E$ ) when available energy ( $H+E$ ) is constant.
- 2) change in available energy when Bowen ratio is constant.

Memo for the Record  
August 27, 1980  
Page Six.

The first case may occur when cloud cover and surface albedo are nearly uniform over an area with large differences in soil moisture content. (Soil moisture differences may be due to previous rainfall distribution, vegetation, and soil conditions.) The available energy can be estimated from the net radiational flux (see equation 8).

$$R + F = H + E \quad (8a)$$

where  $R \equiv$  Net radiational flux at earth's surface  
 $F \equiv$  Heat flux through conduction from subsurface ( $F \ll R$  during periods of high solar radiation)

$$R = \text{Solar (shortwave) flux} \cdot (1 - \text{albedo}) \quad (8b)$$

+ longwave flux from atmosphere  
- longwave flux emitted from earth's surface

Given  $R$ , radar reflectivity could be used to map Bowen ratio over the area. In other words, both evaporation and heating rate could be obtained with the use of radar!

The second case could occur over an area of nearly uniform soil moisture but with differences in albedo or cloud cover. For this condition, both the heating rate and evaporation could again be determined from radar reflectivity if the Bowen ratio is measured or estimated.

STATISTICAL CONSIDERATIONS IN THE ESTIMATION OF WIND FIELDS  
FROM SINGLE DOPPLER RADAR AND APPLICATION  
TO PRE-STORM BOUNDARY LAYER OBSERVATIONS

Albert J. Koscielny

SUMMARY

Various methods have been suggested for the retrieval of the vector wind field from radial velocity data. In all of these methods assumptions must be made about either the temporal or spatial structure of the vector wind field. The most common such assumption is that the vector wind field is spatially linear and time invariant. This assumption has been used for the VAD (Velocity Azimuth Display) method of Browning and Wexler (1968), the VARD (Velocity AREA Display) of Easterbrook (1975), and the VVP (Velocity Volume Processing) of Waldteufel and Corbin (1979).

An attractive feature of these techniques is that direct estimates of the kinematic properties of the mesoscale wind field (i.e., divergence, deformation, vertical shear) can be made from a single Doppler radar. Because these properties are important for thunderstorm development, their accurate estimation would be a powerful tool for the analysis of the pre-storm environment.

Waldteufel and Corbin (1979) investigate the application of the VVP to large volumes, i.e., a full 360° of azimuthal scan. They find that on this scale, the assumption of linearity is a basic limitation to the application of the VVP. In this report, only sectors on the order of 30° azimuthal extent are used. It is assumed that linearity is a reasonably good approximation for scales on the order of 30 km, especially in pre-storm environments. The analysis of radial velocities is not straightforward because of the dependence of the accuracy of the estimates on the model proposed for the radial velocities and on the geometry of the analysis volume. Several methods have been examined and were found to produce estimates that

were biased (VARD) or whose variances were too large (VVP).

The well known statistical regression theory was used to show that the analysis of single Doppler velocities from small volumes is not straightforward but must be tailored to specific applications. Considerations from regression theory were used to design a model and an analysis volume, termed a modified VVP, that allows the estimation of low level divergence with an accuracy of about  $3 \times 10^{-5} \text{ s}^{-1}$  from actual radar data.

The modified VVP was applied to a pre-storm data set for 1530-1630 CST on June 19, 1980. The divergence fields from this analysis were found to be reasonable mesoscale patterns (See Fig. 1). The fields derived independently from the Norman and Cimarron Doppler radars agreed fairly well. Lastly, the areas of convergence are areas where cumulus clouds or thunderstorms later develop.

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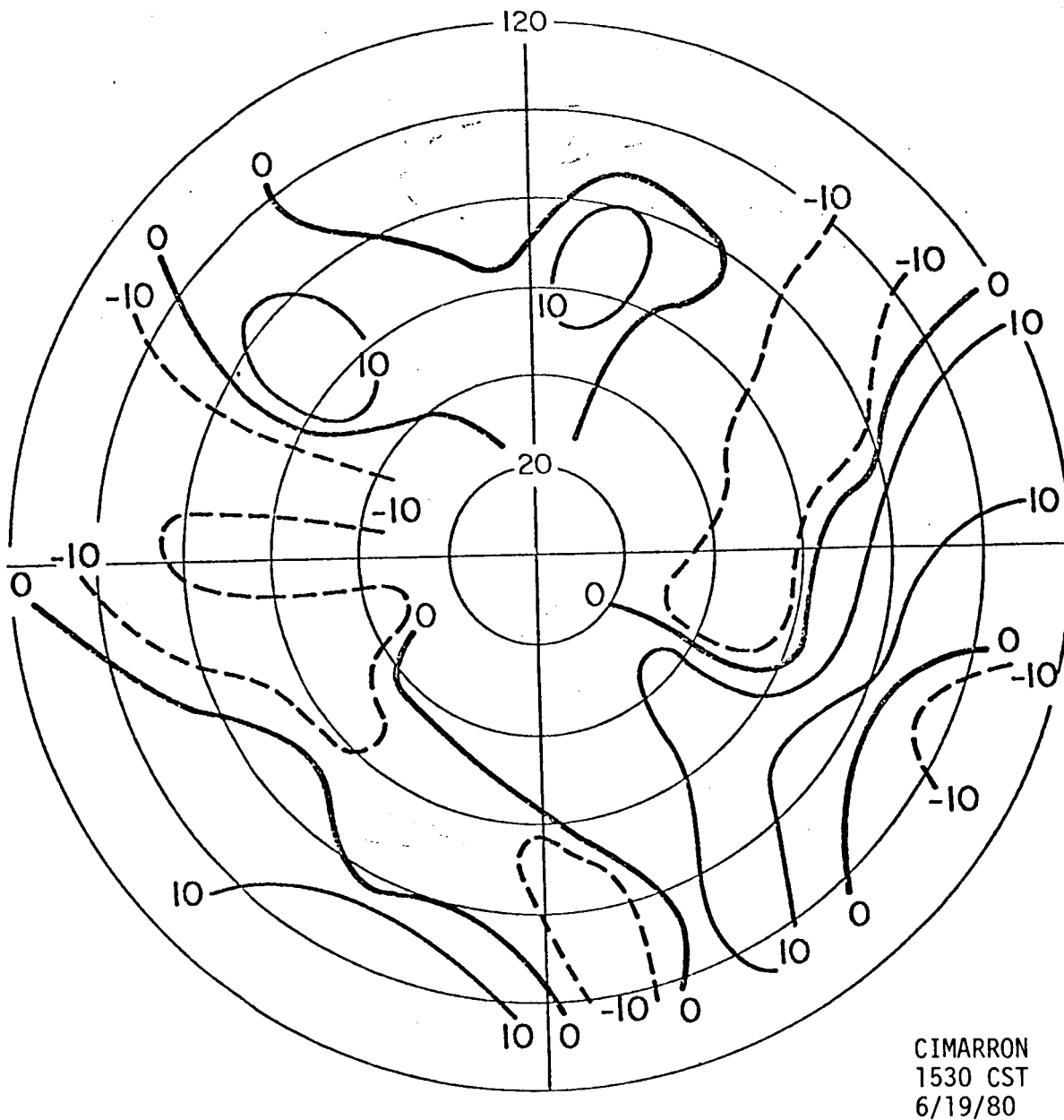


Figure 1. Divergence field produced by VVP of single Doppler data acquired in a pre-storm environment. Elevation angle  $\approx 0.6^\circ$ ; range rings are 20 km apart. Divergence is multiplied by  $10^5$ .

APPENDIX J

REPORT BY DR. L. RANDALL KOENIG,  
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NATIONAL SCIENCE FOUNDATION

WASHINGTON, D.C. 20550

DIVISION OF ATMOSPHERIC SCIENCES

September 2, 1980

Dr. George H. Fichtl  
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Dear George:

Enclosed are some notes on three observations that could be done using the Doppler Lidar. One, the cooperative effort at the BAO could be used in proving the system - finding its accuracy and limitations. The second, the description of the wind flow around St. Louis probably is not appropriate for the FY 81 studies but I would give it consideration for later studies. If your system operates well and a reasonably complete data set on wind flow in St. Louis in spring or summer is obtained, many people will be interested. The last suggestion, the cirrus cloud study might be useful as a target of opportunity type of study. The results could be interesting or they may be uninteresting; perhaps a look at cirrus data gathered in your CAT program would be useful in developing this study.

I agree that the anvil mass budget studies and the lower level flows around large convective storms will make interesting studies and I suppose someone will write them up.

I hope these notes are of use to you.

Sincerely yours,



L. Randall Koenig  
Associate Program Director  
for Meteorology



1. COOPERATIVE EFFORT AT BAO

Purpose: To check out instrumentation and contribute to boundary layer investigations at BAO.

Rationale: Near Boulder a high, well-instrumented tower exists, the Boulder Atmospheric Observatory (BAO). The tower, with instrumentation at various levels is used for boundary layer observations and scientists attempt to use these data to develop boundary layer models, interpret three-dimensional wind fields, etc. This instrumentation should be useful for verifying the accuracy of the Doppler Lidar, and if sufficiently accurate, the Lidar data should be very helpful to the scientist using the BAO for establishing the three-dimensional flow.

Procedure: Coordination with users of the BAO is required. (BAO is operated by the Wave Propagation Laboratory of NOAA at Boulder; contact is Dr. J.C. Kaimal FTS 320-6261.) A step-wise altitude ascent to gather the horizontal winds as a function of altitude is required (altitudes of data gathering should be those at which instruments are placed).

## 2. UNINTENDED WEATHER MODIFICATION

- Purpose:** To detect mechanisms by which regions of industry and urbanization modify weather.
- Hypothesis:** Industry and urbanization modify weather by changing the surface roughness, albedo, etc., and by releasing large quantities of heat into the atmosphere. Both broad area-wide and essentially point sources exist. Urbanization will influence mesoscale wind patterns, causing convergence, etc. Industrial heat rejection will cause local convective anomalies. Both effects should result in unintended weather modification manifested by increased summer convection and associated phenomena.
- What to look for:** The Doppler lidar would be used to map the wind field over the man-altered terrain. Patterns of wind convergence on meso to local scales would be sought. Influences of topography, heat sources, surface roughness changes would be sought. Aerosol distributions would also be of interest.
- Where:** Ideally one would examine different areas, isolated industry that emits large quantities of heat, relatively industry free and flat urbanized areas, etc; however, because of the data on anomalous weather patterns that exist as a result of the Metromex program, I believe St. Louis would be a logical site. This region combines urbanization, industry having essentially point sources of high waste heat rejection and some interesting topography. A three-dimensional wind field from the surface to the convective condensation height would be very useful in sorting out causes of the anomalies that are observed. Such information would also be useful to numerical modeling attempts that investigate this matter.
- Procedure:** Data should be gathered in the spring or summer. A box like flight path should be used, perhaps several rectangles, to cover the needed area. Data should be taken at approximately 250 m intervals from as close to the ground as possible to cloud

base height 1000 m (obtain data at four or more levels with altitude separation between levels increasing with height. Data throughout a day would be quite interesting but I suspect that would be impossible at the time of the data gathering, clouds are not necessary but a sounding would be useful.

The aircraft should carry an IR sensor to map the distribution of surface temperature. Other measurements would also be useful and if you decide to follow this suggestion, you might contact Dick Dirks at NSF. He may be interested in stimulating some additional research.

### 3. CIRRIUS CLOUD STUDY

- Purpose:** To characterize cirrus clouds by their Lidar signal. To compare Lidar and visually observed characteristics.
- What to look for:**
- a. Particle distribution in space how homogeneous are the clouds.
  - b. Motion field around cirrus (and without it).
  - c. Phase change (liquid to ice) in cirrus. Can you observe phase transitions? If so, do they occur more or less continuously implying nuclei are continually being brought into the cloud; or that there is a time constant (variable) for different nuclei; or that some other than heterogeneous nucleation process is taking place.
  - d. Turbulence within and around cirrus.
  - e. Vertical distribution of particles. In particular, how do Lidar and visual observations differ in this respect? Is one more sensitive than the other?
  - f. In cirrus that is precipitating ice that then evaporates, what is the humidity and temperature in the region of evaporation? This information would be useful for modeling the cirrus generating (seeding) cell concept.
- When to do the experiment:** Target of opportunity. Check out phase around San Francisco. Periods of going from one site to another site.
- Flight procedure:** Fly at cirrus level - make measurement from the summit to the "base" in steps that seem appropriate depending upon the thickness of the cloud (steps of several hundred meters I suspect would be appropriate).
- Data required:** Standard. If it becomes clear that the motion field in cirrus is undetectable by the system, one might elect to scan only in one direction to measure solely the intensity and therefore particle distribution in space.

APPENDIX K

ATTENDANCE LIST

FIRST SCIENTIFIC WORKING GROUP MEETING  
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NASA Marshall Space Flight Center, Alabama  
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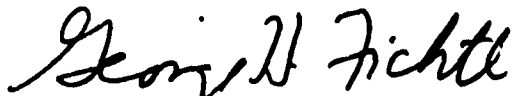
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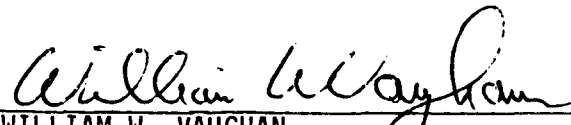
FIRST SCIENTIFIC WORKING GROUP MEETING OF  
AIRBORNE DOPPLER LIDAR WIND VELOCITY MEASUREMENT PROGRAM

Edited by John W. Kaufman

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