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MSFC Doppler Lidar Science Experiments and Operations Plans for 1981 Airborne Test Flight

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FORWARD

This document is the result of approximately one year of planning with scientists and engineers located at universities, government laboratories, non-profit institutions, and private industry. The people and institutions involved are too numerous to mention here. Nevertheless, the experiments and operation plans described in this document for flight testing the MSFC Doppler Lidar System is the integrated result of their inputs.

The support for this program has been provided by Dr. James Dodge of the NASA Headquarters Office of Space and Terrestrial Applications, Manager of the Severe Storm Local Weather Program. This project could not have been undertaken without his enthusiastic support.

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1.0 INTRODUCTION

The NASA Marshall Space Flight Center (MSFC) Doppler Lidar System (DLS) will undergo 66 hours of flight tests during the summer of 1981 aboard the NASA Ames Research Center (ARC) CV-990 aircraft. This document provides the flight experiment and operations plans for the DLS. The support for the development and testing of the DLS has been provided by the NASA Office of Space and Terrestrial Applications (OSTA) Severe Storms and Local Weather Research Program. Figure 1-1 shows the management structure for the DLS project.

1.1 BACKGROUND

The MSFC DLS is the outgrowth of research and development efforts at the MSFC in the area of remote sensing via the use of laser Doppler velocimetry techniques over the past 15 years. These efforts have resulted in remote sensing systems that have been used to detect clear air turbulence, aircraft trailing vortices, and other hazards to aircraft operating systems. Major support for these MSFC projects has been provided by the NASA Office of Aeronautics and Space Technology (OAST), the Federal Aviation Administration (FAA), the Department of Defense (DOD) and the National Oceanic and Atmospheric Administration (NOAA) During the late 1970's the OSTA recognized that remote

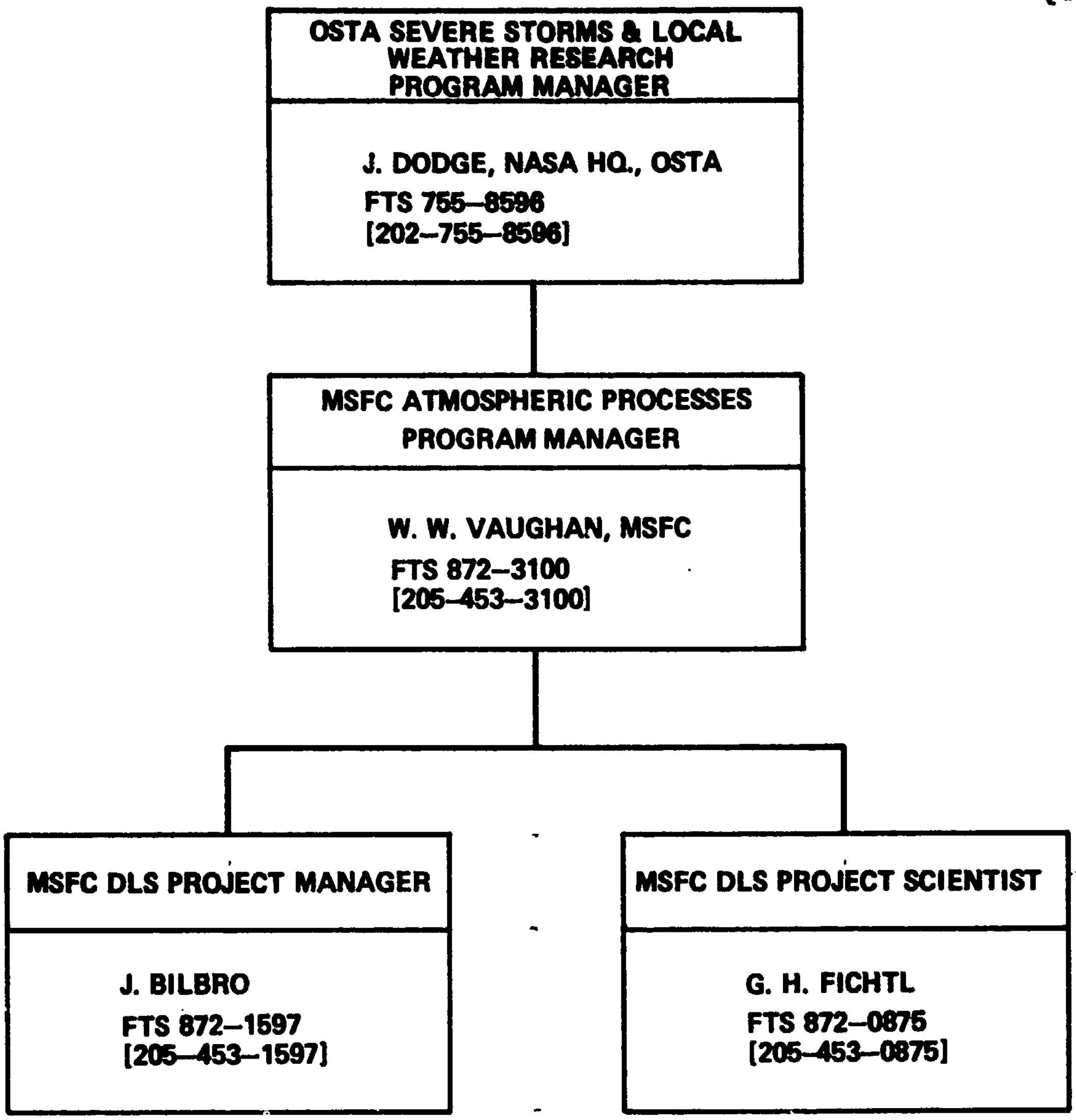

FIGURE 1-1. MSFC/DOPPLER LIDAR SYSTEM PROJECT MANAGEMENT

sensors involving lasers could provide data to satisfy OSTA wind measurement needs in the area of severe storms and local weather phenomena via ground based and airborne Doppler lidar systems and in the area of global weather via Doppler lidar systems flown aboard earth orbiting satellites. As a result of this recognition the OSTA supported the design and fabrication of the MSFC DLS for application to the study of severe storms and local weather phenomena. It was recognized that design, fabrication, and application of this system would result in valuable experience which could assist in the development of a system for the measurement of global scale winds from space.

The flight tests of the MSFC DLS during the summer of 1981 are the first of a series of tests planned to take place over the next five years. Current flight test plans involve 66 hours of flight time extending over approximately a two month period during each year. It is planned that the MSFC DLS will also be used between flight tests to acquire ground based severe storms and local weather data.

1.2 TEST OBJECTIVES

The objectives of the 1981 flight tests of the MSFC DLS are as follows:

- O Confirm the design of the DLS
- O Assess the capability of the DLS to measure detailed wind fields associated with severe storms and local weather phenomena
- O Acquire detailed measurements of horizontal wind fields for a variety of atmospheric conditions to demonstrate the applicability of the DLS to the study of atmospheric phenomena of interest to the OSTA Severe Storms and Local Weather Research Program

The test objectives will be accomplished via a series of experiments which will involve the flight of the DLS aboard the ARC CV-990 during selected atmospheric conditions. "Ground truth" wind measurements are to be obtained from anemometers located on towers, Doppler radars, and gust probes on aircraft. Meteorological measurements are to be obtained from rawinsondes, meso-network observing systems, radars, and aircraft. These experiments will be conducted at the following locations/areas.

- O California
  - o Walnut Grove 473 m Television Tower
  - o Central Valley

- San Gorgonio Pass/Coachella Valley - California Edison/California Wind Energy Resource Board Wind Energy Facility
- Oklahoma - NOAA National Severe Storms Laboratory (NSSL), Norman, Oklahoma
- Montana - NCAR/Department of Interior Cooperative Precipitation Experiment (CCOPE)
- Colorado - NOAA Boulder Atmospheric Observation Tower Facility, Boulder, Colorado

The experiments have been designed to satisfy all of the test objectives stated above. Furthermore, we anticipate that we have planned more experiments than can be accommodated with the available 66 hours of CV-990 flight time. This will permit flexibility in scheduling the use of the aircraft so as to be able to respond to changes in meteorological conditions. We plan to operate the DLS whenever the CV-990 is airborne. This will permit acquisition of data during ferry flights to the various test locations. The meteorological planning for these ferry flights (relative to appropriate flight paths and altitudes) will be determined one to two days prior to take-off. Scheduling of test options at the above listed locations will be discussed later.

1.3 SCHEDULE

A schedule for the DLS flight tests is provided in Figure 1-2. This schedule covers the total test period beginning

MSFC DOPPLER LIDAR SYSTEM TEST AND OPERATIONS SCHEDULE

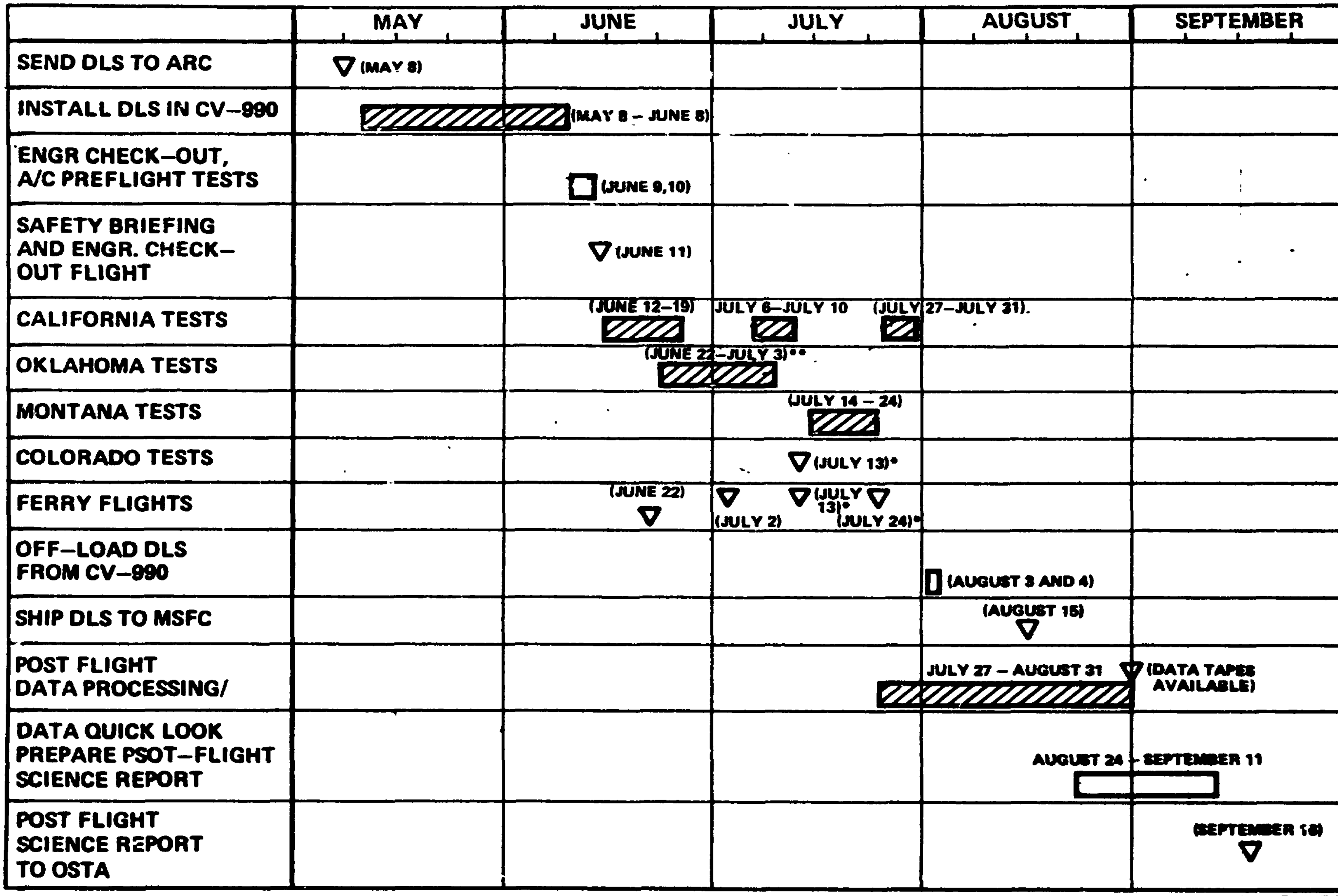

FIGURE 1 – 2

* TO BE PERFORMED ENROUTE ON FERRY TO CCOPE FROM ARC

** FLEXIBLE DUE TO 4TH OF JULY HOLIDAY

with sending the DLS to ARC on May 8th and providing the postflight science report to the OSTA Severe Storms and Local Weather Research Program Manager.

The DLS will be shipped to the ARC from Raytheon Corporation (DLS development contractor), Sudbury, Massachusetts on May 1st. Upon delivery to the ARC it will be unpacked and installed in equipment racks. The racks will then be installed in the CV-990. The completion of this installation activity will be on June 8th.

The ground based engineering check-out and aircraft preflight tests for the DLS will take place on June 9 and 10. The engineering check-out flight of the DLS will occur on June 11th. (The DLS will not be turned on.) The purpose of these tests is to assure that the DLS has been properly installed relative to mechanical interfaces between the DLS and the CV-990 (vibration, weight distribution, etc.). A safety briefing will be provided on June 11th prior to the engineering check-out flight. All DLS team members are required to attend a flight safety briefing. Those members not able to attend the June 11 flight safety briefing will be provided the flight safety briefing prior to the flight tests they will be supporting. The initial flight for system verification will occur on June 12. Upon successful completion of this flight, the CV-990/DLS will be ready to conduct the flight test series.

A six week window has been set aside to conduct the DLS flight tests. This window has been partitioned into two week windows to perform Oklahoma and Montana flight tests. The California tests are distributed throughout the test period. The sequence for the DLS flight tests is as follows:

- O California Tests June 12-19, July 6-10, July 27-31
- O Oklahoma Tests June 22-July 2
- O Colorado Tests July 13
- O Montana Tests July 14-24

The Colorado tests will take place on July 13 enroute from the ARC to the Montana test base of operations. The planned bases of operation for the CV-990/DLS flight tests are as follows.

- O California Tests: Ames Research Center, Moffett Field, California
- O Oklahoma Tests: Tinker AFB, Oklahoma City, Oklahoma
- O Montana Tests: Ellsworth AFB, Rapid City, South Dakota

The ferry flights are as follows.

- O ARC to Tinker AFB, June 22
- O Tinker AFB to ARC July 2
- O ARC to Ellsworth AFB, July 13
- O Ellsworth AFB to ARC, July 24

The total flight test time available is 66 hours. It is planned that approximately 16 hours of flight time will be set aside at each location for conduct of the DLS flight tests, except the Colorado tests, for a total of 45 hours. It is planned that the ferry flights will require 12 hours. Part of the ferry time will be used to conduct the Colorado tests. The additional 6 hours of flight time will be used for initial engineering flights of the DLS and acquisition of β-measurements for Doppler lidar system design.

After completion of DLS flight tests the DLS will be off-loaded from the CV-990 on August 3 and 4 and then shipped to MSFC for further ground based testing. It should be noted that the time interval between the completion of the Montana tests and equipment off-loading is one week. This one week time period should be viewed as the time slip that could take place in the flight tests without impacting the duration time of the flight test windows.

It should be noted that the CCOPE field project will be completed on July 31. Furthermore, the NSSL radars will be taken out of operation in mid-July for maintenance and reconfiguration. These time constraints will be assessed during the CV-990/DLS flight tests if a slip in schedule beyond one week should occur.

Upon completion of the flight tests, the DLS data tapes will be shipped to MSFC for postflight test processing. We anticipate initial postflight test data processing will be accomplished during July 27-August 31. A postflight science report will be prepared during late August and early September.

This report will be provided to the MSFC Atmospheric Processes Program Manager and OSTA Severe Storms and Local Weather Research Program Manager in mid-September. The report will summarize the results of the 1981 flight tests of the DLS relative to the three test objectives listed earlier.

2.0 DOPPLER LIDAR SYSTEM

This section provides a description of the MSFC/DLS, the real time data displays to be used during the DLS flight tests, and the data sets that will result from the postflight test data processing activity.

2.1 SYSTEM DESCRIPTION

The DLS to be used in this test is a pulsed CO_2 system operating at a wavelength of 10.6 μm. The measurement of atmospheric winds with this system is accomplished by detection of radiation scattered by naturally available aerosols within the atmosphere. As a consequence, the performance of this system will be determined largely by the presence or absence of aerosols in the desired measurement region.

The operation of the lidar is best explained with the aid of the simplified block diagram shown in Figure 2-1. The master oscillator laser is an eight watt, continuous wave, plane polarized, CO_2 laser operating at 10.6 μm. A small portion of the output of this laser is picked off for

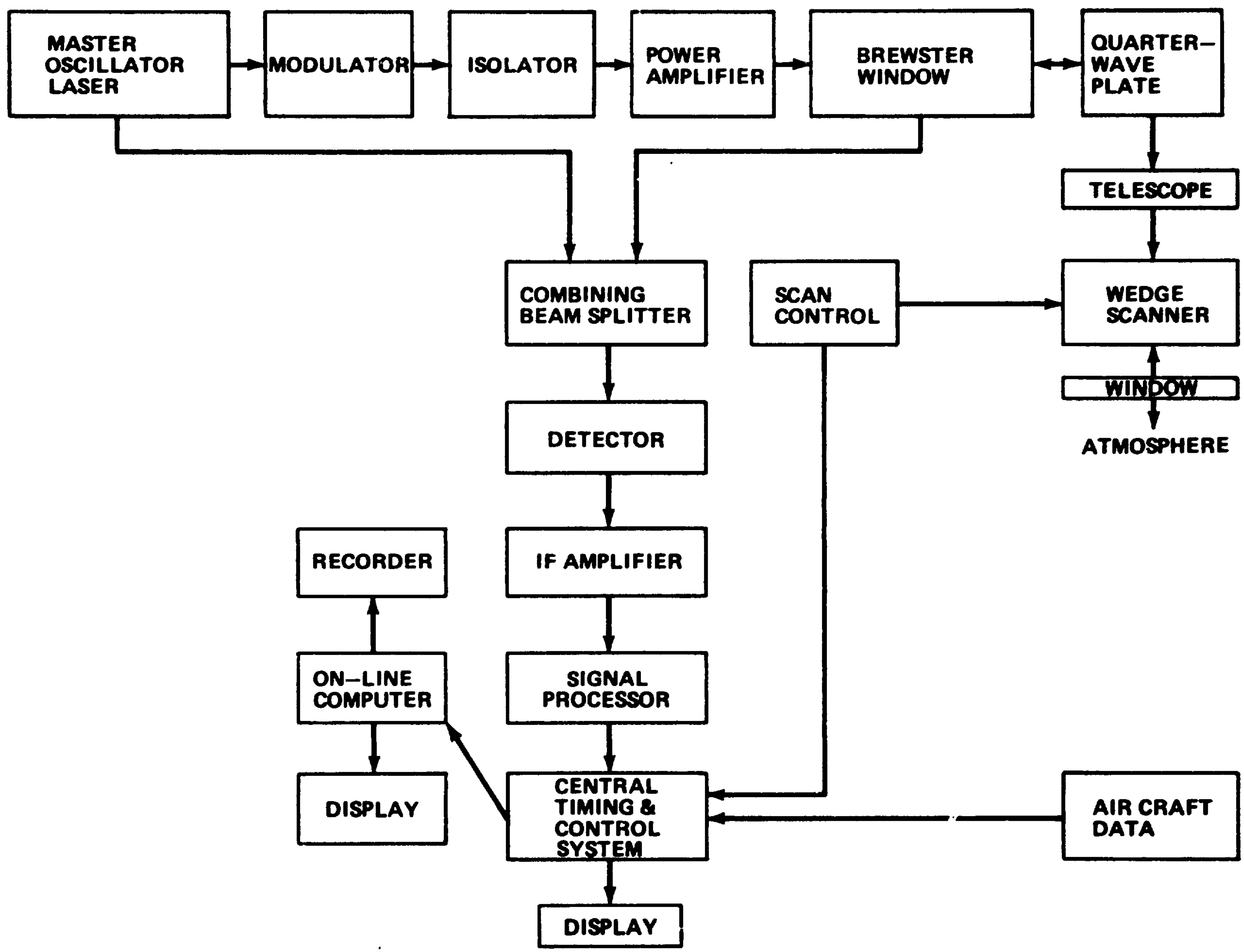

FIGURE 2-1. DOPPLER LIDAR SYSTEM BLOCK DIAGRAM

use as a local oscillator (1.0) in the homodyne detection of the return signal. The bulk of the master oscillator laser output is transmitted to an electro-optic modulator which amplitude-modulates the continuous output at a 140 Hz rate to form a train of pulses each 2 μs in duration. Each pulse is directed into a power amplifier which provides approximately 30 dB of gain and results in a per pulse energy of approximately 10 mJ. The amplified pulse next passes through a Brewster window which is aligned to transmit the particular polarization of the pulse. The next element encountered by the pulse is a quarter waveplate which converts the plane polarized pulse to circular polarization. The circularly polarized pulse then enters the telescope where it is expanded to a diameter of ~24 cm (measured to the $1/e^2$ points of the Gaussian distributed intensity), collimated, and transmitted to the atmosphre. This is accomplished by a rotating double wedge scanner and a germanium window mounted in the exit door over the port wing of the Convair 990 aircraft in which the lidar is installed. The pulse illuminates a volume of air described by the diameter of the transmitted beam (taking into account beam divergence) and the pulse spatial resoltuion. The latter value for a distributed target is defined as

$$\Delta R = \frac{1}{2} C\tau$$

where: ΔR = pulse resolution

C = speed of light

τ = pulse duration.

Consequently, for a 2 μs pulse a region of the atmosphere is illuminated that is nominally 300 m in length and 24 cm in diameter. The aerosols that lie within this illuminated region scatter the incident radiation in all directions. That which is scattered back along the axis of transmission has been rotated in polarization by 180° and Doppler shifted by an amount, Δf, where

$$\Delta f = \frac{2V_r}{\lambda}$$

V_r = radial (line-of-sight) velocity component

λ = radiation wavelength.

For 10.6 μm radiation a Doppler shift of 100 kHz corresponds to a velocity of 0.53 m sec^{-1}. The backscattered radiation is collected by the telescope and transmitted through the quarter waveplate where the polarization is converted from circular to plane (this polarization is 90° out of phase from that which was transmitted due to the 180° shift resulting from the aerosol scattering). The return radiation is then reflected off the Brewster window (due to the polarization) and combined with the local oscillator beam and imaged on a detector. The output amplitude of the detector is the result of the sum of the square of the fields scattered by the individual aerosols (i.e. the power). The frequency of the detector output is the result of a time-varying interference pattern caused by difference in frequency between the return beam and the local oscillator (i.e. the Doppler shift). Therefore, a Fourier analysis of the detector output will yield a power spectral density (Doppler spectrum) of the return signal which in turn is related to the velocity distribution (in a statistical sense) of the aerosols within the illuminated volume. Since the aerosols are small (1 to 5 microns in diameter) they may be assumed to reliably follow the wind, so that the return Doppler spectrum can be interpreted as a wind velocity distribution function in a statistical context. In practice, only three spectral parameters, instead of the entire distribution, are obtained through the use of a poly-pulse pair estimation technique. This estimation technique produces the peak intensity, mean frequency shift, and frequency spread (standard deviation) of the return Doppler spectrum for each resolution element averaged over a selectable number of pulses. The peak intensity provides a relative measure of aerosol density. The mean frequency shift can be used to derive an average value of the line-of-sight wind velocity over the Doppler pulse length. The frequency spread, or standard deviation of the Doppler spectrum, corresponds to the spread, or standard deviation, of line-of-sight wind velocity over the Doppler pulse length. This information is recorded along with position and other pertinent information and at the same time processed to obtain real time vector plots of the wind field in a horizontal plane at the altitude of the aircraft. The acquisition of this wind field map is depicted in Figure 2-2 and is accomplished as follows: The rotating wedge scanner directs the lidar output beam 20° forward of a perpendicular to the aircraft longitudinal axis (roll and pitch are automatically compensated for by the scanner, yaw is accounted for in the data processing). Data are collected from each range gate (contiguous pulse resolution elements) from ~1 km in range to ~10 km. Data from each range gate (i.e. intensity, mean and velocity spread) are averaged for N pulses at which time the data are transmitted to a computer along with their respective position in space and recorded on tape as mentioned previously. At this time the scanner directs the beam to a position 20° aft and the process is repeated. As can be seen from Figure 2-3, a grid pattern will develop where two independent measurements of the wind velocity from two different view angles will result in the calculation of the vector velocity at each intersection point of forward and rearward looking scans. The geometry and spatial resolutions associated with this process are shown in Figure 2-4. No data will be collected closer than 1 km due to lidar turn-on time. Maximum range will be dependent upon aerosol concentrations but for real time

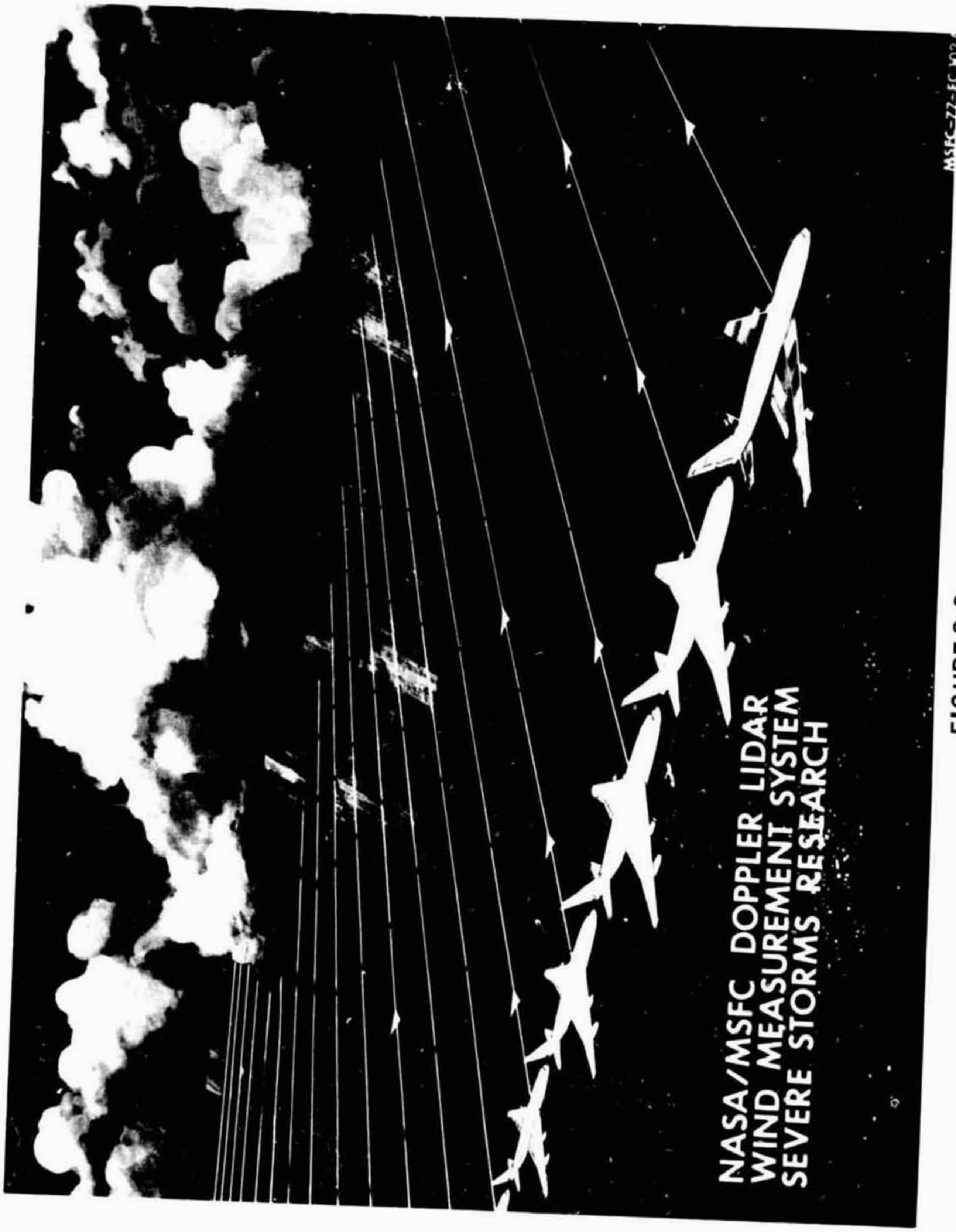
NASA/MSFC DOPPLER LIDAR
WIND MEASUREMENT SYSTEM
SEVERE STORMS RESEARCH

FIGURE 2-2.

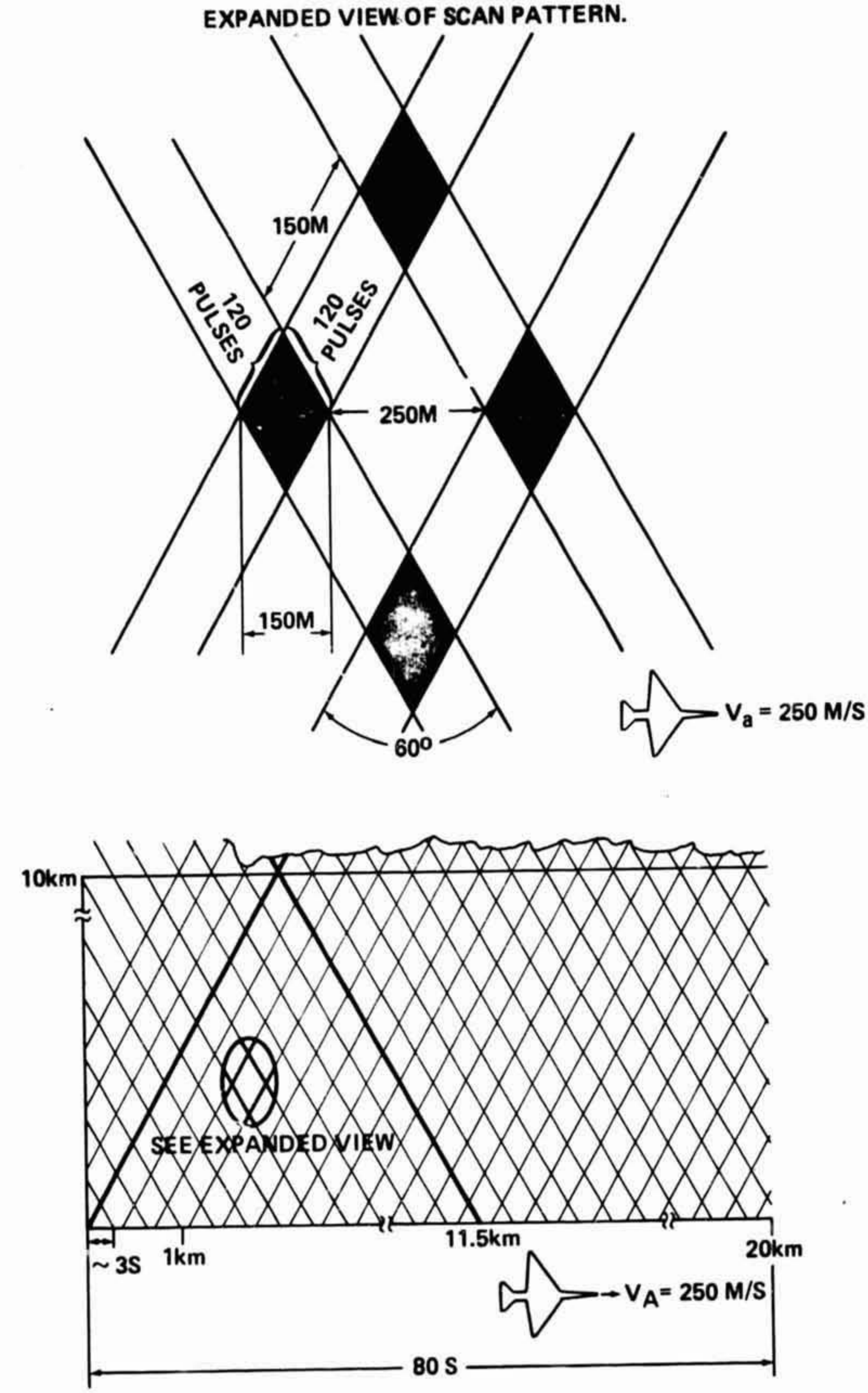

FIGURE 2-3. DOPPLER LIDAR FLOW FIELD SCAN PATTERN.

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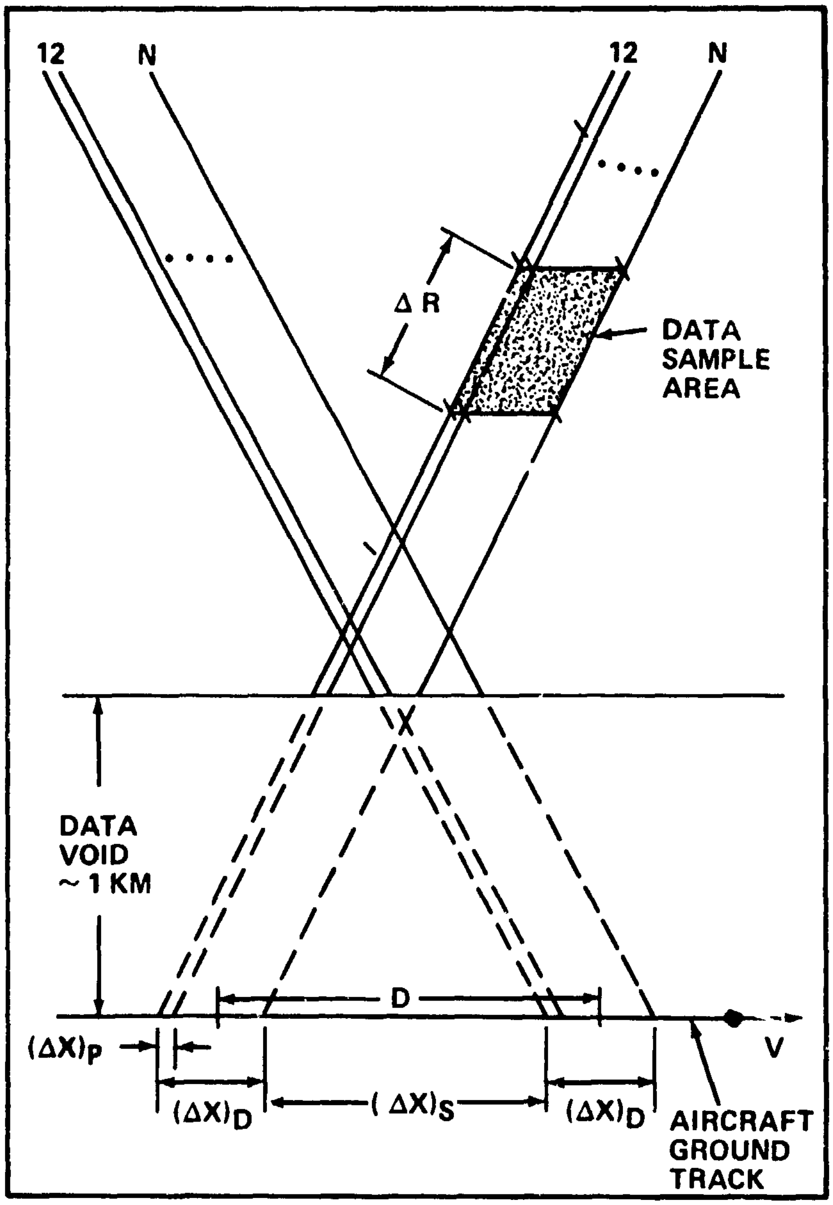

FIGURE 2-4. DOPPLER LIDAR CHARACTERISTICS

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display it has been fixed at 10 km. The extent of the data sample area identified in Figure 2-4 is determined by the pulse resolution, ΔR and the ground track resoltuion, ΔX_D. Where

$$\Delta R = \frac{1}{2} C\tau$$

with

C = speed of light, (3×10^8 m sec^{-1})

τ = pulse duration, (2×10^{-6} sec, 4×10^{-6} sec or 8×10^{-6} sec)

and

$$\Delta X_D = \frac{(N-1)\ V}{PRF}$$

with

N = number of pulses averaged (20 - 200)

V = aircraft ground speed (150 - 250 m sec^{-1})

PRF = pulse repetition frequency (110-140 pps)

The along track distance between peaks, ΔX_p, is given by

$$\Delta X_p = V\Delta t$$

where

$$\Delta t = \frac{1}{PRF} = 7.14 \times 10^{-3} \text{ sec}$$

The along track distance between forward and rearward looking scans, ΔX_s, is given by

$$\Delta X_s = T\ V$$

where

T = scanner turnaround time (.255 sec minimum)

As can be seen from these equations there is a certain amount of flexibility in determining the data sample area. The most notable effects can come from varying N, ΔR, T and V. These equations are summarized in Table 2-1.

2.2 REAL TIME DISPLAYS

Examples of two of the real time displays that will be used during the DLS flight tests are shown in Figures 2-5 and 2-6. In Figure 2-5, the wind field vectors are plotted as a function of distance from the aircraft track (x) and distance from the start of the run (y). Header information includes flight number, run number, date, time, plot number, aircraft position at start of run, position of lower left hand corner of plot relative to start of run, heading altitude, pulse width, number of pulses integrated and scale information. The letters F and A indicate when a signal drop out occurs due to either a forward or rearward looking scan. A B indicates that no signal was received from either scan. Figure 2-6 shows the type of display available for the scalar values of intensity, mean velocity and velocity spread, from a single line-of-sight. Either forward or rearward scans may be selected and displayed. In this case the data is coded and displayed as a function of distance from start position (x) and distance from the aircraft track (y). These displays will be supplemented with a display of the aircraft track relative to the measurement location (Figure 2-7).

V = GROUND SPEED OF AIRCRAFT

τ = PULSE WIDTH

PRF = PULSE REPETITION FREQUENCY

ΔR = RANGE RESOLUTION = $C\tau/2$

Δt = 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 = $(N-1)\frac{V}{PRF}$

$(\Delta X)_S$ = DISTANCE ALONG GROUND PATH BETWEEN FORWARD AND REARWARD DIRECTED BEAMS

T = MINIMUM TIME REQUIRED TO REVERSE LASER PROPOGATION DIRECTION, $T < (\Delta X)_S/V$

PARAMETER	MAGNITUDE	EXAMPLE
V	150–250m sec^{-1}	SPECIFY: ΔR, $(\Delta X)_D$, D
τ	2,4,8 μ sec	
PRF	110–140 PPS	
ΔR	300,600,1200m	CALCULATE:
Δt	0.00714 sec	$\tau = 2\frac{\Delta R}{C}$
$(\Delta X)_p$	1.07 – 1.79M	$N = (\Delta X)_D \frac{PRF}{V} + 1$
N	20–200	
$(\Delta X)_D$	21.4 – 358.0M	$(\Delta X)_S = D - (\Delta X)_D$
$(\Delta X)_S$	113m MINIMUM	
T	0.75 sec	$T = \frac{(\Delta X)_S}{V}$

TABLE 2-1. MEASUREMENT PARAMETERS

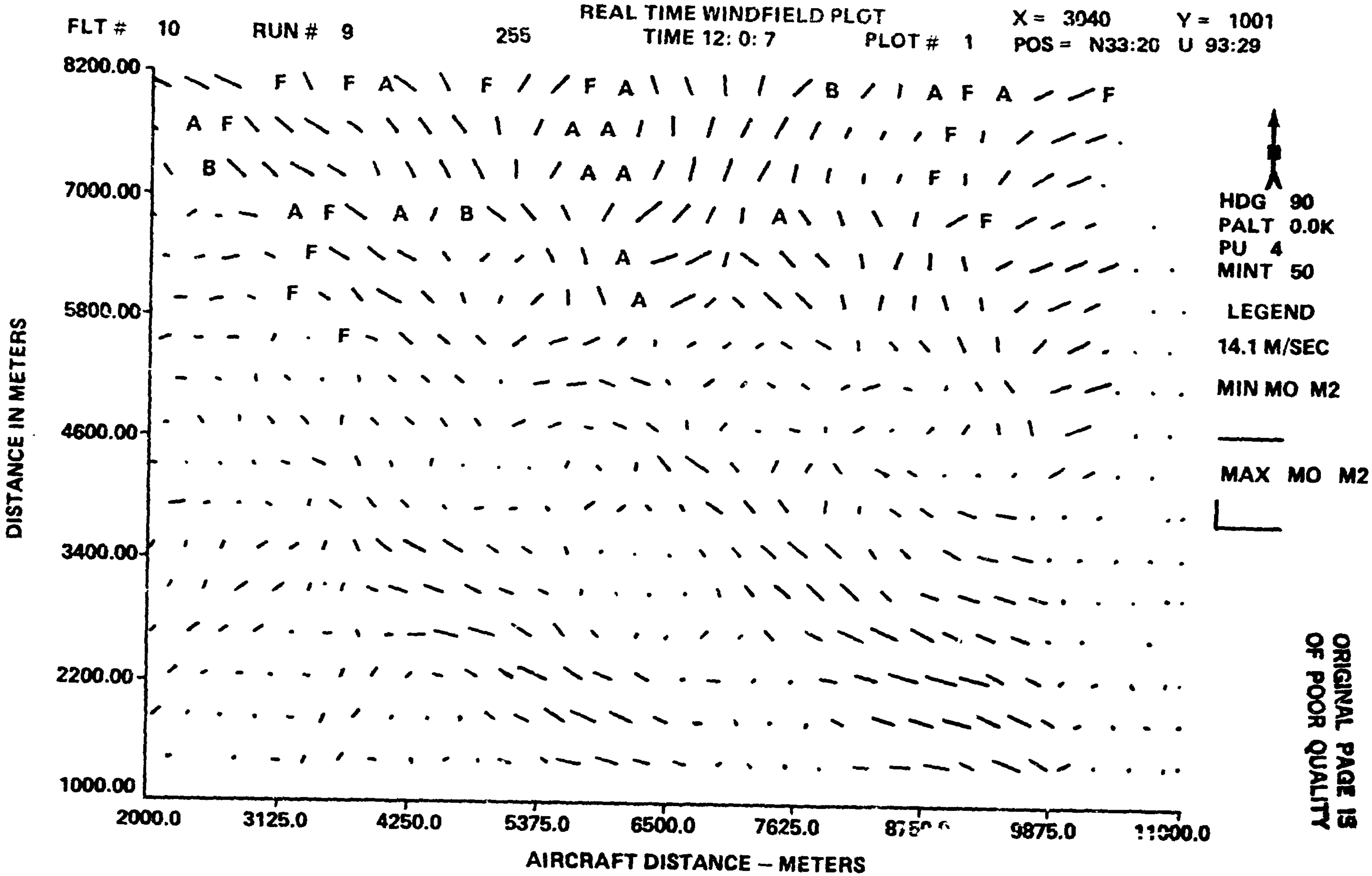

FIGURE 2-5. REAL TIME WIND VECTOR DISPLAY.

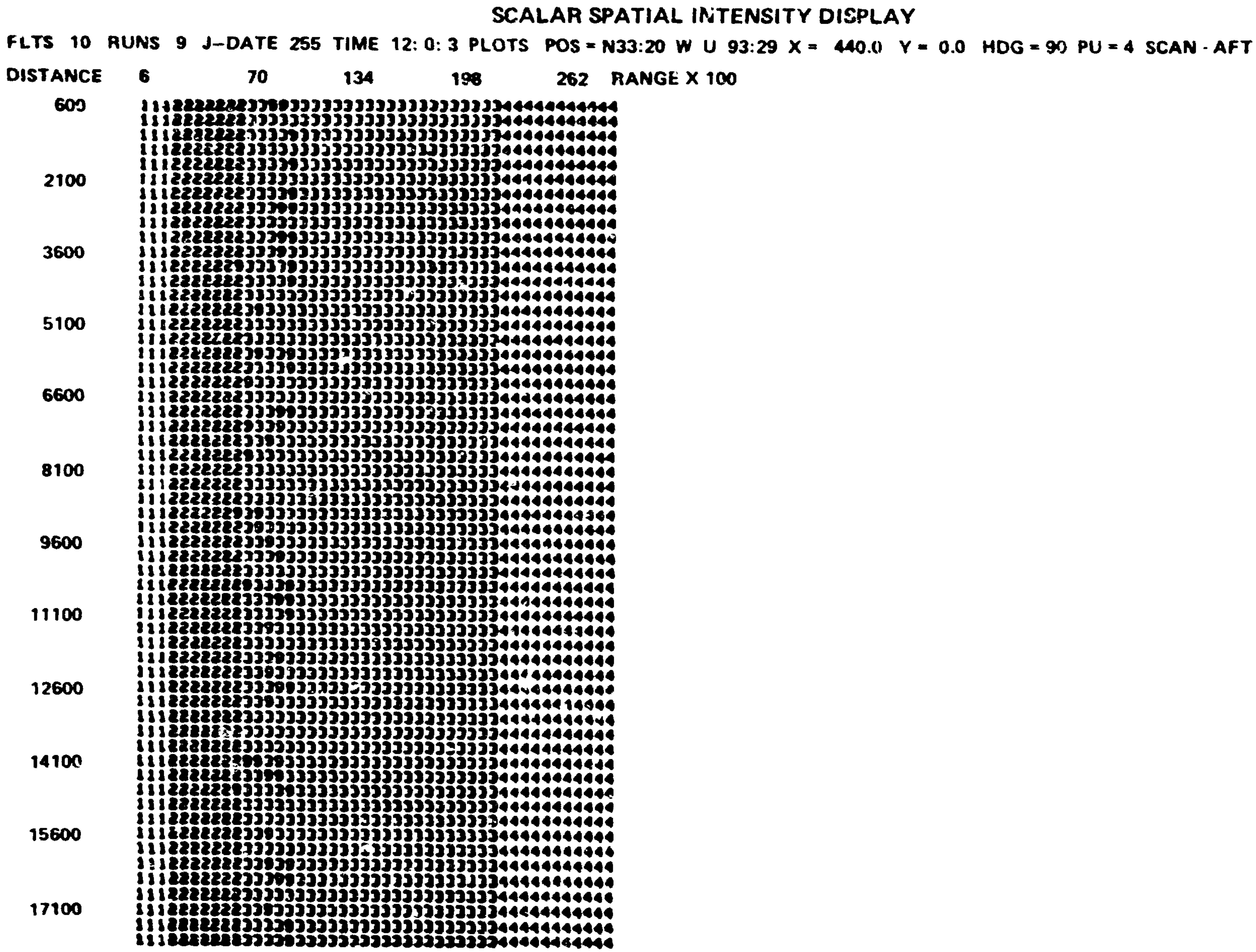

FIGURE 2-6. REAL TIME SCALAR QUANTITY DISPLAY

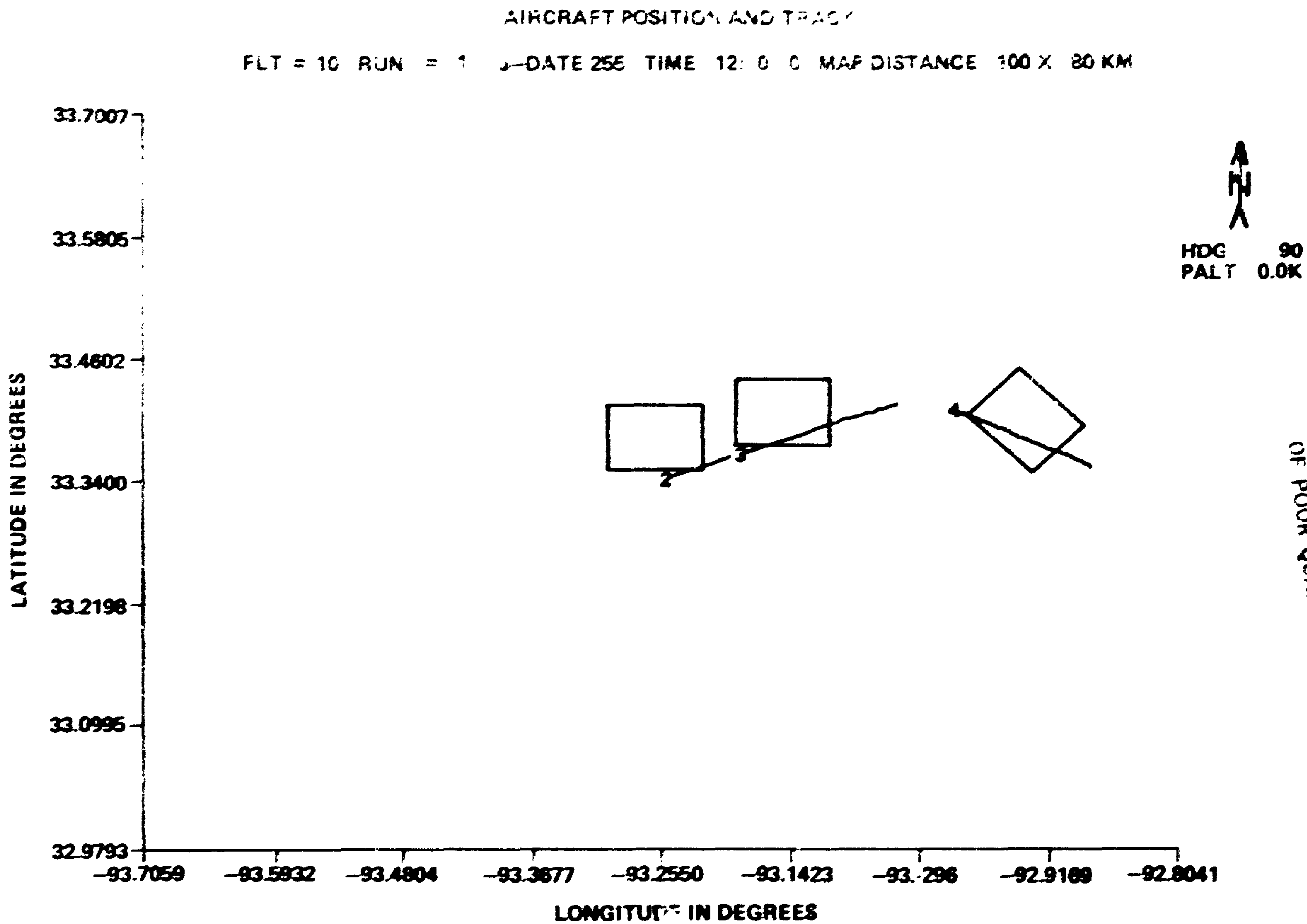

FIGURE 2-7. AIRCRAFT POSITION AND TRACK DISPLAY.

Post processing of this data will be performed to qualify the data and assign error weights to each measurement point. This data will then be provided for analysis.

2.3 POSTFLIGHT TEST DATA PROCESSING

The postflight test processing of the DLS data will be aimed at reducing the horizontal line-of-sight mean velocities. Three types of data sets will be prepared; namely raw data, smoothed fields of line-of-sight velocity, and smoothed vector wind fields. These data sets along with other measurements shown in Table 2-2 will be stored on computer tapes. Limited amounts of hardcopy of these data will also be prepared.

2.3.1 RAW DATA SETS

The most basic set of data that will be prepared consists of the raw line-of-sight velocity measurements. An algorithm will be used to assign a measure of the degree to which each line-of-sight measurement can be considered to be reliable. This quality control parameter will be determined from DLS parameters, e.g. signal-to-noise ratio.

2.3.2 SMOOTHED LINE-OF-SIGHT VELOCITY DATA SETS

These data sets will be obtained from the raw data sets by smoothing the forward and rearward looking line-of-sight velocity fields with a second-order polynomial. This

TABLE 2-2
CCOPE AIRCRAFT RESEARCH INSTRUMENTATION

AIRCRAFT: CONVAIR 990 | **REGIST. NO.: NASA 712**

PARAMETER MEASURED	INSTRUMENT TYPE	MANUFACTURER AND MODEL NUMBER	RANGE	TIME CONSTANT	ACCURACY	USABLE RESOLUTION
HORIZONTAL PLANE WIND MAP	PULSED CO_2 LIDAR	RATHEON CO., SUDBERRY, MA	1–10 km	DATA POINTS EVERY 0.2	TBD	ABOUT 300 METERS ALONG BEAM, 30–300 m LATERALLY
ATMOSPHERIC BACKSCATTER (β–EXPERIMENT)	CO_2 LIDAR	BILL JONES, MSFC	$\lessdot$1.0 km	FUNCTION OF AEROSOL CONCENTRATION	TBD	TBD
TEMPERATURE (TAT)	PLATINUM–RESISTENCE THERMOMETER	ROSEMOUNT 102 AH2AB	+35°C TO –65°C	$\tau \leqslant 1.5$ sec	± 1.0°C	UNKNOWN
DEW–POINT	THERMOELECTRIC	GENERAL EASTERN MODEL 1011	+50°C TO –40°C	1–3°C/sec	~1.0°C	UNKNOWN
FROST–POINT	EG&G (3 STAGE)	MODEL 140	+20°C TO –80°C	~3 TO 5 MIN. (AT LOW TEMPS)	–	–
POSITION OF AIRCRAFT a. GROUND SPEED b. TRUE HEADING c. WIND DIRECTION d. WIND SPEED	INTERNAL NAVIGATION SYSTEM (INS)	LITTON LTN–51	AT POINTS UP TO 41 K FT.	APPROX. 1.0 sec	DRIFT IS LESS THAN 1.0 NAUT MI. PER HOUR	NEAREST 0.1 DEG. OF LAT./LONG.
PRESSURE ALTITUDE	OBTAINED FROM AIRCRAFT FLIGHT INSTRUMENTS	FROM CENTRAL AIR DATA COMPUTER	–1000 FT. TO 50,000 FT.	UNKNOWN	± 20 FT. AT 10,000 FT. TO ± 80 FT. AT 50,000 FT.	–
RADAR ALTITUDE	RADAR ALTIMETER	APN–159 STEWART WARNER COMPANY	SEA LEVEL TO 60,000 FT.	–	± 1%	
AIRCRAFT	3–AXIS ACCELEROMETER	KISTLER INSTRUMENTS	VERTICAL ± 3.5G, LONG. AND LAT. ± 0.5G	~50Hz	VERTICAL ± 0.5G LONG. AND LAT. ± 0.1G	0–10 Hz
STATIC AIR TEMPERATURE	SEE G. ALGER AT AMES RES. CTR.	CALCULATED FOR TOTAL AIR TEMP. AND MACH NO. MEASUREMENT	+35°C TO –60°C	$\tau \sim 1.5$ sec.	± 1.0°C	–
IR SURFACE OR CLOUD TOP TEMPERATURE	IR RADIOMETER	BARNES ENGINEERING MODEL PRT–5	–65°C TO +55°C	UNKNOWN	± 1.0°C	NOT STATED

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process takes into account the signal-to-noise ratio for each measurement and yaw motion of the aircraft to derive smo hed fields of line-of-sight velocity for the rearward and forward looking cases, each.

2.3.3 SMOOTHED HORIZONTAL VECTOR VELOCITY DATA SETS

These data sets will be derived from the smooth line-of-sight velocity fields by removing the time delay of the rearward looking field with respect to the forward looking field. This will be accomplished by first determining area mean values of forward and rearward looking line-of-sight velocities. The area over which this average is to be obtained will be determined during the postflight data processing activity. The mean values of the line-of-sight velocity components will be used to calculate a mean flow horizontal velocity vector. This mean flow velocity vector will be used to advect the forward and rearward line-of-sight velocity fields relative to each other to remove the time delay of the rearward looking velocity field with respect to the forward looking velocity field. The resulting line-of-sight velocity fields will be combined vectorially to obtain an estimate of the horizontal vector wind field.

3.0 TEST OPERATIONS

This section provides a description of the DLS/CV-990 interfaces and operational considerations. The bases of operation for the CV-990 for the various tests are as follows.

California Tests - Ames Research Center, Moffett Field, California

Oklahoma Tests - Tinker AFB, Oklahoma City, Oklahoma

Montana Tests - Ellsworth AFB, Rapid City, South Dakota

3.1 TEST INTERFACES

Figure 3-1 provides a diagram of the interfaces between the respective members of the DLS/CV-990 flight test personnel. The CV-990 mission manager, Mr. George Alger, ARC, is the interface between the MSFC/DLS test team and the CV-990 flight crew (pilot, co-pilot, navigator). The mission manager will work direct with the CV-990 flight crew and the MSFC/DLS test conductor, Mr. James Bilbro, MSFC, or his designated representative. The mission manager is responsible for the conduct of the mission relative to the CV-990 side of the CV-990/DLS interface. The test conductor is responsible for the conduct of the DLS tests. The test conductor works directly with the MSFC/DLS test engineering team and the mission scientist, Dr. George H. Fichtl, MSFC, or his designated representative. The test engineering team is responsible for the successful operation of the DLS under the direction of the test conductor. The mission scientist is responsible for the preparation of scientific flight objectives, preflight

DOPPLER LIDAR SYSTEM CV-990 TEST FLIGHT INTERFACES

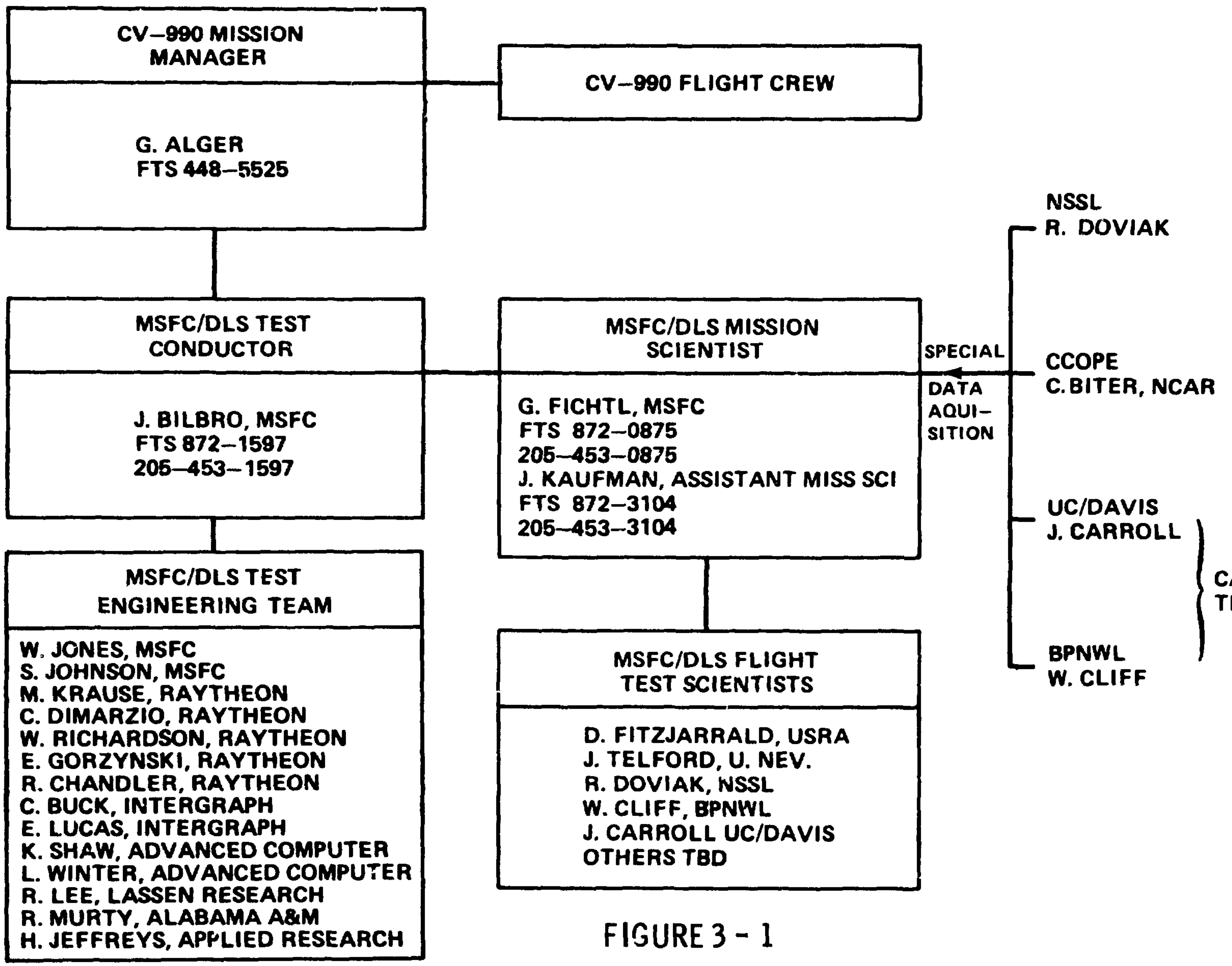

FIGURE 3 - 1

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planning with the various Special Data Acquisition Teams [Natural Severe Storms Laboratory (NSSL), Cooperative Convection Precipitation Experiment (CCOPE), University of California/Davis (UC/Davis), and Battelle Pacific Northwest Labs (BPNWL)], providing necessary scientific support to the test conductor. The mission scientist will be supported by flight test scientists who will fly on the CV-990. Dr. Daniel Fitzjarrald, University Space Research Association (USRA) will fly during all flight tests of the DLS to provide continuity relative to the operation of the DLS from a scientific point of view. Dr. James Telford, University of Nevada (UN), will provide scientific support during the CCOPE and NSSL experiments. Dr. R. Doviak, National Severe Storms Laboratory (NSSL) will provide scientific support for the NSSL tests. Dr. William Cliff, Battelle Pacific Northwest Laboratories (BPNWL) will provide scientific support for the San Gorgonio Pass, California Tests, and Dr. John Carroll will support the Walnut Grove TV Tower and California Central Valley Tests.

3.2 OPERATIONS PROCEDURES

The operational procedures for the CV-990/DLS flight tests are provided in this section.

3.2.1 PREFLIGHT PLANNING

Flight plans for a given mission will be discussed the day before the mission. Participants in this discussion will be, although not limited to, the CV-990 manager, CV-990 flight crew representatives, test conductor, test engineering team member, mission scientist, flight test scientists and appropriate special data acquisition team members. The purpose of these discussions will be to define and set priorities on the flight plan options for the next day's mission depending on the weather forecasts and special data acquisition team operational considerations. We anticipate that during the morning approximately 3 hours prior to CV-990 flight discussions would be resumed to confirm the actual flight operations plan to be used for that day.

3.2.2 WEATHER FORECASTS

Weather forecasts for mission planning purposes will be prepared by the scientific team. The mission scientist or his designated representative will lead this activity. It is planned that weather station facilities at Moffett Field, California; Tinker AFB, Oklahoma City, Oklahoma; and Ellsworth AFB, Rapid City, Montana will be used for preparation of these forecasts. In addition, meteorological inputs will be provided by the special data acquisition team members to support weather forecasts for CV-990 operations. These meteorological inputs will be used in the preflight planning activity discussed in Section 3.2.1.

3.2.3 INFLIGHT OPERATIONS

The flight plan options for a given mission will be those agreed to by the mission manager in the preflight planning discussion. Any deviations from this plan are discussed below. During the mission the mission scientist will determine the order of the flight options to be performed. All scientific inputs to the mission manager and CV-990 crew relative to operation of the CV-990 to attain DLS test scientific objectives will be transmitted from the mission scientist through the test conductor to the mission manager. The mission manager will make a "go no-go" decision on each flight option or deviation thereto.

If it is necessary to deviate during CV-990 flight from operation plans, agreed upon during preflight discussions, the following rules shall be implemented. The mission scientist in coordination with the test conductor and flight test scientists will determine inflight deviations of the CV-990. The mission scientist will confer with the special data acquisition team, if possible, relative to determining deviations. The recommendations for an inflight deviation along with alternate flight plans, to be determined by the mission scientist, will be provided to the mission manager by the test conductor for disposition. The CV-990 will not deviate into CCOPE air operations space unless agreed to by the CCOPE mission scientist.

The test conductor, in coordination with the mission scientist, will determine flight deviations in the event of DLS malfunctions. The recommendation for an inflight deviation along with alternate flight plans will be provided to the mission manager by the test conductor for disposition.

Any inflight deviations of the CV-990 from the agreed to flight operations plan for a given day, which relate to safety or prudent operation of the CV-990 will be determined by the flight crew of the CV-990. All deviations in CCOPE flight operations will be discussed and coordinated by the pilots (in the air) prior to execution of deviations when deviation involves airplanes below 2.1 km (7000 ft MSL). Above 2.1 km (7000 ft MSL) deviations shall be discussed and coordinated by the pilots when aircraft are not under IFR conditions are not being controlled by an FAA flight center.

During the CV-990 operations, we do not anticipate rendezvous with other aircraft. However, we do anticipate CCOPE aircraft may fly in the region in which Doppler lidar wind velocity measurements are being made to obtain in situ turbulence measurements with gust probes for Doppler lidar verification and data interpretation. We anticipate that these CCOPE aircraft would fly parallel to the CV-990 flight path no closer than 200 m from the CV-990 and no further away than 10 km from the CV-990 flight path.

Tables 3-1, 2, and 3 provide operating data for the CV-990 relative to true air speed, climb rate, and fuel consumption.

3.2.4 TIME CONSTRAINTS

All CV-990 flight plans for a mission will be established and confirmed no later than 2 hours prior to flight. Also 2 hours will be required for equipment warm-ups prior to take-off. The crew requires 1 hour to obtain flight clearance. In standby situations wherein flight operations plans have been established, but the CV-990 is waiting for the signal for take-off, the minimum time interval between notification for CV-990 take-off and actual take-off time is 1 hour if the Doppler lidar equipment is warmed-up and 2 hours if Doppler lidar equipment is not warmed-up.

Typically, the CV-990 crew will be available for 8 hour work days; however, it is possible to have 12 hour work days. The total standby time plus mission duration time is determined by these work day constraints. Thus, if standby time becomes excessive such that the mission is adversely impacted so as to significantly reduce scientific return it may be necessary to scrub the mission for that day.

TABLE 3-1

CV-990 TRUE AIR SPEED (TAS) AS FUNCTION OF ALTITUDE

Altitude (m)	TAS (m sec^{-1})
Surface	120-150
3,000	145-170
6,500	170-200
10,000	195-230
13,300*	230-250 (last hours of flight)

*Ceiling 13,300 m. During CCOPE and NSSL tests will probably stay below 11,500 m.

TABLE 3-2

CV-990 TYPICAL CLIMB RATE DATA

Altitude Band (m)	Time to Attain Attitude (min)	Climb Rate ($m\ min^{-1}$)
surface-1,650	4	415
surface-3,200	6	550
surface-6,400	12	550
surface-8,050	15	550
surface-9,600	20	500
surface-11,250	25	465

For fully loaded run to 9700 m
time to altitude 25 min

TABLE 3-3

CV-990 FUEL CONSUMPTION RATE

Altitude	lbs hr^{-1}	gals hr^{-1}
165	16,000	2,443
1,650	15,000	2,290
3,200	14,000	2,137
4,850	13,500	2,061
6,400	13,000	1,985
8,050	13,000	1,985
9,700	12,800	1,954
11,350	12,800	1,954

During any given mission the maximum flight time will range between 5 and 6 hours depending on flight altitude, i.e., 5 hours for a mission taking place below 1.5 km (5000 ft) and 6 hours for a high altitude mission at 10.4 km and 10.7 km (30,000-35,000 ft) with intermediate values of total mission flight time available for altitudes between 1.6 km and 10.4 km (5,000 and 30,000 ft). Typical mission time is expected to range between 4-5 hours. Certain missions, however, could be as short as 2 hours, e.g. Walnut Grove Test. Actual CV-990 flight duration time will depend on science objectives selected for any given mission and meteorological conditions required to accomplish science objectives.

The CV-990 will be scheduled for no more than one mission per day.

3.2.5 METEOROLOGICAL CONSTRAINTS

The CV-990 has certain constraints on meteorological conditions relative to safety. For research flights, the CV-990 is required to maintain at least a 18.5 km (10 nautical mile) horizontal distance from a storm center (as determined from the onboard CV-990 weather radar) for flight altitudes at or above the freezing level. The corresponding horizontal distance for altitudes below the freezing level is 5 nautical miles. If passengers are onboard to observe DLS operations or are not directly involved with satisfying mission objectives the corresponding distances are 37 km and 18.5 km (20 and 10 nautical miles), respectively. All CV-990 VFR flight operations must be conducted under visual meteorological conditions (VMC). At CCOPE CV-990 flight operations at or below 2.1 km (7000 ft) will be under VFR/VMC conditions.

3.2.6 COMMUNICATIONS

All communications to the CV-990 from special data acquisition teams will be transmitted to the mission manager's console onboard the CV-990 on frequencies to be mutually agreed to by the mission manager and the respective data acquisition teams. The CCOPE will provide a special FM transmitter/receiver to the CV-990 for conduct of communications between CCOPE and the CV-990.

4.0 FLIGHT EXPERIMENTS

This section provides detailed descriptions of the summer 1981 flight tests of the DLS. The flight tests have been designed to accomplish the test objectives listed in Section 1.2. Primary emphasis of the test program will be placed on the confirmation of the DLS and assessment of the capability of the DLS to measure detailed wind fields associated with severe storms and local weather phenomena. Flight experiments have been prepared for more flight time than will be available. This will permit the DLS team to respond to changes in atmospheric conditions and will permit the CV-990/DLS team to expedite the summer 1981 flight tests in an efficient manner. The majorit of the tests will be performed in conjunction with various groups to obtain a large body of "ground truth" data and to encompass a wide variety of meteorological conditions.

One item not explicitly discussed in the following test plans deals with dust storms. Interest has been expressed by some of the DLS science team members in data acquisition during dust storms. The motivation for this is threefold, namely 1) dust storms provide aerosol scattering coefficients sufficiently high to guarantee signal return over long ranges provided dust concentration is not too high to result in severe attenuation, 2) large ambient wind velocities and shears, and 3) large local turbulent intensities. Flight plans for studying dust storms would be similar to those for studying cumulus clouds and fronts. We plan to accommodate acquisition of DLS data in dust storm conditions wherever possible, primarily at CCOPE and the NSSL.

4.1 CALIFORNIA TESTS

The California tests consist of three experiments, namely the Walnut Grove TV Tower/DLS comparison experiment, the California Central Valley Experiment, and the San Gorgonio Pass Experiment. The Walnut Grove and San Gorgonio

Pass experiments will provide "ground truth" data for confirmation of the DLS design. Successful accomplishment of these experiments with a favorable comparison between the "ground truth" wind measurements acquired from anemometers on towers with the DLS measurements is absolutely essential before proceeding to the Oklahoma and Montana test sites.

4.1.1 SYSTEM CALIBRATION TESTS

The flight test objectives relating to system performance include:

System calibration as a function of range

Verification of scanner operation

Evaluation of atmospheric performance

Verification of line-of-sight velocity measurements

Verification of two-dimensional velocity vector construction.

The system calibration will be performed by measuring the signal from a hard target at varying ranges, in a method similar to that used in the CAT flights. For this purpose, the scanner will be operated in the manual mode to produce a depression angle, relative to the horizon, of about 12^{o}. This will permit the laser beam to intercept the ground at a range dependent on aircraft altitude. By performing racetrack flight patterns, increasing the altitude on each leg of the racetrack, a varying range may be realized. Specifically, flying at altitudes from 600 meters to 6 kilometers, ranges of 1-10 kilometers may be obtained. Thereafter, it may be convenient to obtain additional, longer, ranges by reducing the depression angle. This experiment will be conducted over an area of smooth, uniform terrain, where reliable backscatter estimates may be made, such as the Carson Sink in Nevada. The amplitude of the signal recorded by the processor and the signal-to-noise-ratio measured with a spectrum analyzer will be recorded at each altitude, thereby providing data sufficient for a system calibration.

The scanner will be tested extensively in ground tests, but a flight test of its performance is desirable to ensure proper orientation relative to the aircraft inertial platform. A suitable experiment for verification of proper orientation of the scanner will be performed, probably using known geographical features as a target, and comparing a map of these features, generated by the system, with a map of the features as they are known to exist. Mountain peaks may provide the best target for this experiment.

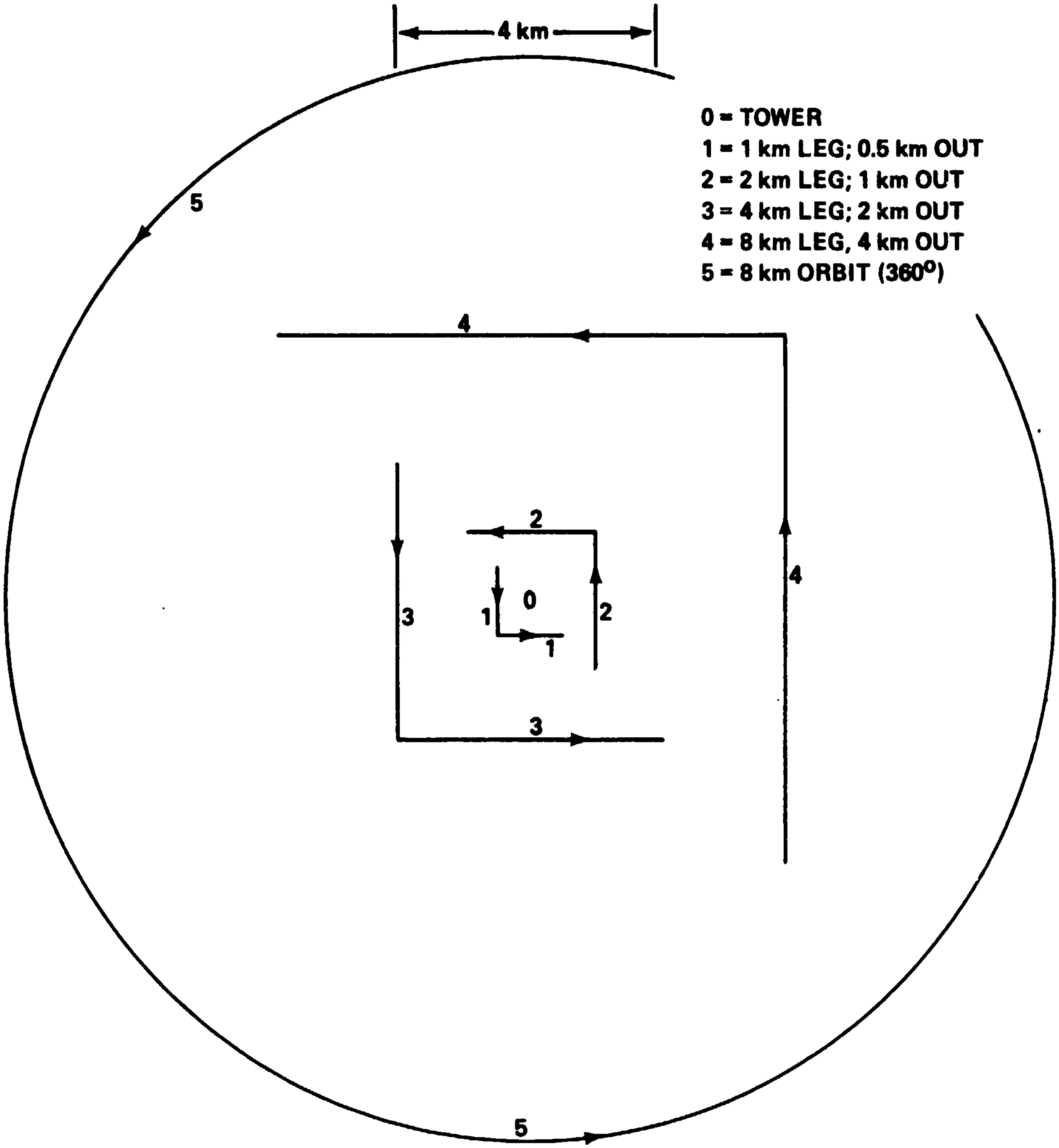
A particularly significant area of concern with regard to the performance of this system is the atmospheric performance at varying altitudes. For this purpose, racetrack patterns will be flown at selected altitudes and amplitude as well as signal-to-noise ratio measurements will be obtained at each altitude. The geographical areas chosen for these experiments will be selected for their similarity to regions of intended use of the system for meteorological purposes.

Verification of the line-of-sight velocity measurements will be made both by measuring the velocity output for ground targets such as the desert floor during system calibration and by comparison of atmospheric velocity measurements to the measured true air speed indicated by aircraft instruments. The latter will only compare on an average basis, since the aircraft instruments are local and the system measurement is remote.

In addition to the above experiments, a verification of the two-dimensional velocity measurement capability of the system will be made. This will be performed by producing a wind vector map in smooth air in the planetary boundary layer. This experiment will be performed in conjunction with tower measurements described in the following section. This experiment will be performed early in the flight test program to provide assurance that the system is operating properly, and to estimate the magnitude of errors in the measurements, for comparison to the theoretical error analysis. This experiment serves a dual purpose providing scientific as well as system data. The calibration, scanner, and atmospheric performance tests will only be of interest as they relate to system performance expectations. This test phase will provide a good basis for interpretation of the meteorological data obtained later in the flight tests.

4.1.2 WALNUT GROVE TV TOWER/DLS INTERCOMPARISON EXPERIMENT

The objective of this test is to obtain "ground truth" data to confirm the DLS design A schematic flight plan is shown in Figure 4-1 A, B, C. In this test, the CV-990 will measure the mean flow at tower height (1550 ft AGL) with the inertial navigation system. The flight pattern will then be oriented relative to the mean wind vector as shown in Figure 4-1 B and C. The navigator will then construct a flight plan consistent with the desired flight path and the mean flow vector as measured by the inertial navigation system as depicted in Figure 4-1 B or C. The flight plans as shown in Figure 4-1 B and C will provide wind measurements for flight path legs normal and



SCHEMATIC FLIGHT PATHS
DURING DATA ACQUISITION

FIGURE 4-1A

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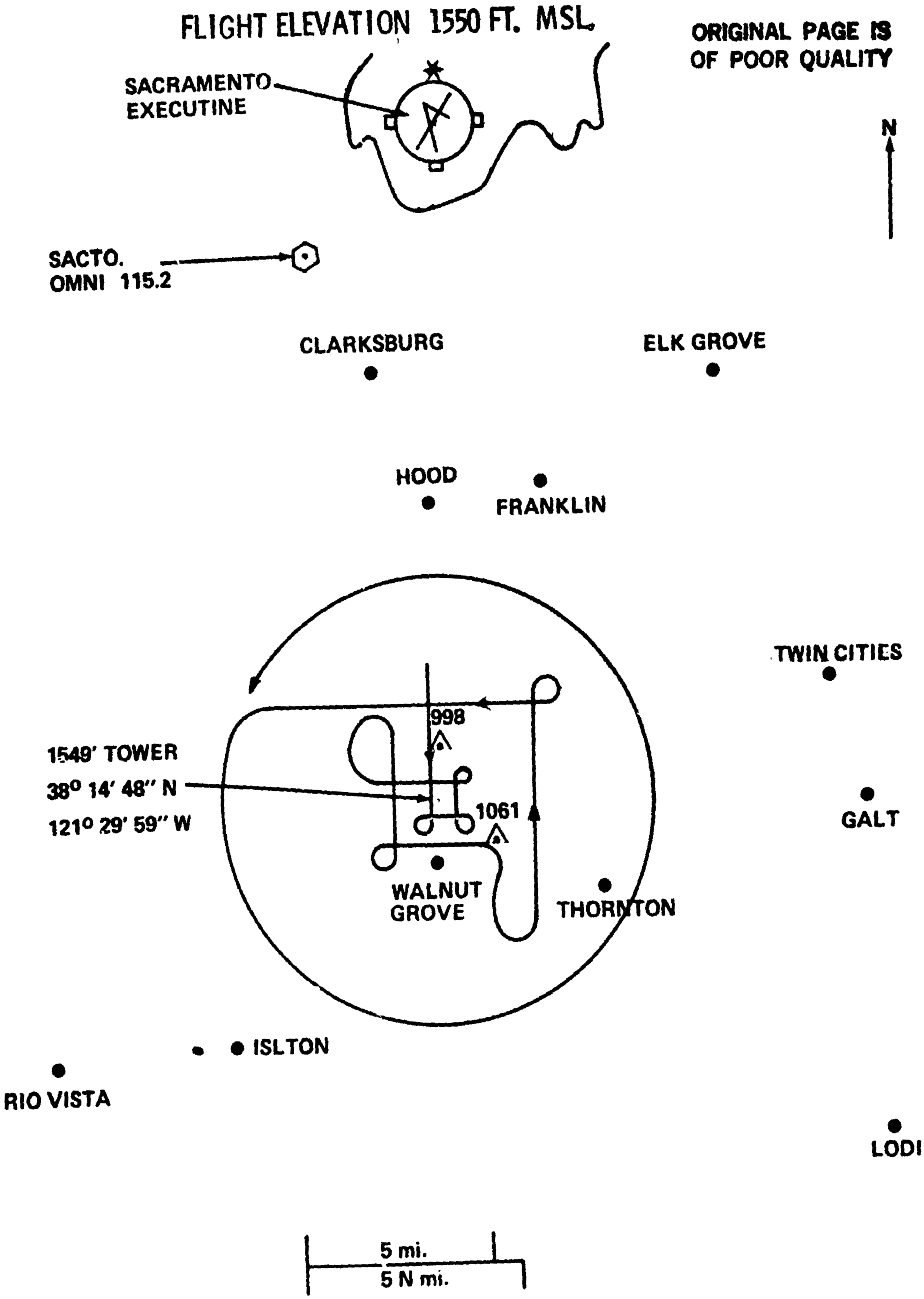
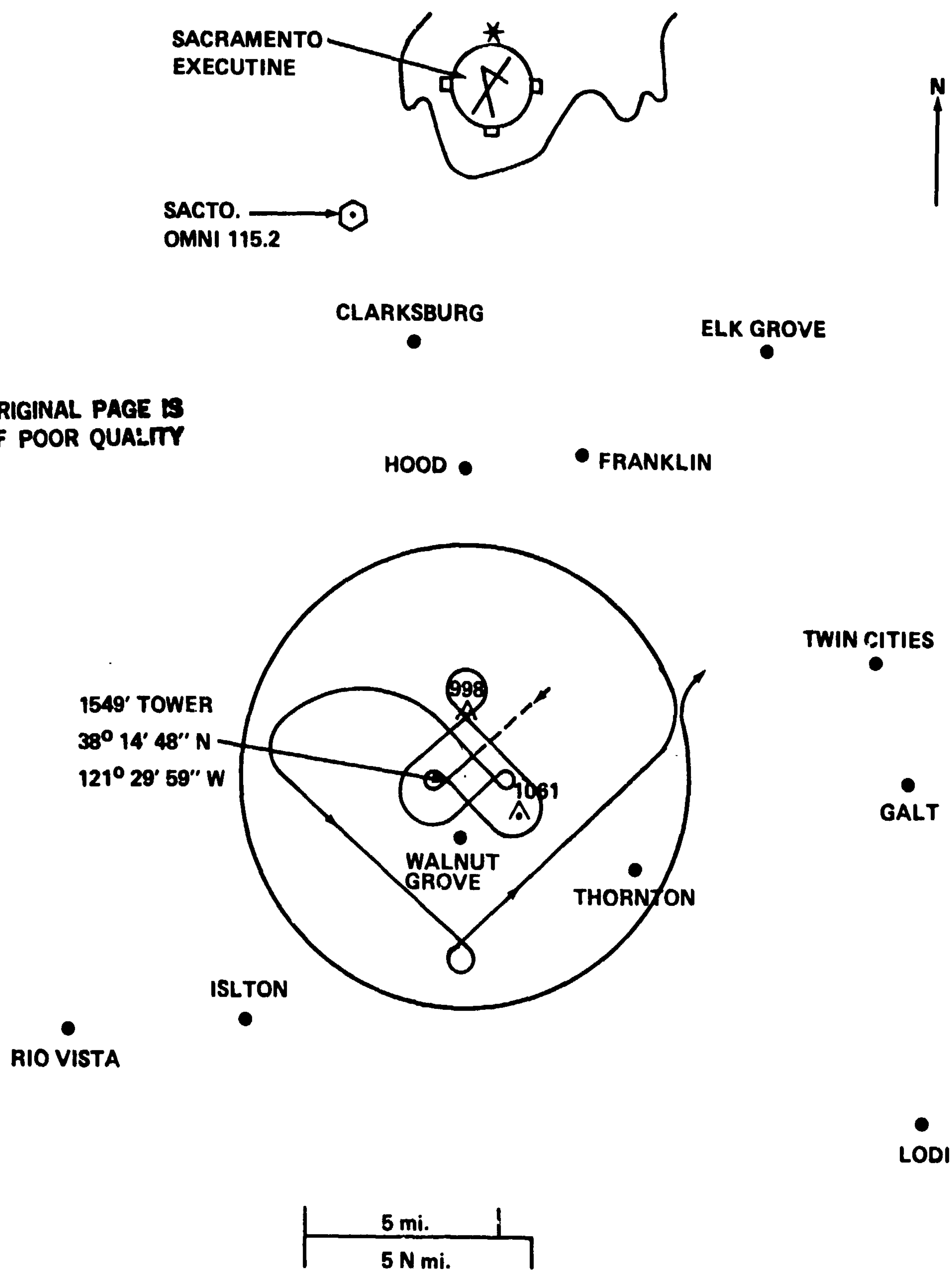


FLIGHT PLAN FOR WIND FROM N, S, E, NW.

FIGURE 4-1B.

FLIGHT ALT. 1550 FT. MSL



FLIGHT PLAN FOR WIND FROM NE, SE, OR NW.

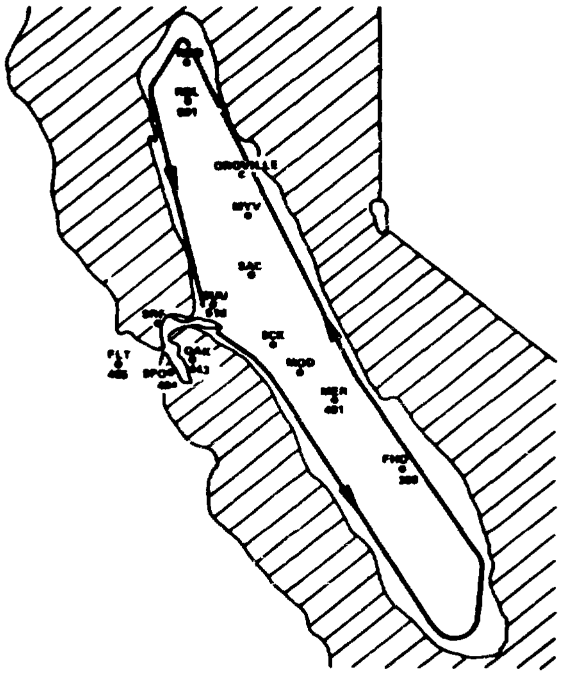
FIGURE 4-1C.

parallel to the mean wind at selected distances from the tower, e.g. 1, 2, 5 km. An anemometer and wind vane at the 472 m level (AGL) on the tower will provide corresponding measurements of the wind. This experiment will be the first test of the DLS. The flight pattern in Figure 4-1 B or C will be flown twice. The CV-990 will then return to the ARC for immediate between the DLS and tower data.

If the flights are contained within the area of the schematic shown, these are within a 15 km radius of the tower. The nearest population centers within this radius are Isleton and Rio Vista to the southwest of the tower 14.5 km and 20.9 km respectively (9 and 13 miles) and Elk Grove 20.9 km (13 miles) to the northeast. The most likely wind directions during the flights would be from the southwest or the north. Presumably we could set up two flight routes based on these two possibilities and lay out a flight plan for each that precludes low level flight over these populated areas.

4.1.3 CALIFORNIA CENTRAL VALLEY EXPERIMENT (Ref. Fig. 4.2)

The objective of this experiment is to investigate the spatial and temporal variation of the boundary layer wind flow patterns in the California Central Valley, examine the detailed flow patterns in the vicinity of agricultural-burning smoke plumes, and the local flow near the Geysers geothermal field. The flight path consists of a racetrack pattern around



NOTES

1. WALNUT GROVE 1500 FT TOWER WILL BE USED TO ACQUIRE GROUND TRUTH DATA WITH ANEMOMETER
2. OPERATE DOPPLER LIDAR IN FORWARD AND AFT SCANNING MODE
3. RECORD ON FILM OR VIDEO TAPE PICTURES OF CLOUDS AND AIR POLLUTION LATERAL TO FLIGHT PATH

FLIGHT OPERATIONS

1. FLY IN VICINITY OF WALNUT GROVE TOWER TO ACQUIRE DOPPLER LIDAR MEASUREMENTS AT 1500 FT LEVEL
2. FLY PERIMETER OF CALIFORNIA CENTRAL VALLEY WITH DOPPLER LIDAR POINTED TOWARD VALLEY (INCLUDE BAKERSFIELD AND RED BLUFF). STAY IN ATMOSHPERIC BOUNDARY LAYER
3. BEGIN FLIGHT THROUGH STRAITS IN EARLY AFTERNOON AFTER SEA BREEZE HAS BEEN ESTABLISHED.

FIGURE 4-2 CALIFORNIA CENTRAL VALLEY STUDY the California Central Valley near the top of the mixed layer (approximately 610 m (2000 ft). The flight would take place from noon through evening. The CV-990 would enter the Central Valley over Benicia and fly southeastward between Tracy and Stockton (altitude ~610 m (2000 ft)), pass just west of the Lemoor N.A.S. airport traffic area to the Taft intersection of V-183 and V-137; turn NNE to Porterville omni then NNW following V-165 but remaining east of Fresno Air Terminal. From there head west of foothills but east of US 99 to Red Bluff and then return along westside of valley to Benecia.

The nature of the flow into the Central Valley is an important applied meteorology problem of great interest to people concerned with the structure of the atmospheric boundary layer. Dr. John Carroll of the University of California, Davis (UC/Davis) will support these tests.

4.1.4 SAN GORGONIO PASS EXPERIMENTS

The objectives of this experiment are twofold, namely 1) to acqurie ground truth data for the intercomparison with concurrent DLS measurements and 2) to acquire fundamental data on flow through the San Gorgonio Pass for use in assessment of the flow through the pass for wind energy applications. The flight plan for the DLS/CV-990 San Gorgonio test is shown in Figures 4-3 and 4-4.

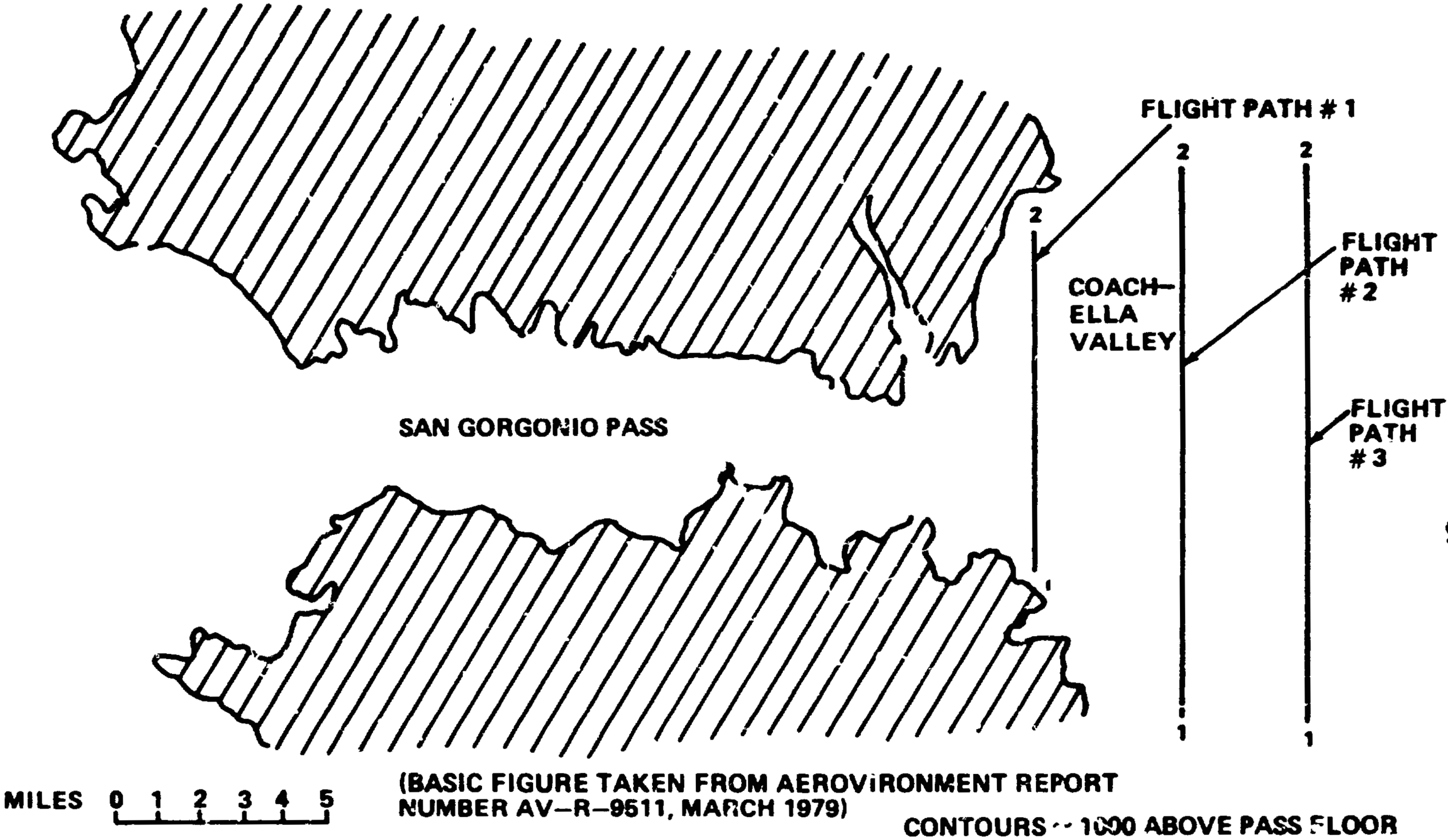


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FIGURE 3-4. SAN GORGONIO PASS TEST OPTION FLIGHT PATHS FOR NASA AIRBORNE DOPPLER LIDAR

FLIGHT OPERATIONS

1. FLY SOUTH–NORTH TRAJECTORIES OVER COACHELLA VALLEY–IN THIS CASE DOPPLER LIDAR WILL BE LOOKING INTO SAN GORGONIO PASS
2. EXECUTE 180° TURN AND FLY BACK TO LOCATION 1 -- FLY AT SELECTED ALTITUDES (100,300,500,1000, 1500m) ABOVE COACHELLA VALLEY

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 4–3

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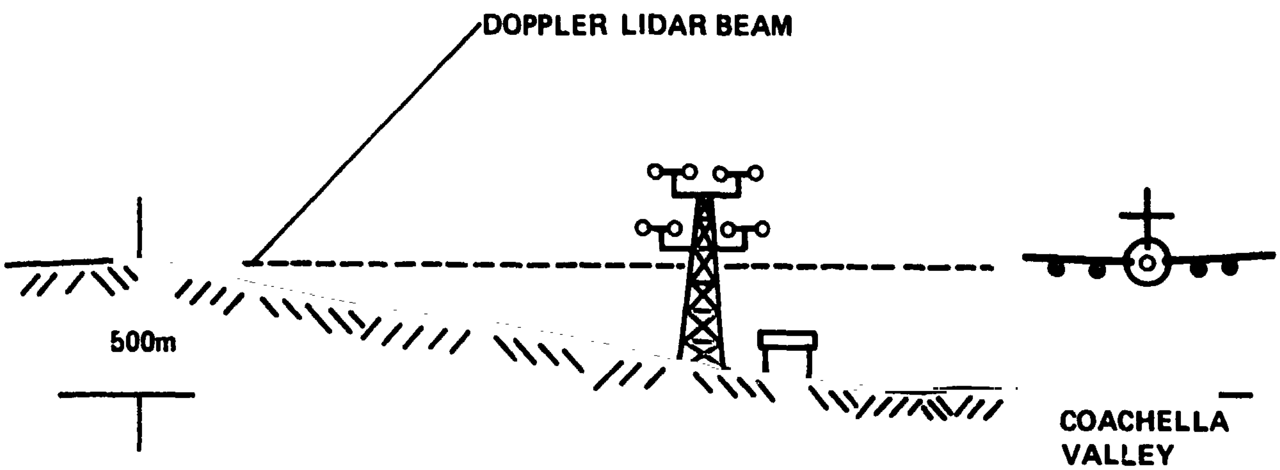
CROSS-SECTION VIEW OF SAN GORGONIO TEST



SIDE VIEW

NOTES

1. GROUND TRUTH DATA IN THE FORM OF WIND OBSERVATIONS ACQUIRED WITH ANEMOMETERS ON TOWERS WILL BE AVAILABLE
2. RECORD FILM OR VIDEO TAPE PICTURES OF VALLEY

FIGURE 4-4.

San Gorgonio Pass is approximately 40 km (25 miles) long with a westerly elevation of approximately 760 m (2550 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 km (11,000 ft) within 16 to 24 km (10-15 miles) on each side of the valley floor.

The region of interest consists of 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. 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 (see Figure 4-3).

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.

These data stations will be located in the pass and will be at heights so as to be available for acquiring "ground truth" data to compare with the DLS. The anemometer array is operated by the Southern California Edison Company. Dr. William C. Cliff of the Battelle Pacific Northwest Laboratories will support these tests.

4.2 OKLAHOMA TESTS - NSSL

The primary reason for conducting the experiments in central Oklahoma is to combine the airborne Doppler lidar observations with observations of clear and stormy air made with NSSL's dual 10 cm Doppler radar, a tall (500 m) meteorologically instrumented tower and rawinsondes. It is expected that this unique combination of observations will advance our knowledge of severe storm phenomena and its forecast. Accordingly, all the flight operations will be conducted so that there is the maximum possible coordination with NSSL.

It is anticipated that there will be 17 hours of flight time available for operations at NSSL. The aircraft will be stationed (Tinker AFB), very close to NSSL, so there will be no ferry delay. The aircraft operational limitations have been detailed in the CCOPE Flight Plans document and will not be repeated here. The limitations should not compromise any of the flight plans given below.

The flight plans below can be separated into two general classes 1) measurements that can certainly be made and compared with the NSSL radars, i.e., convection in the afternoon boundary layer; 2) measurements that can only be made if the weather is favorable, i.e., nighttime boundary layer and low-level jet, prestorm, developing and mature cumulus, gust fronts. We will, therefore, want to accomplish the first group of experiments immediately on arrival at NSSL and then wait for favorable conditions for the second class of experiments. The order, of course, might be reversed if the more interesting weather occurred the first day.

Locations of aircraft and flight altitudes are subject to approval by the FAA and are listed here to guide our request for flight clearance prior to the execution of the experiment. Thus these plans are not necessarily rigid and some adjustments can be made without compromising the scientific objectives.

4.2.1 HIGH RESOLUTION INTERCOMPARISON

This experiment will provide a comparison of lidar observations with the highest resolution achievable with the Doppler radar. In this case (see Figure 4-5) the radar beam is held fixed and the aircraft flown so that the first few range gates of the lidar intercept the radar beam. The aircraft is flown toward the airport located close ($\simeq$ 1 km) to the radar antenna, so that the best possible resolution is obtained from the radar to compare with one component of the lidar-derived wind. Operationally, the flight should be straightforward because it consists of flying a simulated landing at Max Westheimer Field on either of two possible approaches. A 3° glide slope approach is recommended and radar azimtuh angle ϕ will be selected so that (1) the radar beam is in a range where lidar returns can be detected

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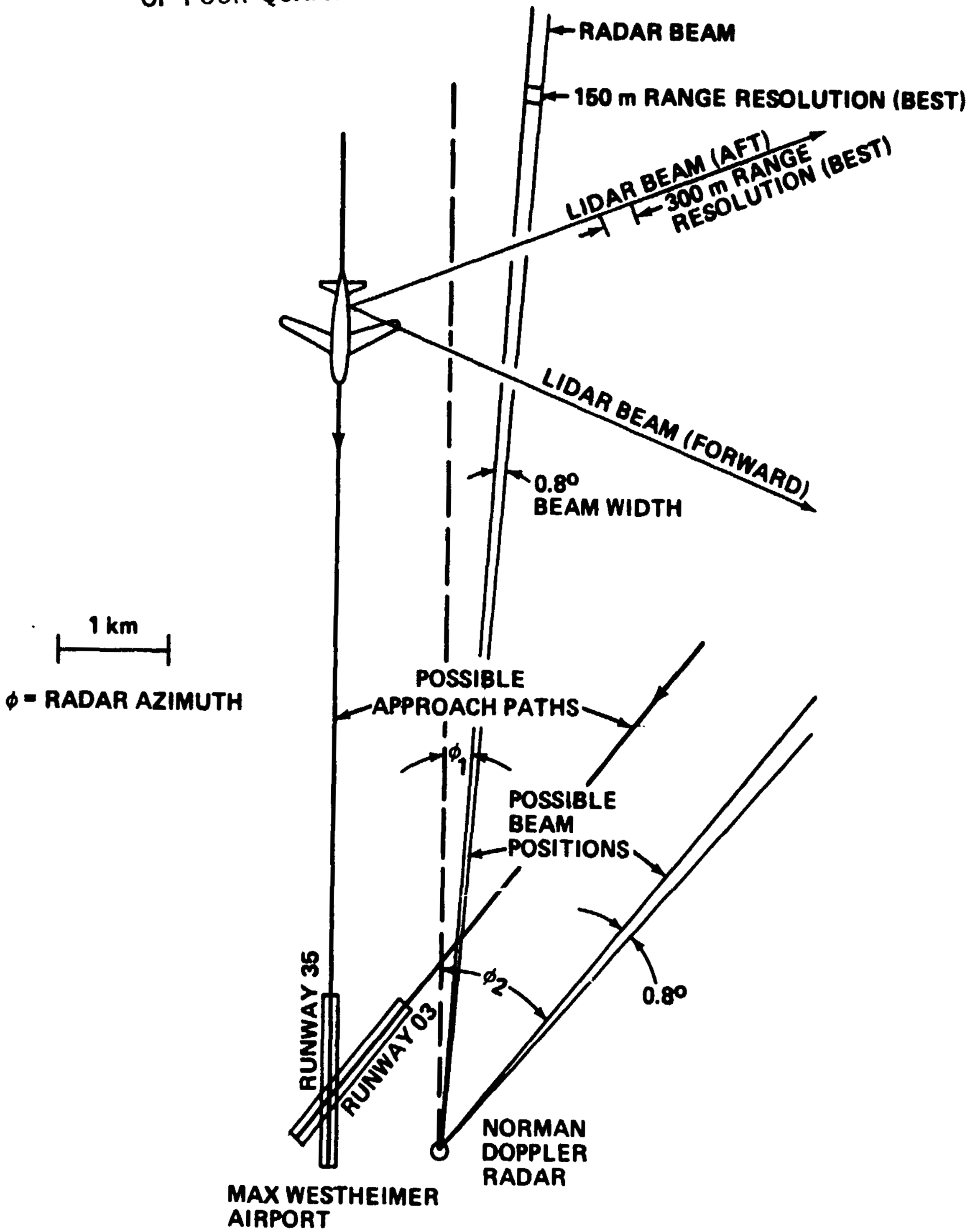

FIGURE 4.5 WIND MEASUREMENT ALONG RADAR BEAM.

and (2) ground clutter return allows measurement to the nearest range of measurement (≈ 5 km). It is desirable to keep the beam as nearly parallel to the approach path so that the lidar beam intersects the radar beam along the entire path. At a 10 km range the radar's resolution volume is almost symmetrical with a dimension of about 150 m. A comparison of Doppler radar radial velocities and *in situ* wind component longitudinal to an aircraft flying parallel to the radar beam is shown in Figure 4-6 .

4.2.2 BOUNDARY LAYER MEAN FLOW, TURBULENCE, AND WAVES

In addition to providing data for comparison of lidar and radar measurements, this experiment will expose the four dimensional (space and time) structure of turbulence and waves in the boundary layer The aircraft will also provide data on the vertical profiles of mean wind, temperature and humidity. There is both a day and nighttime experiment. The daytime experiment will take place mid-afternoon on sunny days during which time convection should be vigorous. We will also attempt to make measurements that might expose the "heat island" effect of Oklahoma City. The nighttime flight is to gather data on the nocturnal jet which is often responsible for the rapid development of moisture in the Great Plains. Radar depiction of turbulence and waves is best in a 50 km by 50 km area centered about the intersection of State

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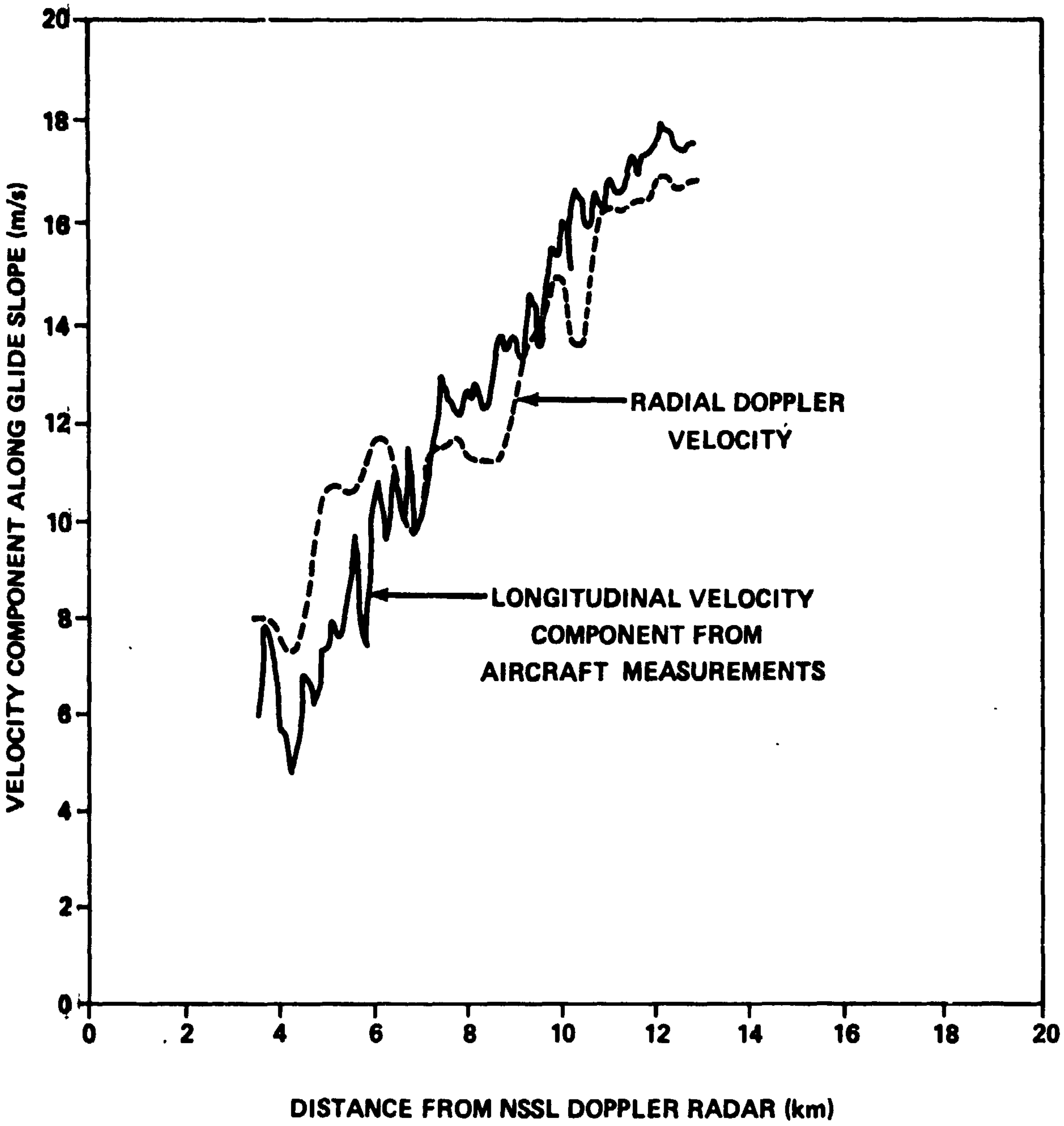

FIGURE 4.6 COMPARISON OF DOPPLER RADAR RADIAL WIND COMPONENT WITH WIND COMPONENT LONGITUDINAL TO AIRCRAFT FLYING PARALLEL TO RADAR BEAM.

Highway 9 and 81 (see Figure 4-7) near Chickasha, Oklahoma. Figure 4-8 shows the flight paths for use in these boundary layer experiments described below.

4.2.2.1 CONVECTIVE BOUNDARY LAYER EXPERIMENT

This experiment will be conducted during sunny afternoon conditions when radar shows detectable targets to at least a 70 km range and to heights of about 1 km or more. Figure 4-8 shows the flight paths to be followed by the aircraft while both the NRO and CIM Doppler radars scan the volume common to both radars and aircraft. The path shown in Figure 4-8 can be moved several kilometers if air traffic will not allow flights about Chickasha, Oklahoma. The aircraft should enter at the highest altitude at which the radar is receiving echoes over large areas within the dual Doppler area (Figure 4-7), or slightly higher than the inversion height (Figure 4-7) and then, after completing the circuit, it should descend by about 250 m. The precise altitudes and separations are not critical to the experiment, but the pilot should fly each circuit at a level that is constant to within the tolerances allowed by the aircraft, weather and air traffic controllers. A descending pattern of circuits is preferred if it decreases noise at the ground. The aircraft should descend to the lowest level allowed by regulation and the air traffic controllers.

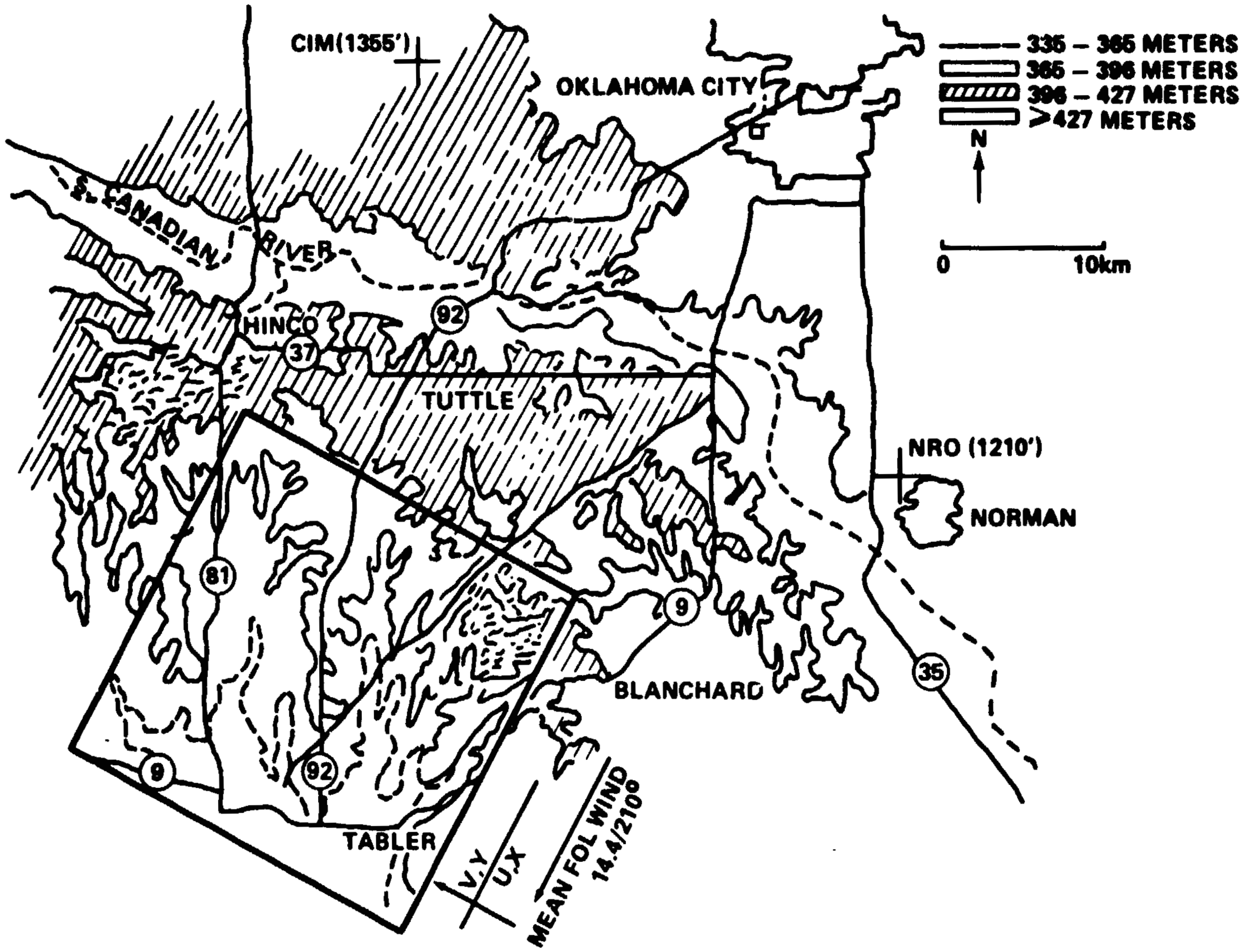

FIGURE 4.7 TOPOGRAPHIC MAP SHOWING LOCATION OF THE DUAL DOPPLER RADARS (NRO, CIM) IN CENTRAL OKLAHOMA. CONTOURS ARE HEIGHT OF GROUND ABOVE MSL IN FEET. A 500 m METEOROLOGICALLY INSTRUMENTED (KTVY) TOWER IS 356° AT 37 km, AND THE RAWINSONDE SITE IS 230° AT 100 km FROM NRO. THE BOX AREA APPROXIMATES THE LOCATION OF THE BOUNDARY LAYER EXPERIMENT AND ITS ORIENTATION WILL BE APPROXIMATELY ALIGNED TO THE MEAN WIND ON THE DAY OF THE EXPERIMENT.

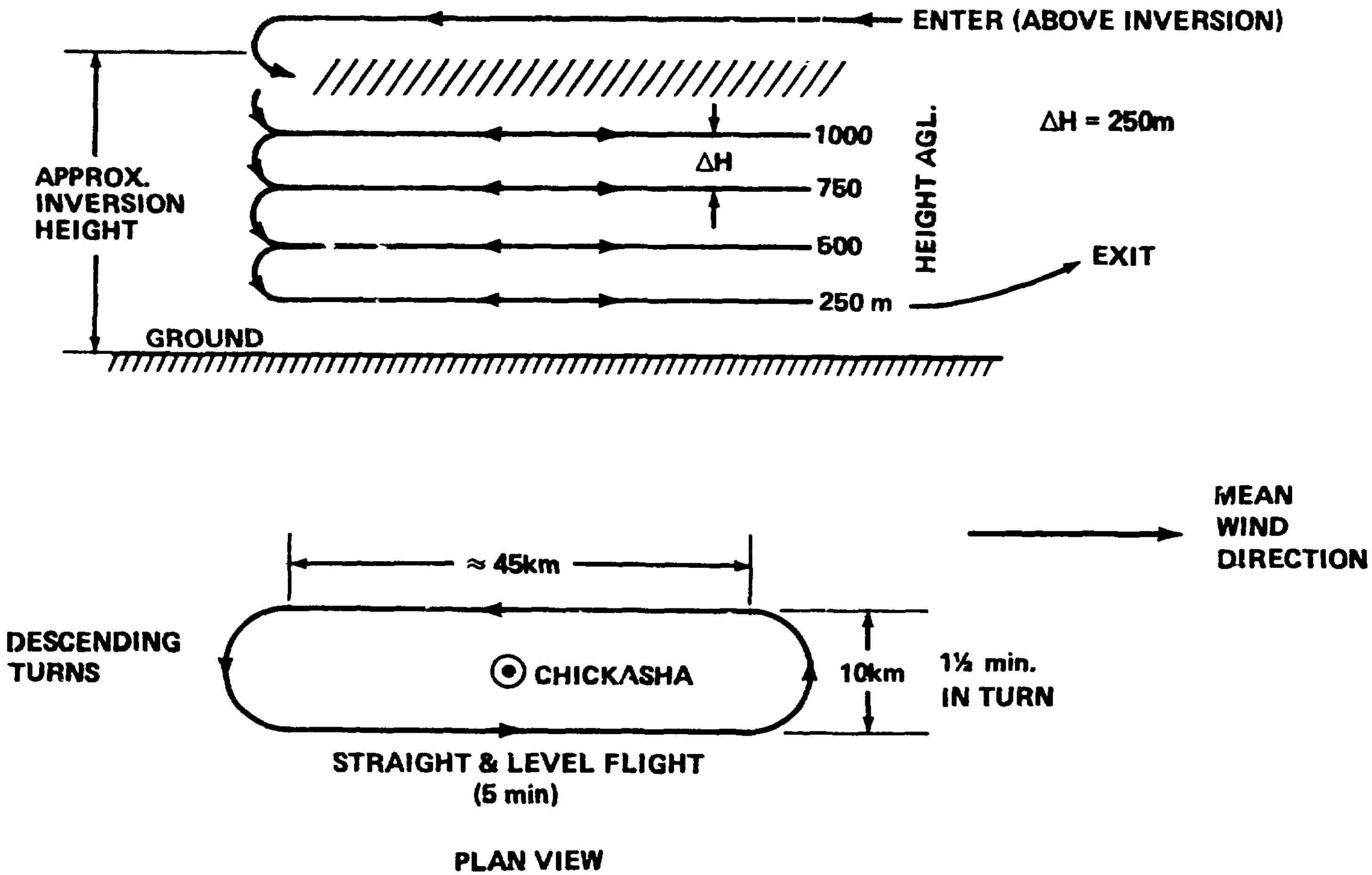

FIGURE 4.8 FLIGHT PATHS FOR BOUNDARY LAYER EXPERIMENTS:
1. LIFETIME (MULTIPLE TRIPS AT ONE LEVEL)
2. NOCTURNAL JET AND 3. CONVECTIVE BOUNDARY LAYER STRUCTURE.

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Each circuit should take about 13 minutes of flight time and assuming that 8 levels are flown, the total time for this experiment will be about one hour and 45 minutes. At the completion of this experiment the lifetime experiment described below can then be executed.

4.2.2.2 TURBULENCE LIFETIME EXPERIMENT

The flight circuits depicted in Figure 4-8 will also be used in this experiment except now the aircraft will fly at one altitude and this will be the highest one at which the radar can detect echoes over a large horizontal region. Radar data collected on previous occasions indicate there is a high degree of temporal coherence (lifetimes of the order of tens of minutes) for the resolved scales ($\geq$ 1 km). Accordingly, at one altitude 3 or 4 entire circuits should be made to see the decay of urbulence. (Four circuits takes 52 min. and the advection time for the 45 km long strip shown in Figure 4-8 is 75 min. for a wind speed of 10 m sec^{-1}.) If this relatively high temporal coherence is maintained during these experiments, then the wind field mapped by the DLS on one pass can be compared to the wind field it maps on the second pass. In other words, the fields should be self consistent for scales larger than 1 km.

It's expected that about 3 hours of flight time will be used by experiments described in Sections 4.2.2.1 and 4.2.2.2.

4.2.2.3 NOCTURNAL JET EXPERIMENT

In the event that there is a high probability of occurrence of a low-level jet, or significant boundary layer winds after sunset, one late night flight should be made. The flight plan is also given in Figure 4-8. The flight levels bracket the level of maximum speed in the case of a jet, or the inversion layer when no jet is present. The flight should commence an hour before dawn and continue until an hour past dawn. The pattern will be repeated during that time. The obtained DLS data can be compared with both the radar data if targets are sufficiently strong or that obtained from the instrumented 500 m tower in Oklahoma City. Radar returns will not be as strong or as extensive as those obtained during afternoon thermal convection.

4.2.2.4 HEAT ISLAND EXPERIMENT

This experiment should be conducted during daylight hours when winds are from the southwest or northeast. The aircraft will sample the air as in the experiment described in 4.2.2.1 and hence that experiment may be part of this one if winds are directed perpendicular to the baseline connecting the two radars. The added feature in this experiment requires samples of wind on the northeast side of Oklahoma City, north of the KTVY tower which is 354°/39 km from the NRO Doppler. At the conclusion of the flight plan described in 4.2.2.1, the aircraft should make a flyby north of the tower at an altitude of about 1000 m (see Figure 4-9) and if possible return along the same path at lower altitude (500 m). If other flights are possible at higher altitudes (e.g. 1500 to 2000 m) then these should be performed. Temperature, humidity, and wind as well as housekeeping data should be recorded on this flight leg. The aircraft should come as close to the city as allowed by FAA controllers and consideration of noise and tower obstacles.

4.2.3 PRESTORM

In the event that cumulus activity is forecast, the following flight plan sequence should be initiated.

1) Based on a suitable forecast, the aircraft and DLS system will be placed on alert.

2) As soon as any indication of increasing convection is seen by the radar or satellite, the flight should be initiated.

4.2.3.1 FRONTAL ZONES AND CLOUD LINE EXPERIMENT

These fronts often move into northwest Oklahoma or western Kansas during June and at this time of the year are in clear air during the late morning or early afternoon. DLS and radar scans across the frontal zone will yield information along the front if the aircraft flies as shown in Figure 4-10. If clouds are not present, flights altitudes

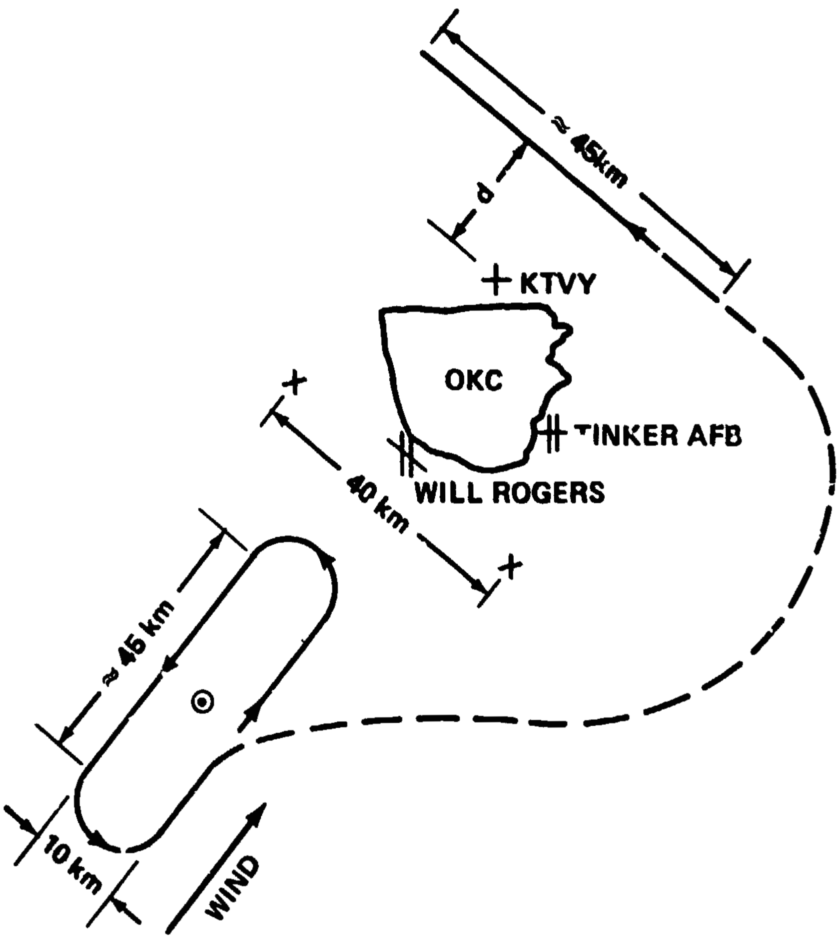
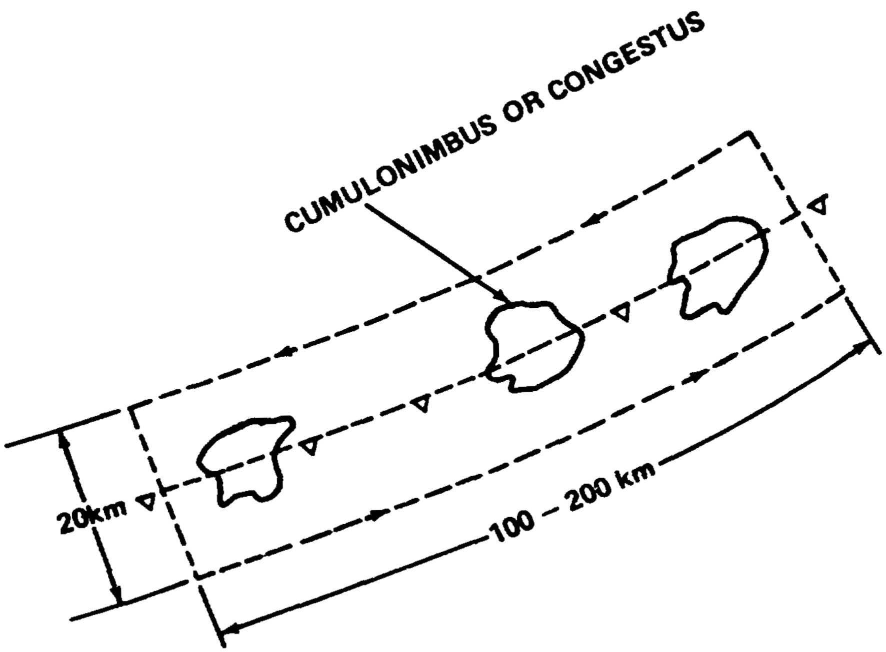


FIGURE 4.9 HEAT ISLAND FLIGHT PATHS. THE DISTANCE d IS THE MINIMUM DISTANCE ALLOWED CONSIDERING AIR TRAFFIC, OTHER TOWER OBSTACLES, AND POPULATION DENSITY.



3 FLIGHT LEVELS

1) BELOW CLOUD BASE ($\simeq$ 0.5 km AGL)

2) NEAR CLOUD BASE ($\simeq$ 1.0 km AGL)

3) 2.0 km AGL

FIGURE 4. 10 FLIGHT PATH FOR AIRCRAFT SAMPLING A FRONTAL ZONE OR CLOUD LINE

will be approximately 500 m or the lowest level that clearance can be obtained from the FAA controller and 500 m above that level. If clouds are present, then the CV-990 should be flown at the three altitudes suggested in Figure 4-10.

4.2.3.2 DRYLINE - FRONT INTERSECTION EXPERIMENT

Sometimes this "triple point" intersection is seen by radar and if the radar observations, surface or satellite observations suggest a dryline - front within 120 km of Norman, the flight plan will be as depicted in Figure 4-11. These dryline-front intersections are often found in Oklahoma in June. The flight altitudes will be selected using the same procedure followed frontal zones described in Section 4.2.3.1.

4.2.4 CUMULONIMBUS EXPERIMENTS

If cumulus clouds mature to the congestus stage and eventually become thunderstorms then there are five experiments that can be attempted: (1) lateral entrainment, (2) cloud top turrets, (3) anvil clouds, (4) gust front, and (5) flanking cloud experiments. In each of these experiments the aircraft will be guided to the area of interest based on information from ground observations with Doppler radar, or visual observations by scientists onboard the CV-990. Once reaching the area and altitude of interest, the aircraft will also be guided by airborne radar to stay out of regions of storm precipitation following FAA guidelines.

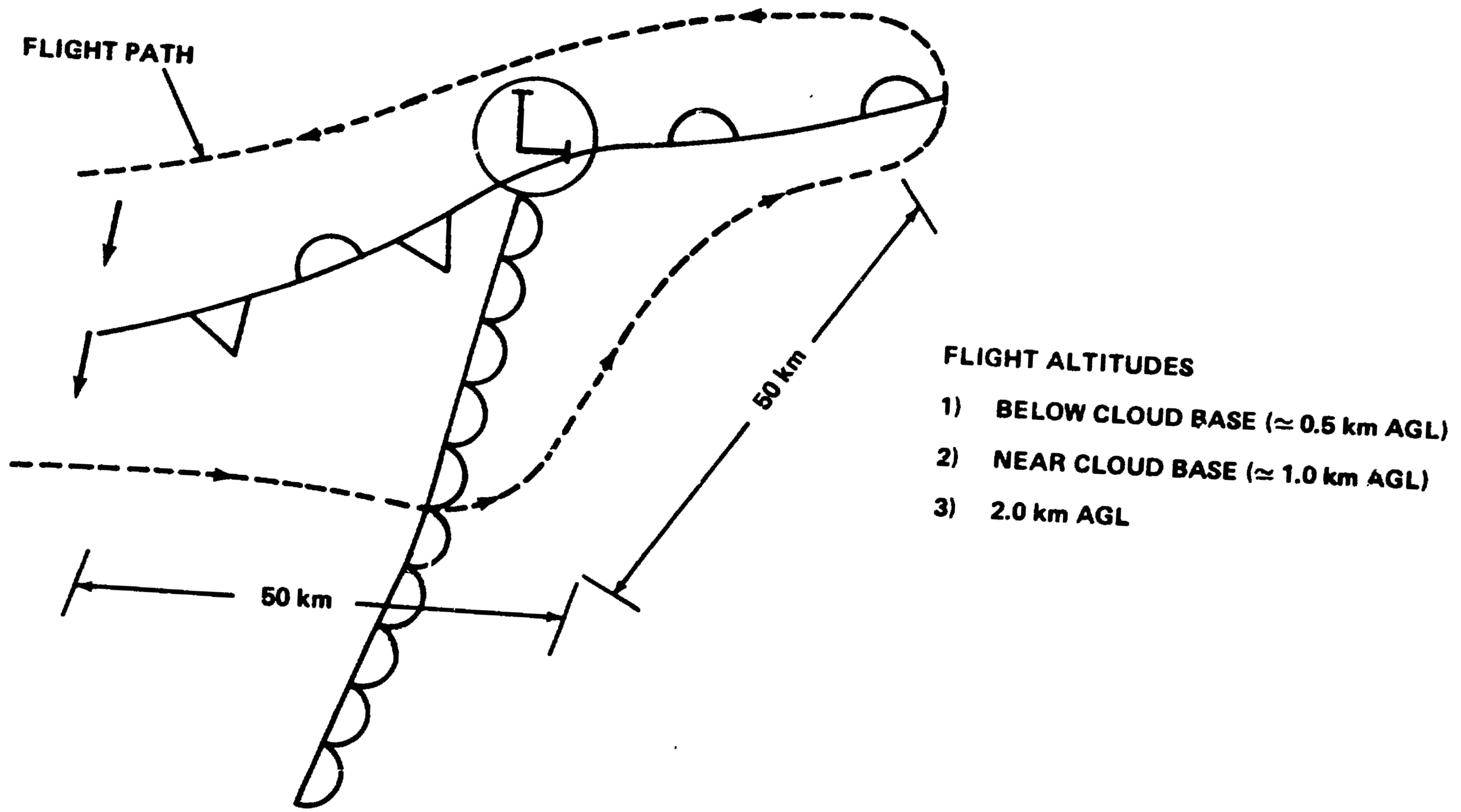


FIGURE 4.11 FLIGHT PATH TO SAMPLE DRYLINE - FRONT INTERSECTION. USING THE SAME PROCEDURE FOLLOWED FOR FLYING ALONG FRONTAL ZONES.

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The entire time between prestorm and thunderstorm development should last approximately as long as the maximum CV-990 test duration time (5 to 6 hours). Thus, if weather conditions were just right, it would be possible to complete two entire cumulonimbus flights consisting of the various parts given above. Two such flights, together with the boundary layer convection and nighttime boundary layer flights, would exhaust the flight time available. It is likely that at least one falsestart into seemingly prestorm conditions without subsequent cumulonumbus clouds will occur. The frequency of occurrence for thunderstorm in July in Central Oklahoma is very low. Hopefully, falsestarts can be terminated before too much aircraft time is used. However, they will serve the useful purpose of comparison with the prestorm conditions that do lead to thunderstorms.

4.2.4.1 LATERAL ENTRAINMENT EXPERIMENT

In this case square boxes should be flown at mid-cloud height around early or mature convective storms as shown in Figure 4-17 for CCOPE without chaff release. The pattern should be close enough to the cloud so that the lidar signal is strong right up to cloud edge. The radar will be used to volume scan the storm to obtain complementary measures of mixing. If cloud development continues, the flight should proceed upwards to the next phases -- turret top measurements and the anvil cloud study.

4.2.4.2 CLOUD TOP TURRET EXPERIMENT

In this experiment the motion of the convective cloud surface at the top and sides of cloud turrets will be measured. The flight plan consists of a circular flight path above the turret, as shown in Figure 4-20. The Doppler lidar will provide line-of-sight velocity measurements at 300 m long contiguous range bins in the cloud-free region between the cloud and the aircraft, and possibly a short distance into the cloud. Radar measurements will complement this data. The flight will be continued for at least one complete circuit around the turret. Additional turret flights will be started until cloud development has proceeded far enough so that the anvil cloud study or gust front measurements can be started.

4.2.4.3 ANVIL CLOUD EXPEIRMENT

This flight consists of rectangles oriented so that the long side is parallel to the anvil and is shown in Figure 4-18. The lidar will be used to obtain horizontal wind field measurements. Concurrent measurements of wind fields in and about the anvil cloud will be made by the radars. Radar returns from anvil regions depend mainly on the size of the scatterers that are present. The radar data, therefore, will either be complementary or comparable with that obtained by the lidar.

The anvil cloud flight will proceed until the flight time is exhausted, darkness interferes, or a gust front is observed.

4.2.4.4 GUST FRONT EXPERIMENT

The formation of a thunderstorm gust front within the radar measurement area would present a superb opportunity for the lidar system. The aircraft could be directed to the most promising areas, based on the clear-air radar returns. The flight pattern would be shown in Figure 4-12, and at the altitude and position indicated by the radar returns or visual observation. As in the prestorm case, the aircraft will be directed by the FAA controller and the targeted storm chosen by the science team. The flight leg nearest the storm will be flown only if allowed by FAA flight guidelines. It is anticipated that a gust front, once formed, would last long enough for the aircraft to descend to the proper altitude.

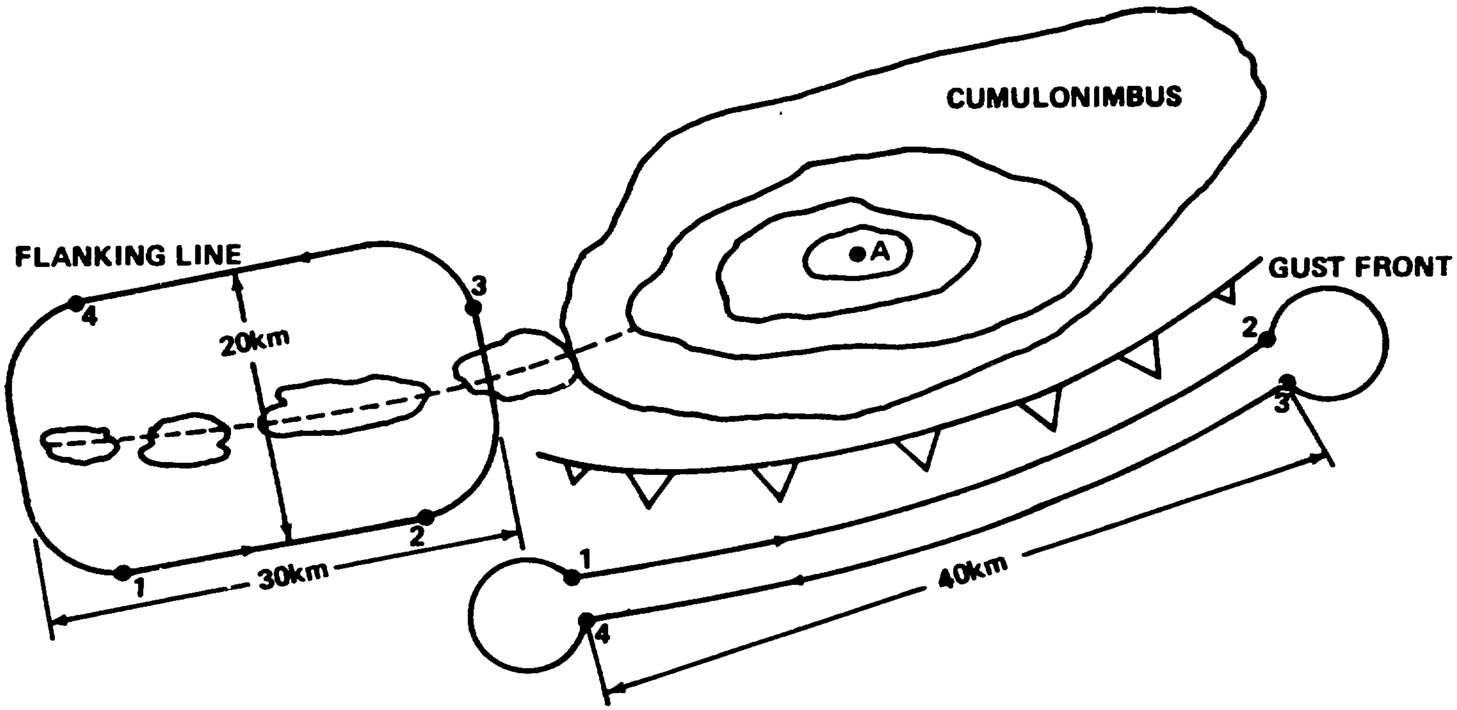
4.2.4.5 FLANKING LINE EXPERIMENT

After the gust front experiment the flanking line experiment will be performed if permitted by aircraft safety considerations. The flight path consists of a racetrack pattern approximately 200 m below cloud base. The flight path is depicted in Figure 4-12 and is similar to the cloud line/frontal zone experiment depicted in Figure 4-10.

4.3 MONTANA TESTS - CCOPE

This section provides descriptions for the DLS CV-990 tests planned for performance in conjunction with CCOPE. Table 4-1 provides a listing of the DLS/CV-990 tests to be performed at CCOPE. Each test is classified according to the portion of CCOPE the test is to perform, i.e. prestorm, early storm, mature storm.

FIGURE 4.12 GUST FRONT AND FLANKING LINE EXPERIMENTS



FLANKING LINE

1. BEGIN FLIGHT PARALLEL TO FLANKING LINE. DOPPLER LIDAR WILL BE POINTED TOWARD FLANKING CUMULUS LINE. FLIGHT ALTITUDE ~ 200 M BELOW CLOUD BASE.
2. EXECUTE 90° TURN SUFFICIENTLY FAR FROM STORM CENTER "A" TO SATISFY CV–990 STORM AVOIDANCE DISTANCE CONSTRAINT. FLY NORMAL TO PLANKING LINE. OTHER–WISE EXECUTE SHARP RIGHT TURN AND TERM–INATE TEST.
3. EXECUTE 90° TURN, FLY PARALLEL TO FLANK–ING LINE
4. EXECUTE 90° TURN, FLY NORMAL TO FLANKING LINE, COMPLETE RACE TRACK PATTERN. IF TIME PERMITS EXECUTE SECOND RACE TRACK.

GUST FRONT

1. BEGIN FLIGHT. DOPPLER LIDAR WILL BE POINTED TOWARD COLD AIR OUTFLOW. DESIRED FLIGHT ALTITUDES 100,300,1000, 2000m.
2. COMPLETE FIRST LEG AND INITIATE 360° TURN
3. BEGIN RETURN FLIGHT LEG;DOPPLER LIDAR WILL BE POINTED TOWARD WARM
4. COMPLETE RETURN LEG – 2 OPTIONS
   a. EXECUTE 360° TURN AND INITIATE NEW RUN AT 1
   b. INITIATE FLANKING LINE EXPERIMENT

TABLE 4-1

LIST OF DLS/CV-990 TESTS PLANNED FOR CCOPE EXPERIMENT

	CCOPE Phase		
	Prestorm	Early Storm	Mature Storm
Boundary Layer Turbulence Experiment	X		
Feeder Flow Experiment	X	X	
Lateral Entrainment Experiment		X	
Anvil Cloud Experiment			X
Gust Front Experiment			X
Cloud Top Experiment		X	

To facilitate the preflight planning of DLS/CV-990 tests with CCOPE a member of the DLS science team will be stationed at CCOPE Headquarters at Miles City, Montana. This individual will coordinate DLS/CV-990 tests with the CCOPE team and the DLS science team and will participate in preflight telephone conferences between CCOPE and the DLS/CV-990 teams. A FM transmitter/receiver to be provided by CCOPE for installation in the CV-990 will permit communications between the CCOPE control center and the CV-990. This receiver will be located in the CV-990 mission manager's console. This communication link will permit inflight coordination between the CCOPE and CV-990/DLS science teams. It is expected that the DLS team member located at Miles City will play a key role in this communications link between the CV-990 and the CCOPE operations center.

Below 2.1 km (7000 ft MSL) the CV-990 will require VFR/VMC flight conditions at CCOPE. This constraint results from the inability for aircraft to be detected by radar at the Salt Lake City FAA Flight Center. Above 2.1 km (7000 ft) the CV-990 will fly under IFR flight rules.

4.3.1 BOUNDARY LAYER TURBULENCE EXPERIMENT

The objective of this experiment is to (1) verify the MSFC Doppler lidar design and (2) obtain detailed horizontal components for characterization of the prestorm atmospheric boundary layer, estimation of turbulence statistics (two-dimensional spectra, etc.), improving our knowledge of planetary boundary layer flow over nonhomogeneous terrain.

Flight Plans: To satisfy the first objective it is planned that the CV-990 will fly horizontal square flight paths as shown in Figure 4-13 (option #1) at altitudes and at a horizontal location in which concurrent measurements are being made with Doppler radars in the CCOPE network. It is anticipated a flight path square will be approximately 15-25 km on a side with 270^{o} turns on each corner. To satisfy the second objective, it is planned that the CV-990 will fly a series of vertically and alternately stacked straight and level flight paths with the lowest one approximately at 100 m above natural grade with additional legs at 300, 600, 1000 m, etc. to a height just above the PBL temperature inversion (option #2) as shown in Figure 4-14. It is anticipated that the straight and level flight legs will be oriented generally from east to west. The flight plan can be initiated from the 100 m level or at the level just above the inversion. The west to east and east to west legs are separated in the vertical as noted above and separated in the horizontal by approximately 10 km. At the end of a flight leg the CV-990 will execute a 180^{o} turn ascending or

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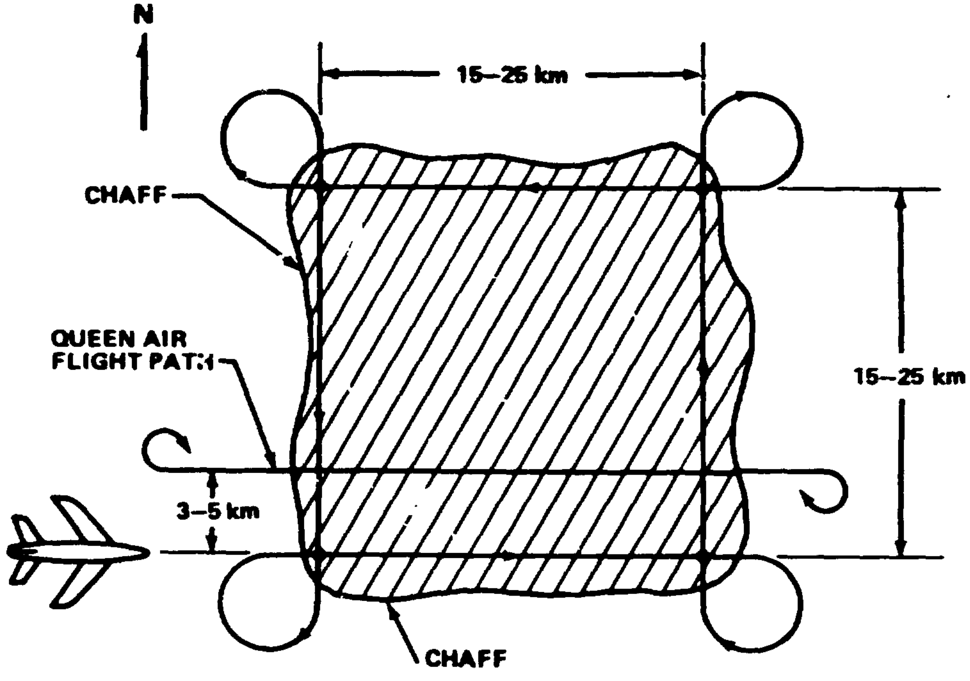
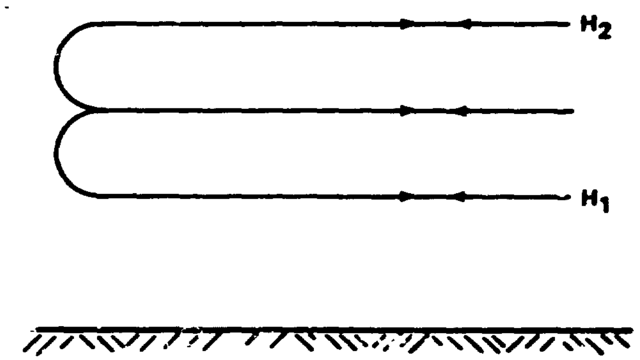
BOUNDARY LAYER TURBULENCE STUDY

(OPTION # 1)



PLAN VIEW



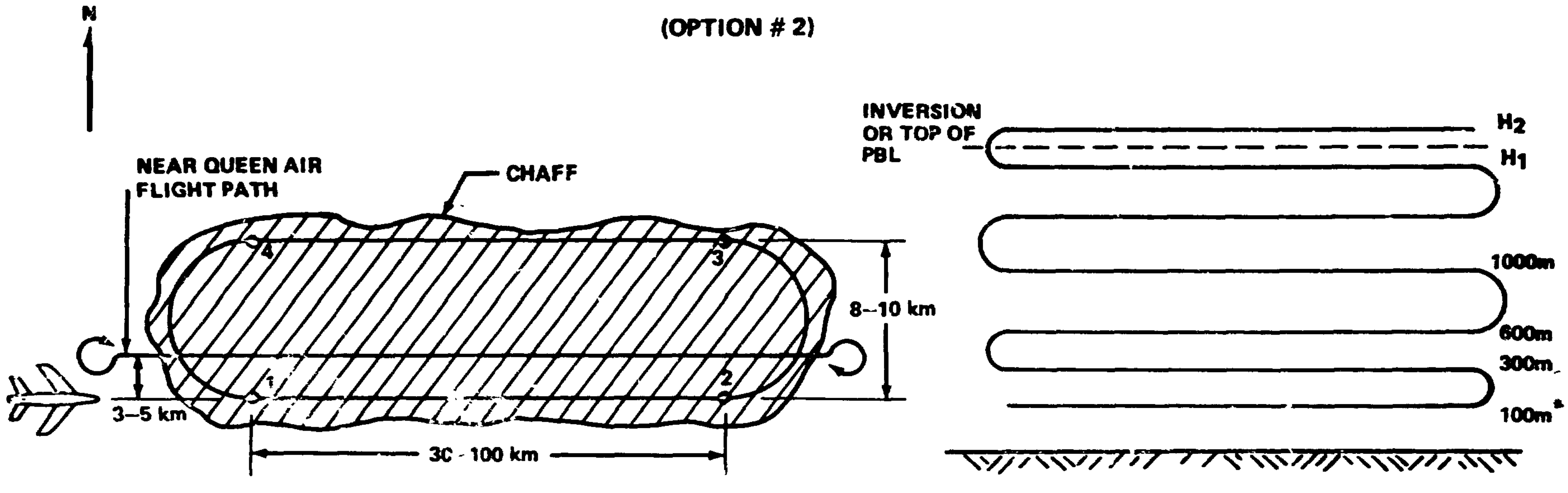
SIDE VIEW

1. BEGIN FLIGHT AT EITHER H_1 OR H_2
2. FLY HORIZONTAL SQUARES AT ALTITUDES IN WHICH DOPPLER RADAR WIND DATA IS BEING ACQUIRED
3. EXECUTE 270° AT CORNERS OF SQUARE
4. ALTITUDE CHANGES TAKE PLACE DURING 270° TURN
5. CHAFF RELEASE PRIOR TO TEST IS REQUIRED

FIGURE 4-13

BOUNDARY LAYER TURBULENCE STUDY

(OPTION # 2)



PLAN VIEW

SIDE VIEW

FLIGHT OPERATIONS

1. BEGIN HORIZONTAL AND LEVEL FLIGHT LEG AT ALTITUDE H_2 (ALTITUDE JUST ABOVE INVERSION) OR THE 100–METER LEVEL
2. EXECUTE 180° TURN AND ASCEND OR DESCEND TO NEXT LEVEL
3. BEGIN NEXT HORIZONTAL AND LEVEL FLIGHT LEG
4. EXECUTE 180° TURN AND ASCEND OR DESCEND TO NEXT LEVEL.
5. COMPLETE OTHER ALTITUDES AS ABOVE
6. NCAR QUEEN AIR FLYS AT SAME ALTITUDE AS CV–990 FOR SELECTED FLIGHT ALTITUDES.

NOTES

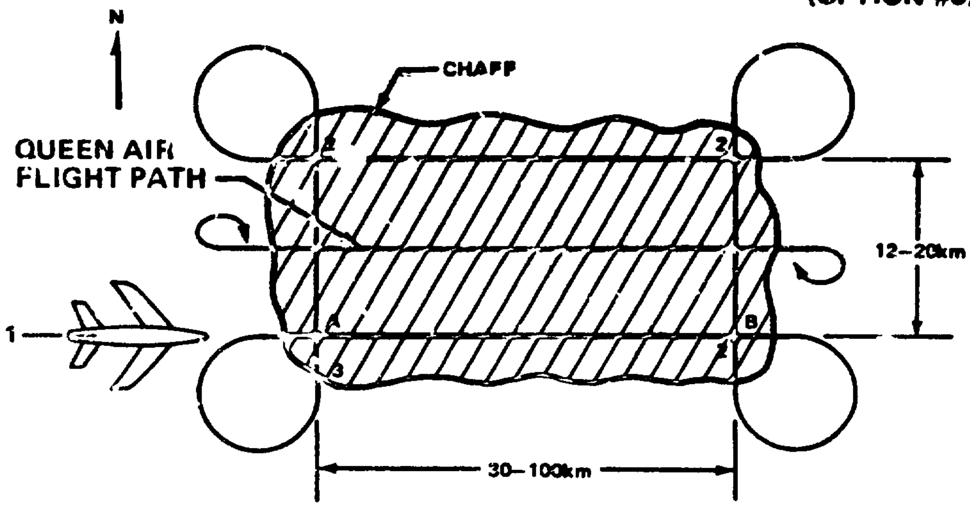
1. CHAFF RELEASE DESIRED–PREFERABLY OVER COMPLETE TEST AREA
2. IF CLOUDS PRESENT RECORD ON FILM OR VIDEO TAPE.

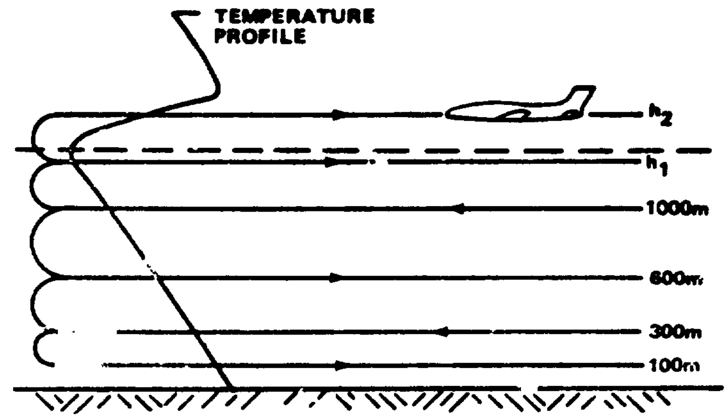
FIGURE 4-14

descending to the next appropriate altitude to execute the next leg. This will result in a vertical stack of east to west flight paths and a second vertical stack of west to east flight paths displaced from the first by approximately 10 km to the south or north depending where the first leg is initiated. A possible variation of this flight plan is to fly stacked rectangular flight paths with east-west and west-east legs at the same altitude and step through the various required altitudes from one rectangle to the next (option #3) as shown in Figure 4-15. In this case the CV-990 would execute 270° turns at the corners of the rectangles or possibly execute a single 180° turn in place of two 270° turns to save flight time.

Measurements Desired: The CV-990 will be used as a platform to acquire horizontal wind component measurements. In support of our first objective we desire Doppler radar wind measurements whenever possible, preferably in association with chaff releases. To provide further support relative to the verification of the DLS it would be extremely beneficial if in situ turbulence measurements were acquired within the DLS measurement region with the NCAR Queen Air. In this case the Queen Air would fly 3-5 km to the side of the CV-990 in a parallel flight path. This data could be acquired during the execution of the square flight paths or the east-west oriented flight legs.

BOUNDARY LAYER TURBULENCE STUDY
(OPTION #3)





PLAN VIEW

FLIGHT OPERATIONS

1. BEGIN FLIGHT EITHER AT h_2 (ALTITUDE JUST ABOVE INVERSION) OR AT 100–METER LEVEL
2. EXECUTE 270° TURN (180° TURN ALSO POSSIBLE BETWEEN LEG (A,B) AND OTHER PARALLEL LEG
3. COMPLETE RECTANGLE – 2 OPTIONS
   a. GO TO NEXT ALTITUDE LEVEL
   b. TERMINATE TEST

SIDE VIEW

NOTES

1. TEST CAN BE PERFORMED
   a. INROUTE ON FERRY RUNS – IN THIS CASE RECTANGLE MAY NOT BE FLOWN
   b. IN CONJUNCTION WITH DOPPLER RADARS
2. PERFORM TESTS WHEN NO CLOUDS IN RECTANGLE AT AIRCRAFT ALTITUDE
3. IF CLOUDS PRESENT ABOVE RECORD ON FILM OR VIDEO TAPE PICTURES OF CLOUDS LATERAL TO FLIGHT PATH
4. CHAFF RELEASE DESIRED – PREFERABLY OVER COMPLETE TEST AREA

FIGURE 3-15

To conduct scientific studies with the CV-990 / DLS data we desire the data that will be acquired from the Doppler radars (wind data), CCOPE surface network and the upper-air network for the time period encompassing the Boundary Layer Turbulence Experiment period plus time periods (to be determined) before and after the CV-990/ DLS data acquisition period. Additional data from other aircraft may be required at a later date. We plan to perform these tests in conjunction with the prestorm field experiments.

Operation Procedures: We plan to perform these tests in conjunction with the prestorm CCOPE field experiments. Flight option #1 is a contingency flight option which we plan to execute first in the event chaff could not be released over the complete extent of the flight path planned for options #2 and #3. We plan to execute approximately 4-6 option #1 flight squares which will require 1 to 1.5 hours of total flight time. We would then execute flight option #2. Assuming six altitudes are involved, option #2 would require .75-1.5 hours. With the current constraints on total CV-990 flight hours available for CCOPE, available on-station time and other DLS experiment requirements we anticipate flight option #2 will be performed 2 or 3 times during a single mission; however, opportunities may arise for executing option #2 on other CCOPE CV-990 missions. Option #2 is our primary flight pattern. Option #1 is an alternative in the event chaff could not be provided in sufficient volume. Option #3 will require approximately 1.25 to 2 hours to accomplish. It is an alternative plan to option #2 and would only be implemented if it is decided that two successive passes through a given altitude region are required instead of one pass as in option #2. Coordination between the CV-990, CCOPE mission headquarters at Miles City and the Queen Air will be required to assure that the Queen Air (gust probe measurements) flies at the CV-990 altitude and at a range lateral to the CV-990 from which DLS returns are being acquired (i.e. at a range with sufficient aerosol for laser radiation backscatter).

Meteorological Conditions: This experiment requires a situation which is characterized by (1) a fully turbulent convective boundary layer during the morning, (2) with an attendant cumulus cloud field forming in the afternoon and (3) transmission to a cumulus congestus stage.

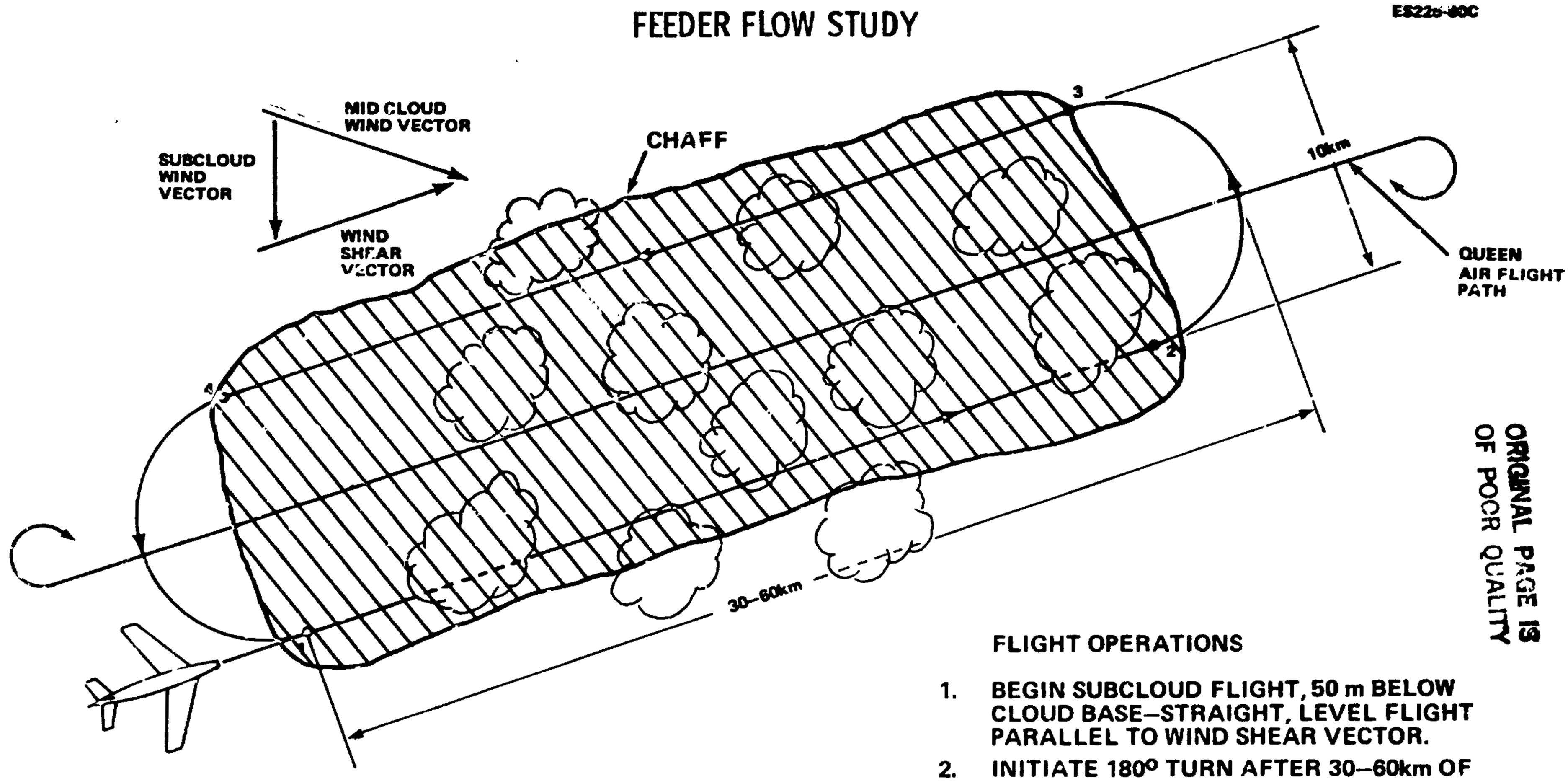
4.3.2 FEEDER FLOW EXPERIMENT

In this experiment we seek to measure the horizontal flow at selected altitudes below a field of cumulus cloud. The scientific motivation for this effort is to acquire sufficient data so that divergence, deformation, and vorticity fields beneath a cumulus cloud cluster can be calculated with Nyquist wavelength ~600 m. The altitudes we would like to fly at beneath cumulus cloud base ranges between 150 m-1.5 km (500-5000 ft) measured from cloud base. This effort is closely related to the Boundary Layer Turbulence (BLT) Experiment. The present experiment in all liklihood would be performed after the BLT Experiment.

Flight Plans: The flight plan consists of an elongated racetrack flight path executed at various levels beneath cloud base (see Figure 4-16). We plan to execute straight and level flight except during turns. During each turn the CV-990 will descend to the next prescribed altitude for conduct of the next straight and level flight leg. Initial flight altitude will be approximately 50 m below cloud base. Successive flight legs are anticipated to be flown at 150-300 m altitude increments. In plan view the flight path looks like a racetrack pattern consisting of two paralle legs (not at same altitude) 30-60 km in length connected by 180^{o} turns. The parallel legs will be separated by a horizontal distance approximately equal to 10 km.

Measurements Desired: The DLS will be used to acquire horizontal wind component measurements at 300 m intervals out to an approximate distance of 10 km

FEEDER FLOW STUDY



NOTES

1. RECORD ON FILM OR VIDEO TAPE PICTURES OF CLOUD BASES ALONG FLIGHT PATH
2. ACQUIRE WIND FIELD MEASUREMENTS WITH DOPPLER RADAR
3. OPERATE DOPPLER LIDAR IN FORWARD AND AFT SCANNING MODE
4. CHAFF MAY BE REQUIRED TO OBTAIN "GROUND TRUTH" DOPPLER RADAR WINDS

FLIGHT OPERATIONS

1. BEGIN SUBCLOUD FLIGHT, 50 m BELOW CLOUD BASE–STRAIGHT, LEVEL FLIGHT PARALLEL TO WIND SHEAR VECTOR.
2. INITIATE 180° TURN AFTER 30–60km OF FLIGHT DESCEND TO NEXT LEVEL (100 300 m ALTITUDE INCREMENTS)
3. RESUME STRAIGHT, LEVEL FLIGHT PARALLEL TO WIND SHEAR VECTOR

FIGURE 4-16

lateral to the CV-990 aircraft flight path. We anticipate CCOPE support relative to providing "ground truth" measurements with the CCOPE Doppler radars and the NCAR Queen Air with the capability of providing *in situ* turbulence measurements. Chaff releases may be required to acquire winds with the Doppler radars. We anticipate the NCAR Queen Air, instrumented with gust probes, will be used to acquire turbulence data along a flight path paralle to the CV-990 flight path with both airplanes being at the same altitude space 3-5 km apart. The Queen Air gust probe data as well as data from the CCOPE surface and upper-air networks are desired for postflight analysis of the Doppler lidar data.

Operations Procedures: We plan to perform this test in conjunction with the prestorm and early storm CCOPE field experiments. Assuming that six straight and level flight legs will be flown to execute the flight plan, a total of 0.5 to 1 hour of CV-990 flight time will be required depending on the length of the racetrack flight plan selected. We plan to allocate 2-3 hours to the cumulus feeder experiment which will permit as few as three and as many as six executions of this flight plan during a single mission or spread out over a number of CV-990 missions. Coordination between the CV-990, CCOPE mission headquarters at Miles City and the Queen Air will be required to assure that the Queen Air (for gust probe measurements) flies at the CV-990 altitude and at a range lateral to the CV-990 from which DLS returns are being acquired (i.e. at a range with sufficient aerosol for laser radiation back-scatter). It is anticipated that the feeder flow flight plan will be executed immediately after the execution of the Boundary Layer Turbulence Experiment (Section 4.3.1). We plan to fly the Cumulus Feeder Flow Flight Experiment flight plan for a total of 2-3 hours which will permit 3-6 executions of the flight plan on a single mission or spread out over a number of missions.

Meteorological Conditions: This experiment requires a situation which is characterized by (1) a fully turbulent convective boundary layer during the morning, (2) with an attendant cumulus cloud field forming in the afternoon and (3) transitioning to a cumulus congestus stage.

4.3.3 LATERAL ENTRAINMENT EXPERIMENT

The objective of this experiment is to measure the horizontal vector wind field of the flow around an early storm/mature storm convective storm with a view toward gaining new insights into lateral entrainment processes associated with growing convective storms.

Flight Plans: The flight plan consists of a square/rectangular flight path about a growing convective storm cloud as shown in Figure 4-17. The typical flight leg of the square is 20-40 km. We plan to execute the experiment

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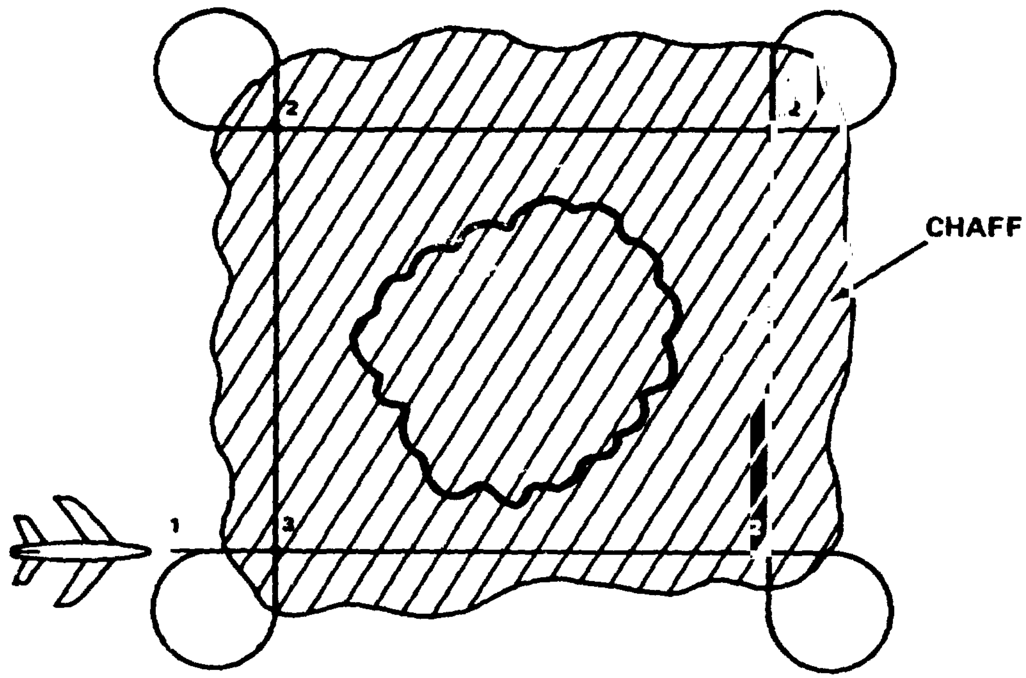
LATERAL ENTRAINMENT STUDY



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FLIGHT OPERATIONS

1. BEGIN SQUARE/RECTANGLE FLIGHT PATH—STRAIGHT AND LEVEL
2. EXECUTE 270° TURN
3. EXECUTE 270° TURN AND DESCEND OF ASCEND TO NEXT LEVEL AND EXECUTE SQUARE/RECTANGLE FLIGHT PATH AT NEW LEVEL

NOTES

1. RECORD ON FILM OR VIDEO TAPE PICTURES OF CLOUDS FORWARD AND LATERAL TO LEFT OF FLIGHT PATH
2. OPERATE DOPPLER LIDAR IN FORWARD AND AFT SCANNING MODE
3. CHAFF RELEASE MAY BE REQUIRED TO ACQUIRE DOPPLER RADAR WIND MEASUREMENTS

FIGURE 4-17

at mid-cloud height and plan to fly 2-3 different altitudes (3,000, 5,000, and 7,000 m for example). Each altitude will be characterized by a complete square/rectangular flight path.

Measurements Desired: We plan to perform this experiment in conjunction with the early storm and mature storm CCOPE field experiments. Concurrent Doppler radar wind field measurements would be highly desirable. This may require a chaff release; however, these measurements (radar/lidar) would provide a rather complete mapping of the flow in convective storms (both interior and exterior), as well as "ground truth" data for DLS verification. We also desire data from the CCOPE surface and upper air networks, as well as any gust probe data from the NCAR Queen Air.

Operations Procedures: We plan to perform this test in conjunction with the early storm/mature storm CCOPE field experiments. A chaff release will be required prior to the flight of the CV-990. Close coordination will be required between aircraft flying in this experiment. We anticipate that the CV-990 will fly under IFR flight conditions.

We anticipate that execution of each flight square will require 0.5 hr so that a complete test of three altitudes will require approximately 1.5 hours.

We plan to fly this flight plan at least once and if conditions are appropriate so as to result in a coordinated test involving CCOPE aircraft and the CV-990 on a well defined isolated convective storm a second test may be possible. We envisiion that this test would be performed after the cumulus feeder flow experiment flight. The use of the CV-990 in a sequence of tests (boundary layer turbulence, feeder flow, lateral entrainment, etc.) will result in efficient use of the CV-990.

Meteorological Conditions: We desire a growing convective storm which is isolated, so that a complete circuit can be flown about the cloud. The presence of additional convective storms may preclude the accomplishment of a complete circuit due to a minimum horizontal distance that must be maintained between the CV-990 and a severe storm.

4.3.4 ANVIL CLOUD EXPERIMENT

The objective of this experiment is to make detailed measurements of the flow field associated with an anvil cloud. The idea is to acquire sufficient wind information to estimate net liquid water/ice and water vapor export out of the top of a convective storm.

Flight Plans: The flight path consists of rectangles oriented so that the long side is parallel to the anvil and extends over the complete length of anvil (~25-100 km as shown in Figure 4-18). The width of the rectangle will be

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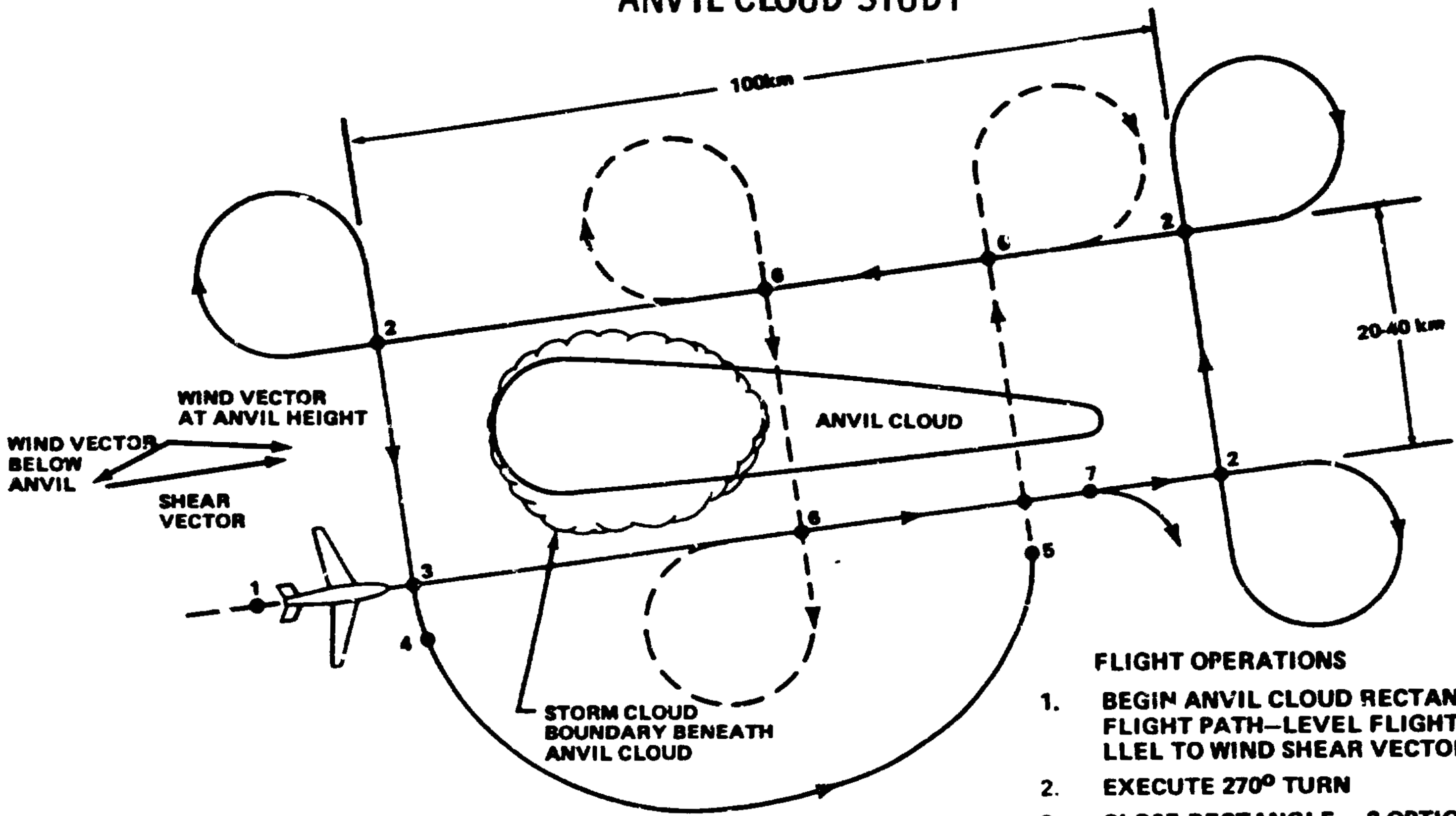
ANVIL CLOUD STUDY



NOTES

1. RECORD ON FILM OR VIDEO TAPE PICTURES OF CLOUDS FORWARD AND LATERAL TO LEFT OF FLIGHT PATH
2. OPERATE DOPPLE LIDAR IN FORWARD AND AFT SCANNING MODE

FLIGHT OPERATIONS

1. BEGIN ANVIL CLOUD RECTANGLE FLIGHT PATH—LEVEL FLIGHT PARALLEL TO WIND SHEAR VECTOR
2. EXECUTE 270° TURN
3. CLOSE RECTANGLE – 2 OPTIONS
   a. EXECUTE 270° TURN AND FLY ANVIL RECTANGLE AGAIN
   b. PROCEED TO 4
4. INITIATE 180° TURN AND DESCEND TO 3–5 k FT BELOW ANVIL
5. BEGIN SUB–ANVIL CLOUD RECTANGLE FLIGHT PATH–LEVEL FLIGHT
6. EXECUTE 270° TURN
7. CLOSE RECTANGLE – 3 OPTIONS
   a. EXECUTE 270° AND FLY SAME SUB–ANVIL CLOUD RECTANGLE
   b. EXECUTE 270° AND DESCEND ANOTHER 3–5 k FT AND FLY NEW RECTANGLE
   c. GO TO OTHER TARGETS OF OPPORTUNITY

FIGURE 4-18

~20 to 40 km. The actual width will depend on operational constraints and the minimum distance that the CV-990 must maintain from the storm. We would like to fly around an isolated anvil cloud. If other storms are in the area they may preclude a complete trajectory around the selected anvil because constraints on CV-990/storm separation distance. After execution of the flight about the anvil the CV-990 would descend in altitude and a fly square/rectangle flight path beneath the anvil, downstream from the storm proper to obtain horizontal vector wind field measurements and Doppler lidar backscatter intensity measurements to obtain a measure of the amount of fallout from the anvil, as well as debris from the storm.

Measurements Desired: The Doppler lidar will be used to acquire horizontal vector winds field measurements. Concurrent measurements of wind fields in and about the anvil cloud acquired with the CCOPE Doppler radars are desired for both "ground truth" for DLS verification and for construction of the "total" wind field associated with the anvil. Measurements of liquid water/ice densities (mass per unit volume of air and liquid water/ice) in the anvil and temperature and dewpoint both in and out of the anvil will be needed for the calculation of water vapor and liquid/water fluxes out of the top of the convective storm. <u>In situ</u>

measurements of wind in and around to the anvil via the INS on the NCAR Sabreliner would also be highly desirable for both verification of the DLS and scientific applications.

Operations Procedures: We plan to perform these tests in conjunction with the mature storm CCOPE field experiments. We anticipate that the CV-990 will be assigned a flight altitude for conduct of the first portion of the flight plan, namely flight around anvil cloud. Once the CV-990 is on-station an assessment would be required by the CV-990 crew and the onboard science team as to whether-or-not the assigned altitude is appropriate. If not, adjustments in flight altitude of the CV-990 would be required. This will require coordination between the FAA Flight Center involved, the CCOPE Mission Operations Center at Miles City, the CV-990 and other airplanes flying in the neighborhood of the anvil. Upon completion of the flight trajectory above the anvil appropriate coordination betweenthe above stated groups would again be required for the CV-990 to descend to an appropriate altitude below the anvil (approximately 500-3,000 m below the anvil) and execute a square/rectangular flight path. If all goes well the anvil cloud experiment would be performed after the cumulus feeder flow and lateral entrainment experiments. A succession of CV-990 experiments, i.e. Boundary Layer Turbulence Experiment first, Cumulus Feeder

Flow Experiment next, followed by the Lateral Entrainment Experiment next, and finally the Anvil Cloud Experiment, would result in the most efficient use of the CV-990. It is anticipated that this ideal execution of CV-990 flight plans may not be possible. However, we plan to strive toward it as a goal.

We anticipate this test will require approximately 0.75 to 1 hour to complete the anvil cloud trajectory and approximately 0.5 hour to complete the sub-anvil cloud trajectory for a total of approximately 1.5 hour.

We plan to accomplish at least one test and if sufficient time is available possibly a second test (on a different anvil) could be performed.

Meteorological Conditions: This experiment will require convective storm in the mature stage of development, characterized by an anvil cloud configuration. It would be best for CV-990 operations if a single isolated storm were selected for the experiment. In the case of clustered storms or squall lines the CV-990 may not be able to perform a complete circuit around the anvil cloud due to requirements on the CV-990 to maintain a minimum separation from convective storms as described in Section 3.2.5.

4.3.5 GUST FRONT EXPERIMENT

The objective of this effort is to improve our knowledge of the detailed structure of cold air outflow from thunderstorms.

We will measure the horizontal wind structure both in, and above the outflow as well as the horizontal flow in the warm air which moves up and over the cold air outflow and ultimately enters the convective storm.

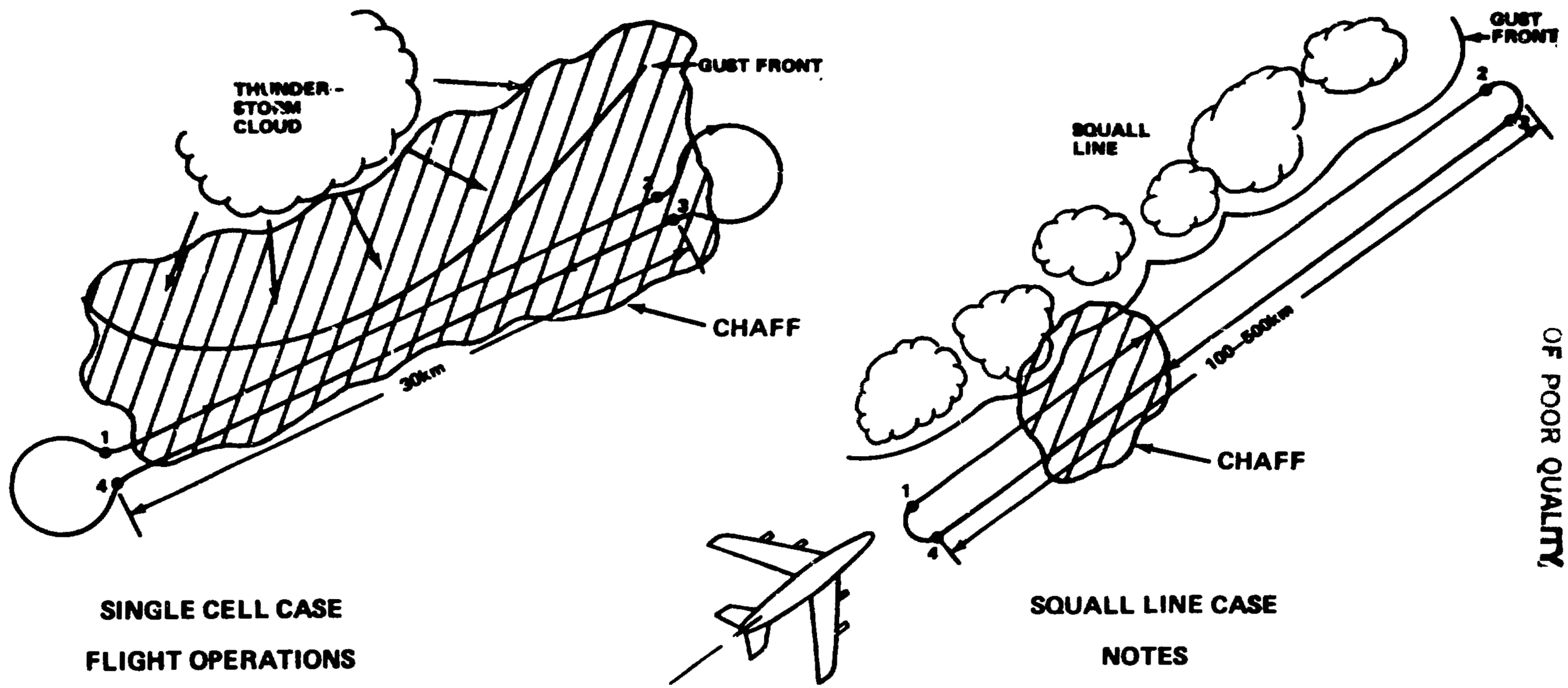
Flight Plans: In this experiment we plan to fly parallel to a cold air outflow gust front in the warm air as shown in Figure 4-19. We will fly the CV-990 such that the DLS will be looking into the cold air from the left side of the CV-990. We will fly parallel to the cold air outflow, ~30 km for a single storm, and ~100-500 km for a squall line. At the end of the first leg we will execute a 180° turn and again fly parallel to the cold air outflow, but with Doppler lidar pointed into the warm air. We plan to fly at altitudes of 100, 300, 1000, 2000 m. It is anticipated that this experiment will be performed in conjunction with the mature storm squall line experiment.

Measurements Desired: We will be acquiring data on horizontal vector wind fields. To analyze these data we will require the data acquired from the CCOPE surface and upper-air networks. We also desire wind data acquired by the Doppler radars (may require chaff release). Radar echo return data and aircraft turbulence measurements may also be required to do a complete analysis of the DLS data (the amount and kind need to be established via discussions between the CCOPE and DLS project personnel).

C-2

GUST FRONT STUDY

E8226-80C



SINGLE CELL CASE

FLIGHT OPERATIONS

1. BEGIN FLIGHT. DOPPLER LIDAR WILL BE POINTED TOWARD COLD AIR OUTFLOW. DESIRED FLIGHT ALTITUDES 100, 300, 1000, 2000m
2. COMPLETE FIRST LEG AND INITIATE 360° TURN
3. BEGIN RETURN FLIGHT LEG. DOPPLER LIDAR WILL BE POINTED TOWARD WARM AIR
4. COMPLETE RETURN LEG – 2 OPTIONS
   a. EXECUTE 360° TURN AND INITIATE NEW RUN AT 1
   b. TERMINATE TEST

SQUALL LINE CASE

NOTES

1. OPERATE DOPPLER LIDAR IN FORWARD AND AFT SCANNING MODE
2. RECORD ON FILM OR VIDEO TAPE PICTURES OF CLOUDS FORWARD AND LATERAL OR FLIGHT PATH.
3. CHAFF RELEASE WOULD BE HIGHLY DESIRABLE FOR ACQUISITION OF DOPPLER RADAR WIND MEASUREMENTS

FIGURE 4-19

Operations Procedures: We view the gust front study as a "science of opportunity" mission. The only way the CV-990 will be able to fly the gust front experiment is to be in the air and available for CCOPE mission control to vector the CV-990 to the gust front location. Thus close communications will be required between the CCOPE mission control and the CV-990 to take advantage of a gust front episode. We anticipate that one opportunity will be available for the gust front study and that 1-3 hours will be required to accomplish this test. We desire two opportunities to fly the gust front flight plan.

Meteorological Conditions: This experiment requires a well defined cold air outflow wherein the warm air region 1-2 km from the gust front (measured perpendicular to the front) is free of cloud. Furthermore the cold air outflow in the vicinity of the leading edge and above the nose of the front should also be free of cloud.

4.3.6 CLOUD TOP EXPERIMENT

In this experment we seek to measure the motion of convective cloud surface at the top and sides of cloud turrets where it is thought that the entrainment of dry air into the cloud begins.

Flight Plans: The flight plan consists of a circular flight path at heigh H_A above sea level and height H_C

above the point of interest on the turret cloud as shown in Figure 4-20. The turning radius is R_a. The bank angle of the aircraft θ_a is a function of R_a. The Doppler lidar beam will be aimed at angle θ_D below the planform of the aircraft.

Measurements Desired: In this experiment the DLS beam will be fixed relative to the CV-990 and will lie in the vertical plane defined by the aircraft flight path radius vector (R_a) and the local vertical. The Doppler lidar will provide line-of-sight velocity measurements at 300 m long contiguous range bins in the cloud free region between the cloud and the aircraft and possibly a short distance into the cloud. In this 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, the DLS will be operating such that the capacity of the data system will be recording as much information as possible about the regions of penetration just into the cloud surface, and from the air just outside.

To support these tests, it would be highlv desirable to obtain concurrent measurements of wind fields in and

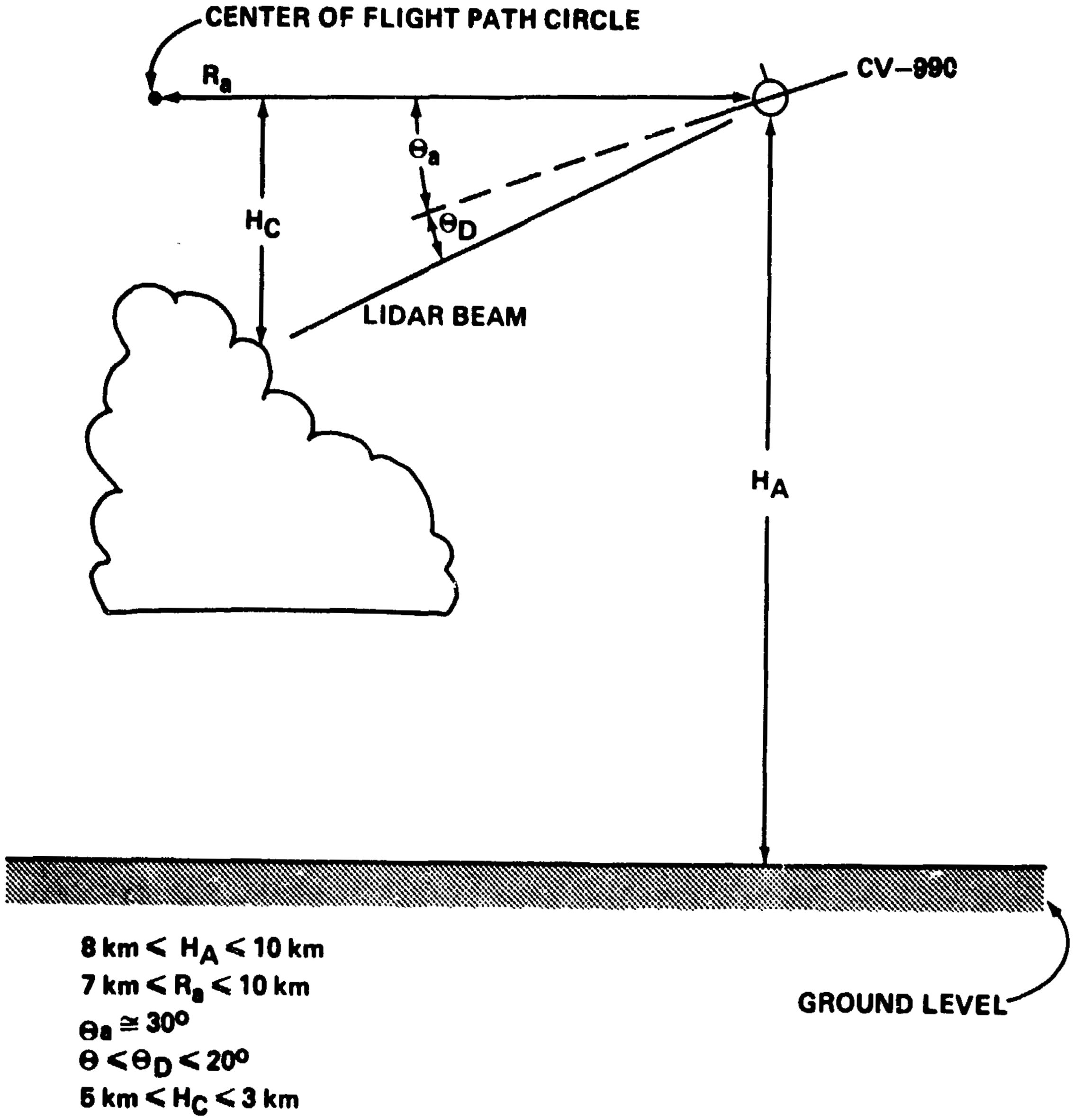


FIGURE 4–20 CLOUD TOP EXPERIMENT

about the turret cloud with the CCOPE Doppler radars. A chaff release may be required to obtain these measurements.

Operations Procedures: Typically the clouds that will be selected for study will be growing convective clouds with tops ranging from 5 to 8 km. The aircraft will be at 10 km altitude. Once the cloud is selected, estimates of the turn radius and circular flight path center (relative to the cloud) will be made. The aircraft will fly a circular flight path about the turret cloud. The DLS optics will permit the DLS beam to be deflected downwards by as much as 20^{o}. The aircraft can maintain bank angles of up to 30^{o} in the circular flight paths to be used. Thus, total angular deflections (from the horizontal) of the DLS beam to 50^{o} will be available in this experiment. The bank angle will depend on turning radius. An optical siting device in the cockpit will be used to assure the pilot that he is maintaining contact with the selected cloud turret top via the DLS. We anticipate that the CV-990 will be assigned a flight altitude for conduct of this test. Once the CV-990 is on-station an assessment would be required by the CV-990 crew and the onboard science team as to whether-or-not the assigned altitude is appropriate. If not, adjustments of flight altitude of the CV-990 would be required. This will require coordination between the

FAA Flight Center involved, the CCOPE Mission Operations Center at Miles City, the CV-990, and other airplanes flying in the neighborhood of the cloud selected for study. If all goes well the cloud top experiment would be performed after the Cumulus Feeder Flow and Lateral Entrainment Experiment and prior to the Anvil Cloud Experiment.

It is not clear what duration of this circling flight can be maintained with accuracy and without incapacitating passengers. The actual number of tests to be flown will depend on availability of CV-990 time.

Meteorological Conditions: We desire a growing convective storm which is isolated, so that a complete circuit can be flown about the cloud top. The presence of additional convective storms may preclude the accomplishment of a complete circuit due to minimum horizontal distance that must be maintained between the CV-990 and a severe storm.

4.4 BOULDER-NOAA

The Boulder experiments will be performed at the NOAA Boulder Atmospheric Observation Tower Facility. These tests will be aimed at performing lidar comparison measurements between the DLS and ground-based lidars located at the NOAA Boulder facilities. Final description of these lidar intercomparison tests will be documented separately. A second set of tests concerns flight of the DLS about the NOAA Boulder Tower to acquire concurrent measurements of the wind field with both the DLS and the anemometers and wind vanes on the tower. These tests will be similar to the Walnut Grove, California experiment described in Section 4.1.2. The accomplishment of these tests depends upon FAA approval regarding aircraft noise constraints and safety.

APPENDIX A

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APPENDIX B

Conversion Tables

A. Length:

1 meter = 3.2808 feet
1 kilometer = 0.6214 stat. mile
1 kilometer = 0.5396 naut. mile
1 inch = 2.54 centimeter
1 foot = 0.3048 meters
1 stat. mile = 5280 feet
1 stat. mile = 0.8684 naut. mile
1 stat. mile = 1609.34 meters
1 U.S. naut. mile = 6080.21 feet
1 U.S. naut. mile = 1.85325 kilometers

B. Area:

1 square inch = 6.4516 square cm
1 square foot = 144 square inches

C. Volume:

1 cubic meter = 35.3147 cubic feet
1 liter = 61.0255 cubic inches
1 liter = 33.815 U.S. fl. oz.
1 liter = 1.0567 U.S. quarts

D. Velocity:

1 meter per second = 3.2808 ft. $sec.^{-1}$
1 meter per second = 1.9425 knots
1 meter per second = 2.2369 mi. hr^{-1}

1 kilometer per hr = 0.27778 m $sec.^{-1}$
1 kilometer per hr = 0.5396 knots
1 kilometer per hr = 0.6214 mi. hr^{-1}
1 kilometer per hr = 0.9113 ft. $sec.^{-1}$

1 knot = 1 naut. mi. hr^{-1}
1 knot = 1.1515 mi. hr^{-1}
1 knot = 1.6889 ft. sec.
1 knot = 0.5148 m. $sec.^{-1}$
1 knot = 1.8533 km hr^{-1}

E. Mass:

1 gram(g) = 0.03527 oz.
1 gram(g) = 0.002205 lb.

F. Density:

1 g. cm^{-3} = 62.428 lb. $ft.^{-3}$

G. Pressure:

1 dyne per sq cm = 10^{-3} mb
1 mb = 0.7501 mm Hg (std)
1 mb = 0.0295 in Hg (std)
1 mb = 0.0145 lb. in^{-3}

1 bar = 10^3 mb
1 bar = 10^6 dynes cm^{-2}
1 in. Hg = 33.8639 mb
1 in. Hg = 0.4911 lb. in^{-2}

1 pound in^{-2} = 2.0360 in Hg (std)
1 pound in^{-2} = 68.9476 mb
1 pound in^{-2} = 0.0703 Kg cm^{-2}
1 pound in^{-2} = 51.7149 mm Hg (std)

1 standard atmos = 1013.25 mb
1 standard atmos = 1.0332 Kg cm^{-2}
1 standard atmos = 760 mm Hg (std)
1 standard atmos = 29.9213 in. Hg (std)
1 standard atmos = 14.696 lb in^{-2}

H. Energy per Area:

1 Langley = 1 cal. cm^{-2}

TELEPHONE CONVERSION FORMULAE

$C^o = (5/9)\ (F^o - 32^o)$

$F^o = (9/5)\ C^o + 32^o$

$A^o = C^o + 273^o$

$R^o = (4/9)\ (F^o - 32^o)$

$K^o = C^o + 273.16^o$

PRESSURE VS GEOMETRIC ALTITUDE (*REF)

Pressure (mb)	Altitude ** (meters)	Altitude** (feet)
1013.25	0.0	0.0
1000	100	330
900	1000	3300
800	1950	6400
700	3040	9970
600	4200	13780
500	5550	18200
400	7200	23620
300	9225	30260
200	11800	38710
100	16200	53140

(*U.S. Standard Atmosphere, 1976;
**Not Exact)

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